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A Review of Spontaneous Combustion Problems and Controls with Application to US Coal Mines

Final Technical Report
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A Review of Spontaneous Combustion Problems and Controls with Application to US Coal Mines

Final Technical Report

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ABSTRACT

Expansion of underground coal mining activity in the Western US will increase the risk of spontaneous-combustion-caused mine fires. Such incidents in underground coal mines have, in the past, frequently led to serious financial loss or loss of life.

The first part of this report is a state-of-the-art review and describes the mechanism of coal oxidation and its development to open fire and, based on overseas experience, the mining and geological conditions with which are associated a risk of spontaneous combustion. The precautions to minimise the risk and methods of combating active fires are also described.

The second part of the report is specific to Western US mining conditions and provides advice for operators on how best to minimise the hazard, both in the planning and operating phase. Guidance is also provided on combating active heatings. Areas for further research are defined.

The report concludes that, given the adoption of the correct techniques, it is possible to mine the high-risk Western US coals safety and profitably.

EXECUTIVE SUMMARY

INTRODUCTION

1. Increases in world oil prices over the past five years have meant that the production of energy from coal has again become economic and interest in its development has been reawakened. In addition to the economic factors, there are strategic advantages in harnessing an indigenous source of energy.

2. The US is well placed to take advantage of this change of emphasis since it has large and comparatively accessible coal reserves. The problem is the sheer size of the US primary energy requirement. If coal is to make a significant impact towards the goal of energy sufficiency, then its expansion must be measured in hundreds of millions of tons per year. Such development will require not only substantial new capacity in established mining areas, but also exploitation of new seams and new areas.

3. Much of the expansion of the coal industry will be in the west and will require new mining techniques to ensure maximum extraction from the thick seams that exist there. It will also require the exploitation of reserves not previously mined because they were difficult to work or because they were too far from the potential user.

4. It is for these reasons that the Department of Energy and other US governmental agencies have sponsored a large number of coal mining studies to define key problems, and to find methods of overcoming them.

5. One such problem, which has existed since the early days of mining, is the liability of coal to spontaneous combustion. Underground fires due to this cause have resulted in a number of serious accidents, the loss of output, the closure of mines and the sterilisation of valuable reserves.

6. The development of Western US reserves involves expansion in conditions where the spontaneous combustion risk is higher than in the traditional Eastern US mining areas.

7. This report presents the current state of knowledge as to the causes of spontaneous combustion and considers in detail how mining methods should be developed to minimise the danger, how to detect and how to combat spontaneous combustion before it becomes a serious danger.

METHOD OF EXECUTION

8. The work carried out during the study fell into five basic categories:-

(i) A world-wide survey of published data on spontaneous combustion.

(ii) Visits to eight typical mines in the Western US to examine the mining conditions in general and to investigate past instances of spontaneous combustion.

(iii) Coal seam section sampling from each of the mines visited. These samples were assayed in the UK following the established analytical techniques developed by the National Coal Board (NCB) for assessing liability to spontaneous combustion. The results of this laboratory examination have enabled a direct correlation to be made with the known behaviour of similar British coals. This correlation is particularly helpful as in many of the UK coalfields, spontaneous combustion is an ever-present hazard. Mining engineers in these areas have day-to-day experience in dealing with the problems that arise and in maintaining production with due regard to safety requirements and statutory regulations.

(iv) Input from Dames and Moore covering geological and legal aspects special to the US, and assessment of the application of UK-based work to US conditions.

(v) A major input of unpublished material and expertise from spontaneous combustion specialists employed by the NCB, who were seconded to PD-NCB for the duration of the project. These included professionals from the Scientific Control Department and mining engineers who are involved in the practical day-to-day problems of controlling and combating spontaneous combustion.

9. The philosophy of the study was based on the belief that an understanding of the basic theory and experience of spontaneous combustion is an essential prerequisite if operators are to be equipped to apply the appropriate procedures to handle the problem in their own specific circumstances.

10. Rigid rules cannot be laid down to cover every possible combination of circumstances, and each case will require flexibility in applying established practices. This report provides the essential background and illustrates its application by reference to many examples of specific incidents.

HISTORY OF SPONTANEOUS COMBUSTION

11. There is a recorded instance of a fire in underground coal waste in a Scottish coal mine in 1674. This was treated by digging out the burning material and then sealing off the area. It is likely that this was one of many such incidents.

12. Official statistics are hard to come by, even for modern times, since many countries do not require spontaneous combustion occurrences to be recorded unless they develop into a serious incident and result in loss of life.

13. The earliest known scientific investigation into the causes of spontaneous combustion was carried out in the late seventeenth century. This attributed the heating to the oxidation of pyrites. The theory that pyrites is an essential element in the development of spontaneous combustion has now been disproved.

14. Work in the second half of the nineteenth century showed that coal itself adsorbs oxygen to a degree related to its own inherent oxygen content, the higher its own oxygen content the greater its oxygen adsorption. As oxidation, following oxygen adsorption, occurs, heat is generated, and if there is no compensating heat loss, a fire is ultimately inevitable.

15. Modern analytical techniques have made possible the monitoring of trace gases produced in the initial stages of oxidation and these can be used to detect incipient heating at a very early stage. Work has also been carried out on the effects of the differences of humidity between coal and the surrounding

atmosphere. It is now thought that the heat of adsorbtion of water vapour may have a significant role in the initiation of spontaneous combustion.

SUSCEPTIBILITY OF COALS TO SPONTANEOUS COMBUSTION

16. All coal, when exposed to air, oxidises slowly, although the rate depends on the rank of the coal and the ambient conditions. If the heat produced by the oxidation is greater than can be transmitted to the surrounding air or strata, spontaneous heating and finally spontaneous combustion will occur.

17. The rate of this oxidation is dependent on a number of factors. These include coal rank, oxygen content, moisture content, particle size and the presence of trace elements. However, the relationships are not straightforward and are in many cases imperfectly understood. This makes the prediction of the liability to spontaneous combustion, based on the fundamental properties of a given coal, uncertain.

18. This leads on, therefore, to the concept of a single test to determine the rate at which coal will absorb oxygen, since this ultimately determines the rate of heating.

19. There are several methods of measuring the rate of oxygen absorption. The more common of these (the so-called isothermal methods) involve placing a ground sample of the coal in a closed vessel and maintaining it at a constant temperature. The gas in the vessel is analysed periodically and hence the oxygen absorption can be measured. The temperatures used vary but are usually above ambient. Each test requires about 100 hours to complete.

20. While these methods place coal in some order of susceptibility, there are serious unexplained anomalies. It has been suggested, therefore, that an adiabatic oxidation test should prove more reliable because, in practice, the development of a spontaneous combustion is not isothermal. Indeed, as the temperature increases, the rate of oxidation accelerates and it should be possible to simulate these conditions in the laboratory.

21. The disadvantage of such a test, if started from ambient temperature, is that it may take several weeks to complete an individual experiment. This has led the NCB to develop a new method based on the "paced adiabatic non-isothermal criterion" (PANIC). This consists of passing a stream of air (or a synthetic mine atmosphere) over a sample of coal. The temperature of the coal is raised artificially at a known and constant rate, and the exit gases analysed continuously using both chromotographic and infra-red techniques.

22. Other methods using so-called ignition temperatures, chemical methods and infra-red analysis have also been used but, as yet, the information they have yielded is doubtful and not comparable with the results from the adiabatic or the paced-heating experiments. A warning must, however, be given about all laboratory tests. The coal used in the tests must inevitably be in a different physical condition to that in the mine. It must be realised that physical considerations such as permeability play just as important a role as chemical considerations. So far no one has devised methods of laboratory examination that combine both chemical and physical considerations.

23. There is a need for an internationally-recognised test procedure that would enable results to be compared and correlated with the known incidence of spontaneous combustion in the mine. At present, it is not possible to make any direct comparisons between the results obtained in the laboratories of all the various coal-mining countries involved.

GEOLOGICAL AND MINING FACTORS

24. There are a number of geological and mining factors that influence the liability of a seam to spontaneous combustion. These fall into two groups. Firstly, what might be termed the geotechnical factors such as seam thickness, seam gradient, faulting, depth of cover, coal friability and the occurrence of rider seams. Secondly, those factors that result from the mining system, including degree of caving, ventilation pressure, pillar sizes, leakage and coal friability.

25. Geological exploration should reveal much of this information before mining is commenced. This allows the choice of a mining method appropriate to the degree of risk.

26. The most important mining factor influencing spontaneous combustion is ventilation, since air, or to be more precise, oxygen, is essential if any heating is to take place.

27. The other major criterion is that fractured coal is more liable to spontaneous combustion than solid coal. This is because it has a larger unit surface area, and therefore oxidises more readily. This fractured coal can be produced in a variety of ways; for example, from pillar crush or leaving roof coal.

28. With coals liable to spontaneous combustion, precautions must be concentrated on two lines of attack. Firstly, to avoid the creation of crushed coal, particularly in worked-out areas. Secondly, to adopt a ventilation system that prevents the inflow of oxygen to caved or worked-out areas.

DETECTION AND MONITORING

29. It is important to detect the onset of spontaneous combustion as soon as possible as this makes remedial action both easier and cheaper. If there is a past history of spontaneous combustion occurring, or laboratory trials indicate that the coal may be liable to spontaneous combustion, it is strongly advised that a continuous monitoring system should be installed. The established technique for this purpose is to monitor changes in the rate of carbon monoxide concentration at key points in the mine, usually ventilation intakes and returns. Precautions must be taken to ensure against false alarms due to increases in carbon monoxide from blasting or diesel locomotive exhaust, but the system can be designed to discriminate and reject unwanted signals. Carbon monoxide monitoring systems are installed in 180 of the 240 coal mines in the UK.

30. In the absence of continuous monitoring, hand-held or other portable carbon monoxide meters or detectors must be used. Such methods suffer from the fact that men must be sent into the mine to get the information.

31. Human detection methods by experienced operators are still important both as a back up for instruments and for situations where instruments are not available. If left unchecked, a heating will initially manifest itself by the appearance of a haze, followed by sweating of the strata, smell, smoke and fire.

The first two stages may be masked by the temperature and conditions of the strata and the ventilation air. Smell is a more reliable indicator to a trained observer.

PRECAUTIONS

32. Precautions to prevent spontaneous combustion fall into two classes, those which can be taken at the planning stage and those which are a factor of day-to-day operation.

33. Although there are many factors involved, ventilation is by far the most important. It is sometimes suggested that spontaneous combustion can be prevented by adopting high ventilation rates which will have a cooling effect and prevent the build up of temperature. In practice, this has proved impossible as there are always boundary layers and air shadow areas where the cooling effect cannot take place, so that the risk in fact becomes greater. The alternative is to restrict airflow so as to starve the incipient heating of oxygen; this is the normal practice in British coal mines. There are a number of techniques that can be used for this purpose and they are described in detail in the report.

34. In the case of advancing mining systems, one area that can pose particular problems is the gob. This is because the air supply to the working face will tend to short circuit through the gob.

35. For this reason, a retreat system, without bleeder ventilation, should be adopted if there is any risk of spontaneous combustion, since this places the gob out of the airflow system. Alternative methods of controlling methane can be adopted.

36. Even then there is an area just behind a working face in a caving system where an airflow into the gob may occur due to the kinetic energy of the main ventilating current sweeping into the gob. This flow may be in the "critical" range, that is with sufficient oxygen to support combustion and insufficient air to provide cooling. Since spontaneous combustion is a time-dependent factor, it is important to ensure that any potentially-combustible material remains in the critical zone for the shortest possible time. Since it is not possible to move the combustible material, it is necessary to move the critical area. In other words, there is a minimum rate at which a working place must be moved. This is just one example of the problems that are considered in the main body of the report.

COMBAT TECHNIQUES

37. Whatever precautions are taken, sooner or later there is a possibility that it will become necessary to combat an active fire. Prompt action is of paramount importance.

38. Small heatings can often be eliminated by digging out, after which the affected area is sealed.

39. Flooding is another technique that is superficially attractive if the seam gradient is appropriate. In theory, it is possible to recover the area by pumping out the water after allowing a period for cooling. In practice, however, spontaneous combustion is likely to restart when oxygen is admitted over the wetted coal surface.

40. The most widely-used technique is to modify the local ventilation so that the supply of oxygen is curtailed. This may involve surface sealing or strata injection, or balancing the pressure across the area, thus minimising the airflow, or more positive means such as placing seals in roadways local to the fire.

41. It is not sufficient merely to know what has to be done in an emergency. Fires can accelerate very quickly; therefore it is necessary for an adequate number of men to be trained to carry out firefighting work, and for supplies of all the essential materials to be instantly available. Emergency stocks should be held at those mines where spontaneous combustion is likely to occur. Plans should be prepared of suitable sealing locations, and it is also necessary to have established a command structure to control the incident.

42. During the initial combat stage, and also during the subsequent cooling off period, it is important to know what is happening in the affected area. This requires regular gas analyses, and in major incidents it is necessary to set up and man a laboratory on site to provide this service.

US CONDITIONS

43. So far the emphasis has been on techniques that are relevant to spontaneous combustion world-wide. The next stage is to consider their relevance to US conditions. However, before this can be done it is necessary to establish what US conditions are.

44. It was to this end that visits were made to eight mining operations. Fifteen face pillar coal samples were collected for testing. It was realised that the information obtainable from the limited sample was not sufficient to cover every possible problem. However, it was sufficient to obtain a generalised insight into the similarities between US and UK circumstances.

45. Four of the mines have had no underground fires due to spontaneous combustion. In general, incidents have been restricted to mines working coal seams with high oxygen contents.

46. This is typical of general experience in the area. The liability of Western US coals to self ignite is well known, although this knowledge is generally associated with fires in stockpiles and at the outcrop. The number of documented underground incidents is small, but there is hearsay evidence that the problem has been serious at various times in the past.

47. The low number of reported incidents is surprising as there are several factors that would be expected to encourage the occurrence of spontaneous combustion. These are the relatively high oxygen content of much of the coal (as indicated by their sub-bituminous to bituminous rank) and the practice of leaving remnant coal either as pillars or as roof or floor coal when working in thick seams. There is also the practice of using bleeder ventilation of the wastes, which is liable to produce pockets where the conditions are conducive to self ignition.

48. Against these must be set the relatively low air humidity, the practice of multiple-entry roads which permit low ventilation pressures and the generally good strata control which results in minimal crushing of the coal. These benefits may have been sufficient to outweigh the other factors to date, but this may not apply in the future when it will be necessary to work the more difficult deposits and to employ more intensive mining methods, including a change to longwall mining and high percentage extraction.

49. From the information obtained, there is no indication that spontaneous combustion in the Western US coals cannot be controlled by the techniques advocated in this report. This does not mean that application of the precautions will eliminate spontaneous combustion occurrences, but if incidents do occur, then the early detection combat techniques described will be adequate to deal with them.

50. In establishing a new mine, or extending an existing one, it is necessary to assess the degree of risk of spontaneous combustion. Obviously such an assessment would include examination of previous spontaneous combustion occurrences in the area and the testing of such core or other samples as were available. In addition, the report provides an empirical system that awards points for the various key coal characteristics and mining factors. The final figure obtained gives a good indication of the risk of spontaneous combustion. Full details of the system, and examples of its application, are given in the body of the report.

RESEARCH AND DEVELOPMENT

51. Although considerable research has been done, there are a number of areas that require further examination.

52. In particular, more information is required on the chemical reactions occurring in newly-mined coal below $100^{0}F$, since this will be invaluable in producing techniques to detect heatings at a very early stage.

53. Further work is required to establish a simple laboratory test to determine the liability of coals to spontaneous combustion. It is desirable that the test should be capable of being carried out reasonably quickly, within hours that is rather than days, and that it should be within the capabilities of a mine laboratory. The test should be standardised in such a way that the results can be compared with coals of other areas and correlated with the known incidence of spontaneous combustion.

54. The role of atmospheric moisture in spontaneous combustion is imperfectly understood and requires further investigation. This is particularly relevant to the Western US coalfields where ventilation humidities throughout the year are consistently low. This is, indeed, the major environmental difference between the US and UK mining conditions and may account for the low incidence of spontaneous combustion in US mines, which, if located in the UK, would be expected to have severe spontaneous combustion problems.

CONCLUSIONS

55. While spontaneous combustion is a more complex subject than is generally appreciated, it has been widely researched. From this, it is possible to estimate the likelihood of spontaneous combustion given specified geological systems, and to adopt a mining method to reduce the risks to acceptable levels.

56. Where there is any risk of spontaneous combustion, it is essential that a monitoring system should be set up so that any heatings can be identified in their early stages. If an actual fire breaks out, it is necessary to have trained men available and adequate materials to contain and fight the incident. In all cases, prompt action is necessary if loss of production and the neutralisation of reserves is to be avoided.

57. Given these precautions, it is possible to mine high-risk coals safely and profitably.

CHAPTER I

THE HISTORY, EXTENT AND MAGNITUDE OF THE SPONTANEOUS COMBUSTION PROBLEM

GENERAL

1. Spontaneous combustion results from the oxidation of coal which may lead to increasingly severe stages of heating and ultimately to open fire. The dangers from such occurrences in underground mines are clear and though incidents have frequently been brought effectively under control, there have been many cases where the consequences have been costly in both lives and material terms.

2. There are coal mining areas, in many parts of the world, which are especially susceptible to spontaneous combustion, while in others the occurrence is rare. Apart from the characteristics of the coal itself, the likelihood of spontaneous combustion depends on many factors associated with the geological and mining environment and changes in any of these may bring about spontaneous combustion in locations where it has not previously been reported.

3. Although specific cases can be quoted where increasing rates of advance, coupled with better extraction practices, have reduced the spontaneous combustion hazard, European experience, in general, is that spontaneous combustion has become a greater hazard as a result of the introduction of more intensive mining methods. The introduction of modern mechanised mining systems puts more capital at risk. At the same time, as depths increase, the effects of crush and higher ventilation pressures lead to an increasing risk.

4. Developments in US mines indicate that more highly concentrated mining, under increasing cover, will be the pattern of the future and even in areas where spontaneous combustion has not been a serious hazard in the past, the danger can be expected to increase.

5. The risk of spontaneous combustion is not directly related to depth, but for any given coal as depth of cover increases, so generally will the spontaneous combustion hazard.

HISTORY

6. Spontaneous combustion is as old as the coal industry itself and records exist dating back to the 17th century. Contemporary accounts describe the self heating of coal both in situ and in coal dumps (Ref 1).

7. At that time, and for two centuries later, it was believed that pyrites was the principal cause of spontaneous combustion. Indeed some people still regard this to be so despite the large number of investigations which have shown that it is no more than a secondary factor. This is due to its easy oxidation, which may assist initial heating, and to the swelling of the oxidation products of pyrites exposing fresh coal surfaces.

8. Several scientific papers appeared during the second half of the 19th century commenting on the changes that occur in stored coal, including changes in weight, and suggesting that the absorption of oxygen by coal was an important factor in the initial stages of spontaneous combustion (Ref 2, 5 and 6).

9. The first fundamental researches into the weathering of coal were carried out in Germany by Richters (Ref 2) who published three papers between 1868 and 1870 and by Fayol (Ref 5) whose work extended over a period of some 20 years. It is noteworthy how many aspects of our present knowledge are covered in these early papers.

10. At the end of the 19th century Haldane and Meacham (Ref 6) made an extensive study of heatings in the "Thick Coal" of South Staffordshire, in the UK, where it was stated that more than 200 fires a year, attributed to spontaneous combustion, were occurring. Their most important observation, however, was made from laboratory experiments on the oxidation of coal which showed that small quantities of carbon monoxide accompanied the other products of oxidation. Thus, by the end of the 19th century the capacity of coal to react with oxygen at ambient temperatures, and at an increasing rate at higher temperatures, had been established and the foundation of a chemical method of detecting incipient heating by means of air analysis had been discovered.

11. Between 1900 and 1940 there was a large and increasing amount of work carried out on the subject covering such aspects as the heat produced by the oxidation of the coal substance, the influence of water on the slow oxidation process, the effects of coal rank, petrography, particle size, temperature and oxygen content. Much of this work, largely carried out in Germany, the UK and the USA, was used to produce theories of oxidation and of the mechanism of coking and to elucidate the actual structural constitution of the coal. Probably the most systematic research during this period was carried out by Winmill and Graham (Ref 17, 22, 23, 24 and 28) in a laboratory specifically equipped for the study of spontaneous combustion by a UK Coal Owners' Association. Their most important discovery was the link between the presence of carbon monoxide, particularly when in association with a deficiency of oxygen, and the initial stages of spontaneous combustion. The oxygen deficiency ratio has now been in general use for more than 30 years as an aid to spontaneous combustion detection and control.

12. The history of spontaneous combustion and its aftermath can be illustrated by reference to the experience of the UK coal industry. In the period 1869 to 1978 there were no less than 14 incidents where spontaneous combustion developed into open fires or initiated methane explosions; these resulted in the death of more than 650 people. The worst incidents included disasters at Gresford (1934) - 265 killed, Cadeby Main (1912) - 88 killed, and Mossfield (1889) - 64 killed. The full record of spontaneous-combustion-caused disasters is given in Appendix "A". Similar tragic histories exist for other European coalfields and elsewhere in the world, though precise documentation is not available.

13. Due mainly to increased financial losses from abandoned equipment and machinery and also loss of output, as a consequence of spontaneous combustion, as well as from the growing sense of responsibility for the safety of the miner, much recent work has been carried out on the oxidation of coal. However, little that is new has been revealed, though techniques have become more elegant and measurements more accurate. One of the main effects of these techniques has been the possibility of examining the products of oxidation for trace gases. This led to suggestions, particularly from Japan, the UK and the USA, that the

monitoring of gases other than carbon monoxide could result in improved detection of the early stages of spontaneous combustion. This subject is, of course, of great importance at a time when decisions have to be taken on the regular, and if possible continuous, monitoring of mine air from mines with a known susceptibility to spontaneous combustion.

14. A great deal of work has also been done on the effects of differences in humidity between coal and the surrounding atmosphere. Although the absorption of moisture by dry coal from high humidity air produces more heat than oxidation at low temperatures (less than 100°F), in practice this can only be a secondary factor in aiding the development of spontaneous combustion to the stage of heating. Most of the modern work represents a long-term approach to the problem and deals with the use of the advanced physical analytical techniques that have become available, such as infra-red spectroscopy, the use of tracer isotopes and spin resonance measurements in order to determine what reactions are taking place and to study their kinetics.

15. While a better appreciation of the fundamental background will ultimately help in understanding what is happening and hence provide new ideas on how to approach the problem, it seems unlikely that there will be any major changes in the practical aspects of detection in the mine during the next decade. The basic principles of the mining techniques that minimise spontaneous combustion are well established, the problem is to apply them effectively under all underground conditions. This is why it is important to develop and apply the best possible early-warning system of incipient heating. For early action can, relatively easily and safely, prevent a serious fire situation from developing.

GEOGRAPHICAL EXTENT OF OCCURRENCE

16. The universal nature of the problem of spontaneous combustion is amply illustrated by the number of countries in which it has been reported. The selected references (Appendix "B") include papers dealing with spontaneous combustion problems from the following countries:-

Australia	India
Canada	Japan
Czechoslovakia	New Zealand
France	Poland
Germany	South Africa
Great Britain	USA
Holland	USSR
Hungary	

17. This list does not imply that spontaneous combustion does not occur in other countries, for it is known that the problem is serious in Belgium, China, Indonesia, Pakistan, Turkey, Yugoslavia and elsewhere. Neither is it restricted to particular districts in these countries. Spontaneous combustion can occur with all types of coal and all methods of mining.

MAGNITUDE OF THE PROBLEM

18. The range of countries listed above indicates that the occurrence of spontaneous combustion on a geographical basis is virtually world-wide. The examples given later in this chapter illustrate a range of incidents of differing magnitude, and show that where the precautionary and combat techniques are unsuccessful, spontaneous combustion can be a source of major mining disasters.

19. One mine in Europe, with an annual productive capacity of about 1 million tons was lost as a result of an uncontrollable underground spontaneous combustion incident. The cost was many millions of dollars in lost equipment and productive capacity.

20. In the western United States a major underground coking coal mine, with an annual capacity of about 1 million tons, had to be abandoned after an underground heating. Although the mine was subsequently reopened, millions of dollars' worth of production were lost.

21. Any heating underground which can lead to the production of significant amounts of carbon monoxide, or in some cases open flame, is clearly a major hazard. Underground heatings have resulted in the loss of many lives, either from carbon monoxide poisoning or from methane or coal dust explosions initiated by the spontaneous combustion.

22. The difficulty of controlling an underground coal mine fire is well illustrated by the paper in the Mining Congress Journal, January 1978, by C.B. Stone et alia entitled "Olga Coal Company's 5 West Mine Fire". Although the actual cause was unknown, the fire presented many problems that will be associated with spontaneous combustion incidents. The fire was eventually controlled by the use of a foam/fly ash/rock dust slurry pumped through surface boreholes but at a cost of $2.5 million.

23. However, the magnitude of the problem should not be unduly daunting. There are hundreds of examples of mines operating while heatings are being effectively controlled by the many techniques now available. In the East Midlands coalfield of the UK, with an annual production of about 8 million tons, there are frequently three or four active heatings at any given time. Some of these heatings, unfortunately, eventually lead to sealing off of sections and some losses of equipment. However, if the control techniques were not implemented and effective, a significant part of this coalfield would be unworkable.

24. The techniques used in this coalfield are described in more detail in Appendix "D". This, and other examples, show that though spontaneous combustion is a very real hazard, it can be contained within manageable proportions by techniques currently available.

EXAMPLES OF SPONTANEOUS COMBUSTION INCIDENTS

25. From the many examples of spontaneous-combustion-caused fires that have occurred in the coal mining areas of the world, the following have been chosen to illustrate the geographical spread, the risk involved in mine designs and methods of working, the action taken to control the fires and the degree of success achieved. The examples have been summarised from the sources indicated and

underline the variety of circumstances associated with spontaneous combustion incidents, although the authors do not necessarily agree with all the comments. A synopsis of seven case histories is included in this chapter and fuller descriptions of these incidents are provided in Appendices "E" to "K".

26. In selecting the examples, a factor which has to be taken into account is the availability of adequate documentation. Many cases are available where spontaneous combustion has caused fires, but they have been dealt with successfully as a matter of routine and have not been adequately documented for the purposes of this report; for example, in the Yorkshire, Staffordshire and Scottish coalfields of the UK. In general, minor spontaneous combustion incidents are so common in many coalfields that they are not recorded unless they result in loss of life or a major loss of production. It has not therefore proved possible to obtain meaningful statistics of their occurrence.

27. Case No 1 at a mine in West Germany (see Appendix "E") illustrates a spontaneous combustion fire occurring in an abandoned longwall face in an 8-ft-thick seam, dipping at about 11^0. The mine was designed on the "horizon" principle, ie having the main access roads driven approximately level in rock.

28. The fire was detected by mine officials smelling fumes and simultaneously the carbon monoxide monitoring device was triggered at the surface control. The investigation showed that the fire was inaccessible and that the only possibility of saving the section and recovering the longwall supports, machinery and materials inbye of the fire zone, would be to delay the rate of propagation by reducing the pressure drop across the gob so that stoppings could be installed under the least hazardous conditions.

29. Ventilation doors outbye of the site were opened to reduce the differential pressure across the old face line where the fire was located and the erection of stoppings at strategic points led to a gradual decrease in the air flow, combined with increases in carbon monoxide and methane concentrations. To reduce the differential pressure at the site of the fire and to provide sufficient air at the longwall face, an auxiliary fan was mounted in the ventilation tube of one stopping to act as a pressure generator. A regulator outbye of the fire zone was adjusted to limit the pressure across the fire to 0.24-in water gauge. Carbon monoxide emission was kept within reasonable limits and 90% of the longwall equipment was recovered and the final stopping off operations were completed successfully.

30. Case No 2 occurred at another West German mine (see Appendix "F"), again laid out on the horizon system, working longwall in an $8\frac{1}{2}$-ft-thick seam. Spontaneous combustion was detected at an early stage by a slight increase in the carbon monoxide concentration in the methane drainage system, the source of which was traced to the caved area behind the working face. It was decided to salvage the longwall equipment including shield supports and a double-ended shearer. This was successfully accomplished in 21 days and the section was sealed off 4 days later.

31. It was anticipated that the sealed off heating would be extinguished, as the methane concentration exceeded the upper explosion limit. However, several explosions occurred behind the stoppings and it was decided to build additional stoppings as soon as conditions free from the explosion hazard could be created. This was achieved by introducing large quantities of an inert gas - nitrogen - into the combustion zone. A series of existing pipelines, previously utilised for compressed air and pack pumping was used for this purpose.

32. This example illustrates a successful operation which prevented loss of materials and reserves of coal, and the knowledge gained in the process provides a basis for controlling mine fires in similar circumstances, in the presence of an explosion hazard.

33. Case No 3 relates to a mine in India (see Appendix "G"), working a 4-ft to 7-ft-thick seam by the pillar and stall method, where spontaneous combustion had been almost unknown for a period of 60 years.

34. Due to difficult economic conditions, working had been discontinued in the dip side of the mine, leading to consequential flooding. In order to achieve rapid build-up of output when financial circumstances became more favourable, depillaring of the rise side workings was carried out under a cover of only 70 ft. This resulted in crushing of pillars, accumulation of broken coal in worked out areas, and the formation of cavities through to the surface, causing leakage of air followed by spontaneous combustion and several fires.

35. This case is similar in several respects to Case No 4 which occurred in a mine in the Canadian Rockies (see Appendix "H"). The 45-ft-thick seam pitching at 50^0 was being worked by sub-level caving. Access to the mine was from a low point in the outcrop, with a gradient to the rise so that the main roads reached the outcrop on the other side of the ridge. A strip of coal 500 ft to 1,000 ft in width was left between the main roads and the outcrop. A fire was first noticed in the outcrop one year after completion of production in that area. Very little barrier coal had been left against the hillside and inspection showed that cracks caused by subsidence extended to the surface, connecting the old gobs and leading to air leakage and spontaneous combustion.

36. The shape of the reserves and the method of working made the elimination of spontaneous combustion difficult and therefore early detection of heatings and their elimination before the fire stage was reached was especially important.

37. Case No 5 relates to a mine in the UK (see Appendix "I") where spontaneous combustion was a known hazard. A method of lining a roadway near the shaft bottom, which had been the site of a previous heating, with polyurethane foam, to eliminate air leakage, allowed a subsequent heating to reach a dangerous condition by masking the smell of fumes during the early stages. This meant that in the absence of monitoring there was virtually no warning of the initial heating and an inspection of the site less than one hour before the fire broke out had proved negative. The fire gained such a rapid hold and produced such quantities of dense smoke that the whole mine had to be sealed and written off as a total loss.

38. In Case No 6, pillar and stall working was practised in a thick coal seam, under a coal roof in a Queensland, Australia, mine (see Appendix "J"). Barriers were left between panels for ease of sealing off old workings. It was known that fires in this seam had an incubation period of six months. Poor roof conditions, holidays and industrial action culminated in a protracted extraction period, resulting in a fire in fallen roof coal. The subsequent investigation underlined the part played by poor organisational structure and lack of knowledge in dealing with spontaneous combustion incidents, which in this case precipitated a methane explosion, which in turn propagated a coal dust explosion and resulted in the loss of 13 lives and closure of the mine.

39. Case No 7 deals with another room and pillar mine working a 22-ft seam in the Western USA (see Appendix "K"), leaving 10 ft of bottom coal and 4 ft of top coal and known to be liable to spontaneous combustion. A fire occurred in the main entries and conventional fire fighting methods and sealing of the section affected apparently resolved the problem. Urethane foam was used on the stoppings to prevent minor leaks.

40. Shortly after working recommenced, smoke was seen to issue from underneath a seal and the urethane foam was seen to be discoloured. A fire broke out which was surmised to have resulted from chemical reaction in the urethane foam. This fire was extinguished and a back up seal erected. Some three weeks later the fire re-occurred in the main entries and it was verified that an active fire was burning. A decision was made to seal off the mine and, whilst fortunately there were no injuries to employees, a very valuable property had to be abandoned.

41. Appendix "L" describes an incident occurring at Coventry Mine in the Warwickshire coalfield of the UK. The method of working was advancing longwall in the upper section of a 25-ft thick seam especially prone to spontaneous combustion. The plan was to advance the face to the boundary and then to prepare another longwall face in the lower section of the seam, below and within the width of the old gob, and retreat it back towards the main entries. This multi-lift system of working is anticipated in the USA.

42. The heating occurred at the return end of the face start line and was detected by an increase in carbon monoxide content.

43. The rate of rise was too rapid to seal off the ends of the face start line in time and it was decided to construct a pressure chamber and balance the pressure difference across the leakage to cut off the flow of air.

44. This is an instance of successfully controlling a heating thereby allowing a fully mechanised longwall face to continue in production.

45. Because of the practical lessons, this example is also used to illustrate Chapter VII.

46. Appendix "M" is also mentioned in Chapter VII and refers to a case at Newdigate Mine, UK, working a retreating longwall face in the lower section of a 25-ft thick seam in a multi-lift operation.

47. The seam is very liable to spontaneous combustion but this example illustrates that mining can be successfully conducted in these circumstances.

48. A rapid increase in the carbon monoxide content was detected at the routine control sampling point and it was apparent that a heating had started inbye of the working face.

49. Quick action was necessary to avoid losing the district and it was decided to pressurise the inbye side of the return airway in order to close the return path from the heating and deny it oxygen.

50. Stoppings were built in the return airways behind the face and an auxiliary fan installed in one of them. When the fan was started and regulated to a pressure equal to that across the face, there was an immediate drop in the carbon monoxide content and the face was able to continue in operation.

THE SIGNIFICANCE OF SPONTANEOUS COMBUSTION

51. Spontaneous combustion occurs in many different mining and geological situations and must always be considered during the planning and operation of mines. When mining has already taken place in a particular coalfield, past experience can give some indication of the probability of spontaneous combustion risk, although such evidence should be assessed in the light of any subsequent changes in mining or geological circumstances. In the case of coalfields where no previous mining has taken place, use should be made of the prediction techniques available, coupled with precautionary measures developed from world-wide experience.

52. Above all, it should be remembered that in certain circumstances virtually any coal can be induced to a state of spontaneous combustion and the assumption must never be made that a spontaneous combustion risk does not exist.

CHAPTER II

FACTORS AFFECTING SUSCEPTIBILITY

INTRODUCTION

1. It is essential to consider briefly the concept of coal oxidation, since it is the basis of an understanding of the occurrence, detection, prevention and control of spontaneous combustion.

2. The oxidation of coal begins as soon as it is exposed to air during mining operations, and under normal conditions continues at a very slow rate until the coal is used. The mechanism of the process is complex and not perfectly understood, but the generally accepted steps are:-

(i) The absorption of oxygen and perhaps water vapour at ambient temperatures, with little evolution of carbon dioxide, carbon monoxide, or water, partially by reactive groupings forming complexes which arise from molecular or even atomic rearrangements within the coal substance and partially surface adsorption (Ref 8, 110, 125, A6 and A7).

(ii) As the temperature rises, these complexes, which are unstable, break down setting free moisture, carbon dioxide and carbon monoxide; this process appears to become significant at about 160°F and becomes increasingly important thereafter. Recent work by the NCB (Ref 108) has shown that the small amount of carbon monoxide produced at ambient temperatures is independent of the oxygen content of the atmosphere and is due to the breakdown of oxygen-containing groups already in the coal and that this reaction continues up to about 185°F; this theory has been confirmed by US Bureau of Mines' experiments using oxygen isotopes in the oxidising atmosphere.

(iii) A true oxidation reaction, ie the breakdown of complexes formed by the absorption of oxygen, commences at about 110°F with an increasing production of carbon monoxide as the temperature increases. After about 160°F this rate accelerates at an increasing order of magnitude. The combination of these three reactions results in a hyperbolic curve (Plate 1) when carbon monoxide in the effluent gases from oxidising coal is plotted against temperature. As the temperature rises, further detectable amounts of hydrogen, ethylene and propylene are evolved.

3. Despite its complicated nature, a number of factors have been shown to affect the rate of oxidation of a coal, and hence are of importance in considering spontaneous combustion. The effect of some of these factors is discussed below.

RANK

4. The rank of a coal depends on the character of the original plant debris from which it was formed and the amount of change that its organic matter has undergone during the period of formation. An increasing content of carbon and with it a decreasing content of oxygen (both being calculated for the dry, mineral-matter-free coal) are the most commonly accepted criteria of increasing rank, but other properties such as the yield of volatile matter on distillation accompanied by

changes in the reflectance of the coal substance also tend to characterise the rank of a coal.

5. It has long been recognised that rank is an important factor; the higher the rank and the lower the inherent oxygen content of the coal, the slower the rate of oxidation. Lignite, which is very low rank, oxidises so rapidly that it is often stated that it cannot be stored after mining without ignition. Low rank bituminous coals oxidise fairly readily, whilst for anthracite, which is high rank, the reaction proceeds much more slowly.

6. There are, however, many anomalies to a straight rank order. For example, one part of a seam may be particularly liable to spontaneous heating, a seam of higher rank may prove more troublesome than one of lower rank, or even the same seam in different mines may react differently.

7. Many attempts (Ref 108) have been made to correlate the rate of oxidation, or quantity of oxygen absorbed, with fundamental properties of the coal - particularly oxygen content and moisture - but although there is a fairly consistent relationship, there are still a number of unexpected results. These anomalies are probably due to some of the factors discussed in the following paragraphs, particularly petrographic composition and physical factors such as hardness and porosity. There is some experimental evidence that adsorbed methane may, in some cases, inhibit the initial oxidation reactions, since while the methane is desorbing, oxygen is inhibited from entering the coal substance.

PETROGRAPHIC COMPOSITION

8. In the past, a number of papers have been published putting emphasis on the relationship between the self-heating of coals and their petrographic constituents, though not always reaching the same conclusions. It was once held that fusain was the most dangerous petrographic constituent, but this is most likely due to its physical form and large surface area rather than any inherent qualities; it is possible that layers of fusain would provide an easy access of air to coal in much the same way as cracks or along cleat lines. This matter was fully discussed by a specialist commission in the UK in 1920, when contradictory evidence was recorded, particularly concerning the significance of fusain, and although the commission considered this aspect of importance, they did not draw any definite conclusions. Later work (Ref 77) generally concluded that vitrain, clarain, and durain, in that order, are more susceptible to oxidation than fusain.

9. In view of these uncertainties, the NCB decided to carry out a series of controlled-rate oxidation tests on hand-picked petrographic constituents from five coals ranging from high rank coking coal to low rank bituminous steam coal. The results of these tests (Ref 110) showed that in all cases fusain was least reactive and, in general, durain was more reactive than vitrain. It should be stressed that these tests were carried out on similar-sized particles in each case; in practice, fusain, durain and vitrain occur in different physical conditions regarding strength, particle size, cracks, etc, and hence such factors as available surface may affect their relative importance in the commencement of spontaneous heating in the coal underground. These results, however, enabled calculations to be made of the reaction velocities of vitrinite, exinite and inertinite, and showed that exinite has a much greater oxidation rate, certainly above 165^{0}F, than the other two constituents, so that it appears that exinite has more active centres and coals with high exinite concentrations will be more subject to spontaneous heating. Thus a count of these "macerals" may be useful, together with rank. in determining the

susceptibility of a coal to spontaneous combustion, and variations in maceral content may account for some of the anomalies of oxidation characteristics of the same rank coal from different seams. Since reflectance is an indirect measure of maceral types, it may also be a useful means of indicating the relative activity of different coals.

TEMPERATURE

10. The initial rate of oxidation of fresh coal falls away rapidly if the temperature is maintained constant, but can continue for a long time at a slow rate depending on the rank of the coal. There is a pronounced temperature co-efficient of oxidation, and the average rate of oxidation approximately doubles (1.4 to 2.3) for every rise of 18°F. The oxidation of the coal produces heat and thus supplies its own source of temperature rise and, in the absence of cooling, it oxidises faster and faster so that the rate of oxidation is self-accelerating.

11. Furthermore, not only is the absorption of oxygen more rapid as the temperature is increased, but the total quantity absorbed by the coal is also much increased. This latter is not a general phenomenon of oxidation or absorption, since, for example, the total absorption of nitrogen between 86°F and 212°F decreases by a factor of 6, whereas over the same temperature range the rate of absorption of oxygen increases by a factor of about 8, and the total amount absorbed by about 15.

12. It is this combination of circumstances - rate of absorption, total absorption and heat produced by oxidation - that is the fundamental reason why potentially all coals are capable of heating spontaneously.

AVAILABLE AIR

13. The amount of air available is very important. Where there is only a small amount of air, the rate of oxidation, being governed by this factor, certainly above about 110°F, is very slow and there is no appreciable rise in temperature. Where there are very large quantities of air passing through the coal or over thin layers of coal, any heat produced may be carried away so that the temperature does not rise and the oxidation rate remains at a low level. In between these two limits there is a state where the amount of air available is sufficient to promote oxidation, but not sufficient to carry away the heat formed, so there is an accelerating rate of oxidation until ignition occurs. This is illustrated on Plate 2. The effectiveness of the action taken is indicated on the vertical axis by the final temperature rise in the coal concerned, whilst on the horizontal axis the amount of air passing through the coal is plotted. The curve passes through the origin, that is when no air is allowed to pass there is no temperature rise; this corresponds with natural storage in the earth. In certain cases, control can be exercised by excluding as much air as possible on the one hand or by adequate ventilation through the coal on the other; there is a zone between these two, however, in which a pile of oxidisable coal pieces inevitably goes on fire by spontaneous ignition.

14. This factor is very important when dealing with the flow of air through coal wastes underground and stockpiles on the surface.

PARTICLE SIZE

15. When considering the relevance between particle size and surface area, it must be remembered that the coal substance itself has a complex micelle with its

own surface area, something akin to a sponge. This micro-structure in turn depends on the type of plant debris that formed the coal and the subsequent geological history of its formation. Some coals will have an extensive intercommunicating network of fine "tunnels", relatively permeable to air. While in others, such as anthracite, this structure hardly exists at all at normal temperatures.

16. It is convenient for present purposes, although not strictly accurate, to regard the coals' external surface as a macro-structure and the hidden surface, which may or may not be available for oxidisation, as the micro-structure.

17. There is little doubt that the oxidisation of coal begins at active centres on the macro-surface, and if the temperature is prevented from rising, these centres will eventually become deactivated. Crushing the coal reveals fresh active centres, while any increase in temperature will increase the permeability of the coal to oxygen.

18. The macro-surface of a lump of coal increases asymptotically as it is crushed. For example, a cube of 2-in side has a surface area of 24 in^2, but if it is crushed to pass through a 1,000-mesh sieve, its surface area increases to 50,000 in^2. This means that crushing has increased its susceptibility to spontaneous combustion by a factor of 2,000. This emphasises the importance of breakage because the presence of fines will give an increased rate of oxidation, until the point is reached when the packing of the coal prevents the diffusion of oxygen.

19. Crushing also increases the rate of desorption of methane which, while it is held in the coal, may prevent the penetration of oxygen into the micelle structure. Indeed, there is some evidence that the presence of methane in coal tends initially to reduce its susceptibility to spontaneous combustion.

20. However, there is much experimental evidence that oxygen penetrates into the pores of coal, so that the rate of oxidation increases with decrease in particle size until a size is reached at which any further increase in oxidation rate is very small, ie when oxygen can penetrate the particle completely. Experimental work has indicated that the rate of oxidation increases with sub-division, but not in direct proportion to the new superficial surface (Ref 23 and 59), so that there must be penetration of the coal particle; maximum rate was assumed for particles less than 0.002 in. In other work (Ref 54), similar conclusions were drawn from the loss of calorific value of different sizes in a cold storage heap, the loss increasing with decreasing particle size, but not to the extent that would be expected from specific surface area, and becoming almost constant below 0.004 in, indicating that the oxidation is not restricted to the surface but penetrates the particles.

21. A solid coal face generally presents very little danger of spontaneous combustion, partly due to the small surface area and partly to the very low permeability of solid coal to gases. It is, therefore, generally when coal is shattered in mining, or disintegrated by roof pressure, falls (for example into the waste behind a working face), faulting, etc, that spontaneous combustion is likely to occur in a mine.

MOISTURE

22. Water can be physically absorbed, chemically bound, or mechanically mixed with the coal, and this makes it difficult to draw conclusions from the literature on the relationship of moisture and oxidation. However, the moisture content of a coal depends not only on the properties of the coal, but also on the

humidity of the environment, and given sufficient time it will reach an equilibrium moisture content depending on both factors. With low rank coals this may be quite a short time, a matter of hours only. This is probably the most important point from the aspect of spontaneous combustion, because heat of absorption of water vapour is much greater, by a factor of 10, than heat of wetting by liquid water since it includes the latent heat of condensation of the water. Most coals contain large quantities of inherent moisture and the transfer of heat by the evaporation of this moisture will result in considerable cooling effects. On the other hand, if the water pressure of vapour in the air is higher than that at the coal surface, water is absorbed producing heat; under unfavourable conditions this can cause a considerable rise in temperature and an increased rate of oxidation (Ref 75, 80 and 91).

23. In the past, most of the experimental work (Ref 91) has used dry coal and saturated oxygen in order to accentuate the effect and has obtained temperature rises of a few degrees to more than 120^{0}F, depending on the rank of the coal. Recent tests at the US Bureau of Mines on a Wyoming sub-bituminous coal showed that dry coal and dry oxygen or dry nitrogen gave no rise in temperature, but with dry coal and saturated nitrogen there was a rise of 20^{0}F, and with saturated air the temperature went on rising until ignition took place (Ref Private Communication); presumably the initial rise of temperature by heat of wetting was sufficient to increase the rate of oxidation above the critical temperature of about 110^{0}F. Other work carried out recently in France (Ref A8) illustrates these points (see Plate 3); using coal and air of differing humidities gives a series of curves which show that the wider the difference between the humidity of gas and coal, the greater the temperature rise.

SULPHUR

24. From the first publication on spontaneous combustion in coal in 1686 (Ref 1) until about the middle of the 19th century it was assumed that sulphur (mainly as pyrites) was the main cause of spontaneous combustion. In 1868 (Ref 2), it was shown that coal, even in the absence of sulphides, would absorb oxygen and heat spontaneously. This was followed by much work in Europe and the USA which indicated that it was the oxidation of the coal that was responsible for the heating.

25. Further research (Ref 24 and 36) during the first half of this century has modified this view and led to the present theory that pyrites plays a subsidiary role in promoting deterioration and spontaneous combustion. The general conclusions were that organic sulphur is unaffected by oxidation, but that pyrrhotite, which in recent years has been identified as occurring in association with pyrites (Ref A1), particularly in moist conditions, oxidises and plays a part, although a minor one, in spontaneous combustion. This is due partly to the actual heat evolved by its oxidation leading to an initial rise in temperature and increased coal oxidation, and partly to the fact that it swells and causes disintegration of the coal and thereby assists the diffusion of oxygen. Thus weathering of pyrites (FeS_2) and pyrrhotite (FeS) produces pockets of fine coal which in turn oxidise more rapidly than they otherwise would as a result of their temperature being somewhat elevated during the oxidation of pyrites and pyrrhotite. Any effect would thus be more noticeable with high inorganic sulphur coals.

OTHER MINERALS

26. Many other chemicals affect the rate of the oxidation to some extent, either accelerating or retarding it, and thus have some influence on the early stage of the reaction. Alkalies can act as accelerators, and borates, calcium chloride and some wetting agents as retardants.

27. Most of these chemicals are present only in small quantities in coal seams, but they have been used - notably in the form of limestone and calcium chloride - in a number of European and Japanese mines in an attempt to control spontaneous heating.

THE EFFECT OF PREVIOUS OXIDATION OR HEATING

28. The experimental work on the effects of previous oxidation or heating on the subsequent rates of oxidation indicates a situation that apparently lacks consistency. If the temperature of a stock of coal rises to 110°F to 120°F and then cools, this stock is unlikely to reheat as its initial avidity for oxygen has been satisfied. On the other hand, if coal heats to about 400°F to 750°F out of contact with air and then cools, it appears to be more oxidisable at low temperature; if it heats to 950°F and cools, its oxygen absorption at low temperatures is reduced.

29. From experimental work on the effects of preheating coals in vacuo, cooling, and then comparing their oxygen reaction with that of untreated coal (Ref 30), practical conclusions have been drawn. The main ones were that by preheating certain coals their liability to spontaneous combustion is greatly increased; that lump coal, previously almost impervious to air and therefore without danger from the point of view of heating, may become, through being in the neighbourhood of a fire, a source of danger owing to a large increase in its oxygen absorption capacity; and that coal in a sealed off area, even after the fire is completely extinguished, in addition to its greater permeability and oxidisability, may also have formed much fine coal caused by a reduction in strength following partial distillation.

30. These factors are important in the re-opening of a district which had been sealed because of spontaneous combustion. In a number of instances when attempts have been made to re-open workings that have been sealed for long periods, sometimes years, following fires, it has been found that there was no indication of fire, but on the re-establishment of ventilation, progressive re-heating occurred after a few days and the districts had to be re-sealed.

PHYSICAL PROPERTIES

31. A number of physical properties, such as porosity, hardness, thermal conductivity and specific heat, can affect the rate of oxidation of coal. The effect of porosity is obvious as oxidation is not purely a surface phenomenon; moisture content is normally taken as a measure of porosity, and the more porous a coal, the greater is the area exposed to oxidation. Porosities vary considerably even in coals of the same rank, but average values increase from 3% to 20% as carbon decreases from 87% to 80% (Ref A5 and para 15). Hardness - both friability and grindability - affects the ease with which the coal breaks down to smaller and more oxidisable products.

32. The two thermal properties of coal which affect its behaviour during heating, whatever its physical condition, are specific heat and thermal conductivity. Specific heat, the measure of thermal capacity of coal compared with that of free water, will determine the rise in temperature for a given heat input; its value is about 0.2, and it differs relatively little between different coals. The thermal conductivity, a measure of the rate of transfer of heat over unit area for unit temperature gradient, is relatively low.

OTHER FACTORS

Heating Due to Earth Movement

33. The crushing of coal under the pressure of superincumbent strata has occasionally been suggested as a source of heating contributing to spontaneous combustion. Such crushing certainly produces some heat, but the general opinion is that whilst this heat would contribute to the start of heating, it was not normally important compared with other factors. Crushing in a mine is important because it increases the surface and fineness of coal exposed to oxidation.

Bacteria

34. From time to time it has been suggested that microbiological agents could promote spontaneous combustion in coal mines in a way analogous to the development of fires in hay stacks and the decay of cellulose and lignin debris. A study of the comprehensive literature review "Microbiological activity in relation to coal utilisation" by A.P. Ponsford (Ref A9) suggests, however, that direct microbiological attack, including enzyme attack, leading to spontaneous combustion is highly unlikely. It may be concluded that, even with lignites, coals provide an environment alien to the culture of both aerobic and anaerobic micro-organisms and indeed may contain substances of high bactericidal power. There is no evidence that freshly-mined coal is other than sterile and the large number and variety of micro-organisms found in all mines have been introduced by the seepage of infected water, by the ventilation air and by in-brought materials including, specifically, timber.

35. The literature (Ref 10 and 38), however, provides ample evidence of microbiological attack on sulphur minerals associated with coal and the infection of coal mines, when pyrites is present, by thiobacillus-thio-oxidans and thiobacillus-ferro-oxidans. Serious corrosion problems can arise from this attack as the result of the high concentration of sulphuric acid that is formed. This occurred at two mines in Lanarkshire, Scotland, Baads and Harwood, where the mines were finally closed because of the serious corrosion problems and the environmental pollution caused by acidic mine water resulting from microbiological infection. At neither mine, however, was there any incidence of spontaneous combustion in spite of the fact that the coals being mined were low rank and would normally be expected to be liable to heatings.

36. Microbiological attack on timber is, however, another matter and there is practical experience from both South Africa and Australia that microbiological degradation of timber can be accompanied by a high temperature rise sufficient to trigger off spontaneous combustion leading to actual fire conditions. This sequence of events applies particularly to timber chocks left in the waste and emphasises the danger of leaving timber in the gob, but timber chocks mainly contribute to spontaneous combustion as a result of fine coal falling into the chock when crushing of the roof takes place.

CHAPTER III

TESTING FOR SUSCEPTIBILITY

INTRODUCTION

1. All coals when mined begin to oxidise slowly, and in conditions where the rate of heat produced by the oxidation process is greater than the heat lost to its surrounding air or strata, spontaneous heating and finally spontaneous combustion will occur. However, the rate of oxidation varies considerably and is roughly related to rank (see Chapter II), which in turn is directly associated with the oxygen content of the coal; however, a number of other factors give rise to modifications of this generalisation. Many apparently similar coals show considerable differences in their liability to spontaneous combustion.

2. These basic principles have long been accepted, and in evidence to a royal commission in the UK, J.S. Haldane said "I want to put it clearly that I am quite convinced that a gob-fire can be produced in any kind of coal at ordinary temperature however little it oxidises, as long as it oxidises; and it is only a matter of size and insulation and so on. Any sort of coal we have ever examined oxidises sufficiently to produce gob-fires. Some coals are inherently more liable to rapid oxidation than others, but I do not want anyone to think that by doing a chemical test on coal he can tell whether he is going to have gob-fires or not. It depends so much on other things". (Ref 18)

3. This view still holds good and experience shows that tests for susceptibility must be considered as only a part of an overall risk assessment, which must include due consideration of all the circumstances of a particular mining situation.

4. The oxidisability of a coal, though important, is only one factor in the chain of events and, in practice, it is mining factors that are decisive in determining if spontaneous combustion will occur in any particular place. However, a knowledge of the relative oxidisability of different coals is valuable, for example, when starting to mine a new seam, in helping to make decisions on the precautions needed in selecting mining methods, or to determine if one part of a seam is likely to prove more troublesome than another. For these reasons, a number of laboratory methods have been suggested for such a test. All these methods have been examined by the NCB in the UK and the following paragraphs describe most of the well-known methods reported in the international literature, with critical comments and a recommendation for future procedure.

STATIC ISOTHERMAL METHOD

5. This was the earliest attempt to devise a laboratory method for assessing the liability of coals to spontaneous combustion, and has undoubtedly been the most widely used.

6. Essentially, a series of bottles (usually 6), each fitted with an airtight bung and tap containing 5 g of glass wool, 1 ml of distilled water and 10 g of freshly ground coal to be tested, are placed in a thermostat at 30°C (86°F). A bottle is then removed at intervals, from 3 to 96 hours, and the gas in the bottle analysed, allowing a calculation to be made of the oxygen absorbed per gram of coal.

7. Between about 1913 and 1920, experiments on the rate of absorption of oxygen at 30°C (86°F) were carried out and confirmed earlier published results by Winmill and Graham that absorption was rapid at first, but gradually approached zero. Time-absorption curves were published for 40 British coals, whose reputation for being the cause of spontaneous fires varied greatly. It was found that coals not liable to "fire" absorbed less than 200 ml of oxygen per 100 g of coal during 96 hours at 30°C (designated as "A96"), and those liable to "fire", more than 300 ml in the same time. The method was also used to investigate the effect of particle size, temperature, oxygen content of the oxidising atmosphere used, etc.

8. From this and other work (Ref 56), the US Bureau of Mines has produced equations for the various reactions including:-

$$A = Kt^n$$

where A = ml oxygen absorbed
t = time
K and n are constants ("n" being constant for all coals at all temperatures)

9. More recently, work using isothermal methods, carried out with sophisticated equipment automated so that gas samples were taken and analysed hourly for oxygen, carbon dioxide and carbon monoxide, has been used in Germany at Bergbau-Forschung (Ref 90). From tests on five coals it was concluded that the oxidation rate after 100 hours at 40°C (104°F) was a suitable index for characterising spontaneous combustion tendencies.

10. More recent work by the same group (Ref 90), based on tests of 75 samples covering the whole range of coal rank, has altered the views, and it is now concluded that the spread of results for any given rank of coal (as expressed by volatile matter content) is too large to be very meaningful, and although there is a rank relationship, this is affected by other properties such as petrography and porosity. From an examination of the curves for a number of other coal properties, it is concluded that the rate of oxidation of a coal is more closely related to the total internal surface than to any other rank-dependent factor. On the practical side, it is now recommended that the isothermal tests should be carried out at 60°C (140°F), presumably to minimise the hindering effect of smaller pore size on the rate of oxygen diffusion. Though no attempt seems to have been made to correlate the experimental oxidation test results with actual liability of coals to spontaneous combustion in practical circumstances, the work indicates that, although important, the properties of the coal are only one of a number of factors determining whether spontaneous heating will take place in any particular seam or mine.

11. Over 50 coals have been examined by the NCB using this method, covering most types of coal in the UK (Ref 108). The results of statistical analysis showed no correlation of "A96" (ml oxygen absorbed per 100 g of coal after 96 hours at 30°C) with history of actual heatings in mines which would depend on mining conditions as well as coal properties, but a highly significant correlation with rank. Statistical significance, however, only tests the assurance with which the existence of a relationship can be checked and not the practical value of that relationship. Statistical analysis of the results indicates that although rank is an important factor in ease of oxidation, it is not sufficient alone to forecast liability to spontaneous heating. It seems that the "A96" figure is undoubtedly a good guide to the susceptibility of coal itself to spontaneous heating.

12. Further work on this subject is being carried out in the USA, Hungary and other countries.

ADIABATIC METHODS

13. It has been suggested that a true adiabatic method of testing - where the oxidising coal sample would be enclosed in a calorimeter that was constantly maintained at the changing temperature of the sample - would be nearer the reality of what is happening in practical conditions. The great disadvantage of this approach is that starting at ambient temperatures, it may take several weeks, or even months, to complete an experiment.

14. Experimental work, at present unpublished, using this technique is being carried out in the USA, the UK, France and Germany, where automated equipment is used for continuous measurements of the temperature in the coal bed, oxygen used, and carbon monoxide and carbon dioxide produced. In general, to speed up the process, the experiments were started at 100°C (212°F) so that an experiment, producing a temperature-time curve, could be completed in 10 to 20 hours.

15. The main object of this work was to place coals in order of their liability to spontaneous combustion. At the US Bureau of Standards, Washington (for the US Bureau of Mines) the reaction chamber is raised initially to a temperature of 150°F to 160°F, the coal sample being in an atmosphere of nitrogen, before air is admitted to the coal and the adiabatic controls keep the enclosure to within 0.1°F of the coal sample thereafter. It is reported that an experiment, which was stopped when the temperature of the coal sample reached 200°C (392°F), took one to five days. At present only temperatures are being recorded, but it is intended later to introduce analysis of the product gases.

16. The main drawback of this work is that by starting the experiment at 160°F to 210°F, the critical temperature range from the point of view of the initiation of spontaneous heating, between ambient and 100°F, where the reactions are different from normal chemical oxidation, is not investigated.

PACED ADIABATIC NON-ISOTHERMAL CRITERION

17. In order to overcome the time factor inherent in the adiabatic method, a new method, paced adiabatic non-isothermal criterion (PANIC), has been introduced by the NCB. This consists essentially of passing a stream of air or oxygen, nitrogen, etc, through a bed of coal in a tube placed in a reaction chamber, which can be raised in temperature steadily, normally 60°F per hour. The exit gases are analysed continuously in a train of equipment consisting of both chromotographic and infra-red instruments. A full description of the method in given in the Mining Engineer, 1970 (Ref 93).

18. A comparison between the results of the German adiabatic tests and those obtained from the NCB paced adiabatic non-isothermal method, which enables a test to be completed in a day, has shown that there are no fundamental differences in the conclusions, either regarding the liability to spontaneous combustion or the temperature sequence pattern in which gases arising directly from "oxidation" occur.

19. A full range of British coals from anthracite to high volatile bituminous has been tested in this apparatus over a temperature range from 60°F to 400°F. At

lower temperatures there was a rather slow increase in oxygen absorption - say up to 160°F - but as the temperature rose so did the reaction rate until it became extremely rapid and continued until almost complete removal of oxygen from the air stream was achieved. On Plate 4, oxygen deficiency is plotted against coal temperature between 120°F and 300°F. The lowest rank sample is the most and the highest rank (anthracite) the least oxidisable within this temperature range. The results can be separated, as is seen from Plate 4, into at least three groups. The group covering the high volatile, medium to non-caking coals is the most reactive showing a marked rapid increase at about 165°F. These types of coal gave oxygen deficiencies of 1% before 200°F, and after about 210°F the oxygen deficiency increased by about 1% for each 13.5°F rise. The high volatile, strongly caking coals (gas coals) show a similar rate of reaction, although commencing at a higher temperature in the region of 250°F. The least reactive samples, anthracite to medium volatile coals, did not obtain maximum reactivity until 285°F to 300°F; at lower temperatures their oxidation rates varied, sometimes fluctuated and were relatively slow up to 250°F. Oxygen deficiences of 1% were not observed until at least 275°F. Thus, as with all other methods, there was a relationship between coal rank and reactivity, although as usual there were a number of anomalies showing that rank is not the sole factor controlling oxidation.

IGNITION TEMPERATURES

20. A number of attempts, mainly in the UK and the USA, have been made to relate liability to spontaneous combustion and ignition temperatures. The main difficulty is to find some critical point in the temperature scale at which the behaviour of a coal alters in a manner which can be defined and determined; a number of different criteria have been suggested. The most widely used is the "crossing point" index of ignition (Ref 29). When a coal in a tube is slowly heated (about 10°F per minute) in a furnace or preferably by passing hot air through a coal bed, a point is reached at which the coal bed temperature curve and the input air or furnace temperature curve cross over; this is commonly, but inaccurately, known as the "ignition temperature" and it has been suggested that this is associated with liability to spontaneous combustion. Modifications of this method using different rates of heating (27°F and 135°F per minute) have also been carried out (Ref 51).

21. So called "ignition temperatures" have been determined for a number of UK coals by the NCB, and the results varied from 345°F to 950°F. There is again a distinct relationship between rank and ignition temperature, but it is not possible to draw any definite conclusions relating ignition temperature with spontaneous combustion, except that low values were more often associated with coals having a known liability to heating.

22. A crossing point index has the advantage that it is easily determined, not unduly subject to experimental errors and the variables are easily controlled. It undoubtedly represents a danger point in the progress of oxidation, even though the question of whether the coal will reach that danger point will certainly depend on other factors operating earlier in the history of its exposure to oxygen.

CHEMICAL METHODS

23. Chemical methods of assessing the tendency of coals to spontaneous combustion have the advantage that, if meaningful, they are very simple to carry out.

24. For example, it has been suggested (Ref 67) that bromine absorption by coal could be used to measure in a few minutes its tendency to spontaneous combustion, since it has been shown that coal exposed to air for a few hours at 265°F absorbed much less bromine than unexposed coal. Other work (Ref 9) has used iodine instead of bromine and concluded that iodine-absorption value was a measure of liability to spontaneous combustion. These methods do not seem to have been developed.

25. Attempts have been made in the USSR and Poland to avoid some of the disadvantages of using gaseous oxygen by measuring the lowest temperature at which explosion will occur when the coal is intimately mixed with a solid oxidising agent such as sodium nitrite, although it does appear that such methods are measuring a property far removed from a tendency to spontaneous combustion at normal temperatures. Mixtures of 0.1 g of ground coal and about the same amount of sodium nitrite were heated (Ref 67) in test tubes in a copper block, the temperature of which was raised at 8.1°F per minute. The "ignition temperature" (slight explosion) of the sample was measured as received, after oxidation with hydrogen peroxide, and after admixture with benzidene to restore the sample to its condition prior to mining. It was concluded that the degree of reduction in "ignition temperature" by treatment with hydrogen peroxide was a measure of liability to spontaneous combustion. It was stated that the difference between the exploding temperature after treatment with H_2O_2 and after treatment with benzidene (ΔT) is an index of self-ignitability, and that if ΔT is below 54°F a coal is not liable to spontaneous combustion but above 72°F the coals are very liable. Some 30 British coals have been tested by the NCB using this method (but substituting p-phenylene diamine for benzidene which is a "prohibited" chemical) giving ΔT varying from 27.7°F to 123.5°F. No relationship was found between ΔT and history of spontaneous combustion for these coals, but there was a significant relationship between ΔT and rank, so that it can be confidently stated that ΔT is influenced by rank although it is of little practical value as a means of predicting spontaneous combustion. According to recent literature, the Russians have now reverted to the static isothermal oxidation tests for classifying their coals.

INFRA-RED METHOD

26. Work is now being carried out by the NCB on the examination under an infra-red microscope of a freshly-exposed coal section in an oxidising atmosphere. This is a method which would not destroy the physical structure of the coal as it examines the cut face of a lump. At first, small white spots are observed, and these then increase in area. It may be possible to assess the rate of oxidation of a coal by counting the number of spots formed or the area of white patches after a given time. A report will be prepared on this work in due course.

CONCLUSIONS

27. A number of laboratory methods for listing coals in order of liability to spontaneous combustion have been outlined. In all cases there is a relationship between rank and reactivity, but there are a number of anomalies indicating that although rank is an important factor, there are physical properties, eg porosity, associated with petrographic constituents which affect the oxidation of a coal. All the tests described require a fundamental alteration in the physical condition of the coal, eg it has to be crushed and the various petrographic types become mixed. The tests, in general, confirm that oxygen content (which is, of course, closely related to rank) gives the best "first" assessment of liability to spontaneous combustion, but this is affected - particularly in the low temperature range at

temperatures up to about 100°F - by a number of secondary factors (eg oxidation of pyrites, chemisorption of moisture, external heating through geothermal influences, etc) which are additive and so complicate the process. Further details on these factors were given in Chapter II.

28. The most reliable methods for listing coals are those connected with oxygen absorption, and it is recommended that either isothermal methods or the paced adiabatic non-isothermal method should be used for this purpose. It would be of great value if there could be an agreed international method for laboratory testing to assess the liability of a coal to spontaneous combustion; at present, because of the need for a comparatively simple test, this would probably have to be a standardised isothermal method although the paced adiabatic method gives much additional valuable information about the temperatures at which various gases are evolved (see Chapter V).

29. For practical purposes related to monitoring, it is essential to carry out programmed heating oxidation tests, particularly with any different types of coal to confirm that the order of appearence and the rates of evolution of detector gases, eg carbon monoxide, hydrogen, ethane, etc, are following the expected pattern. In any long-term programme on the development of a new coalfield adequate laboratory facilities should be available for carrying out both the isothermal and programmed heating tests on the coals to be mined.

30. A method of assessing the liability of a given coal to spontaneous combustion "Rapid Appraisal of Spontaneous Combustion Assessed Liability" (RASCAL) is given in Appendix "N".

CHAPTER IV

GEOLOGICAL AND MINING FACTORS

GEOLOGICAL FACTORS

Seam Thickness

1. Where the seam thickness is greater than that which can be completely mined in one part, the greater the seam thickness, the more liable the workings will be to spontaneous combustion, as there will be more coal left in the extracted area under the influence of the critical airflow zone.

2. In thick seams, certain bands within the section can be more liable to spontaneous combustion than others. The thicker the seam, the more difficult it becomes to avoid leaving relatively high-risk coal within the gob area. In some cases it is necessary to mine the seam selectively, so as to leave the lowest-risk coal in the waste.

Seam Gradient

3. Within the extracted area, movement or leakage of air or gases may take place as a result of forces other than those of ventilation pressure. Flow into the worked-out areas may be due to buoyancy as a result of the different densities of methane, carbon dioxide or nitrogen and the effect of temperature, which may influence the development of spontaneous combustion within the waste. The greater the gradient involved, the larger will be the effect of such flow.

4. The rate at which a heating develops, particularly in the later stages, is sometimes much greater with larger gradients because of the buoyancy effect. This can affect the rapidity with which control measures against a heating need be applied.

Caving Characteristics

5. The caving characteristics of the strata above the extracted section may have a considerable influence on both the likelihood and the method of control of spontaneous combustion. In partial extraction, where adequate pillars are left to support the super-adjacent strata, the caving characteristics are of little significance. However, on a totally caved longwall face, where coal is left in the waste, the caving characteristics are of considerable importance.

6. In order to reduce the amount of leakage airflow within the extracted area, it is desirable for the waste to be filled with as fine a material as possible. Such a characteristic ensures that the material occupies the greatest volume possible and, consequently, it more adequately fills the total void. It is therefore advantageous when the strata immediately above the seam is friable. Conversely, a greater heating hazard is associated with a strong "blocky" roof.

7. The strength of this material is also an important factor - the weaker the material the more closely it will cave to the back row of supports and tend to close up the waste area. This is an important feature when the risk from leakage airflow into the extracted area is high.

8. Where the immediate roof is not friable, the caving characteristics may be improved by working the face at such an angle as to take advantage of the natural cleavage planes. Working "on end" (that is with the face perpendicular to the cleat) will result in a stronger roof, working "on bord" (that is with the face line parallel to the cleat) will encourage more rapid caving.

9. In some instances it may be necessary to extract a certain section of a thick coal in order to take advantage of the caving characteristics of the section above.

Faulting

10. Faulted ground frequently has an influence on the incidence of spontaneous combustion.

11. Any grinding action with consequential production of fine coal may lead directly to spontaneous combustion, as may the possible flow of leakage air along fissures within the fault plane itself. This leakage airflow may well reach a critical area within the gob or within the seam.

12. If the fault gives rise to bad roof conditions, this may slow down the rate of advance to below the safe minimum, with an attendant risk of heating developing. This is particularly the case if wooden supports have to be used to control the roof in the fault area. Plate 5 shows a typical circumstance, where a fault retarded face movement to such an extent that a heating had sufficient time to develop. The fault throw varied between 7 ft and 12 ft in the last five months of the life of the face. The leakage paths included those from the intake entry road across the gob to the face, and also possible paths from the face into the upper leaf gob and/or airways sited within the upper leaf gob. In spite of extensive airway sealing and attempts to balance pressures across these leakage paths, the face had to be abandoned.

13. It is certain that the fault caused this heating, either by providing the leakage paths for air or, indirectly, by slowing face movement and allowing a normal gob heating to develop.

14. Where a section of the seam is particularly liable to spontaneous combustion, it may be necessary to include this section within the extracted horizon. Any faulting which throws this section outside the working horizon and into the gob may add very considerably to the risk of heating developing.

15. The direction of known faulting relative to adjacent working should be taken into account when planning the layout of a new district. Some of the most difficult heatings to control have their supply of leakage air from an interconnection of fault planes and current or abandoned workings.

16. In longwall workings it is particularly important to take account of the position of any known faults relative to the planned finishing line of the face. The prolonged salvage time that may be caused by bad conditions due to a fault close to the workings is to be avoided wherever possible. If this situation is unavoidable and the risk is considered high, then the area around the fault intersection with the face or airway should be surface sealed and injected with a sealant.

Coal Outbursts

17. Coal outbursts are most likely to occur in the harder formations, rather than in the softer, lower rank coals under consideration.

18. Where there is a likelihood of coal outburst and spontaneous combustion occurring concurrently, the best known techniques for detection, prevention and control of spontaneous combustion must be rigorously applied. The modern techniques for relieving or initiating controlled outbursts of this type must also be utilised to the fullest extent.

19. The danger from allowing the products of an outburst, ie finely powdered coal and/or methane, to pass over the site of an active heating are very great. In this regard, any districts containing an active heating should be sealed off at an earlier stage than would be necessary if there was no outburst potential.

Coal Friability

20. The more friable the coal, the bigger the surface area exposed by physical shock. This leads to a greater liability to spontaneous combustion.

21. Within the extracted area, the smothering effect of a friable coal is greater than that of a coal which breaks into larger sizes. The smaller particle size of the more friable coals will also tend to fill the waste more completely. The quantity of leakage air flowing through the gob will be less the more friable the coal, but the danger from the leakage that does occur is potentially much greater.

22. The relatively large surface area exposed to oxidation will tend to yield more heat per unit volume of coal. As a consequence, the temperature rise will tend to be greater. As a further consequence of the broken nature of the coal, the oxidation may increase at a more rapid rate and open flame occur more readily.

Rider Seams

23. Rider seams may have a considerable effect on the likelihood of spontaneous combustion in a particular working. If breaks extend from the current workings into the rider seams, it is not unknown for these to fire spontaneously. In such cases both preventive measures and methods of control may be difficult and expensive to apply.

24. A strong rider seam may bridge across the extracted area. The consequential bed separation within or above this seam allows leakage air to flow under possibly critical conditions. In these circumstances, the rider coal should be encouraged to fall into the extracted area by whatever means are available. In critical conditions it may be necessary to increase the strength of the waste edge supports or the width of the working area to achieve this objective.

Depth of Cover

25. Depth of mining does not necessarily affect the spontaneous combustion risk. For example, there are coals at or near the outcrop, and seams at shallow depth away from the outcrop, that are more susceptible to spontaneous combustion than other coals lying at great depths; this may be due to the friability of the coal,

cracks and the availability of air. However, increased depth can have an indirect effect, since mining at greater depth generally results in greater methane liberation needing higher ventilating pressures with consequent risk of leakage and a higher likelihood of crush circumstances.

26. The greater the depth of cover, generally, the higher the natural strata temperature and, consequently, the higher the base temperature of the in-situ coal.

Geothermal Gradient

27. Geothermal gradient itself does not directly affect the heating hazard. However, where geothermal gradients are high, the strata temperature in the workings is likely to increase more rapidly with increasing cover than where the gradient is low, resulting in the possibility of a higher base temperature. This then means that only a small additional temperature rise is necessary before the critical temperature is reached.

MINING FACTORS

Mining Method

28. An advancing system of mining leaves extracted areas lying between the entries serving the working places. The ventilation pressure differences will encourage air to flow across these areas, with attendant risk of combustion.

29. In high-risk situations a retreat method of working is normally to be preferred. In extreme cases it may even be essential, provided it does not create serious fire problems in the coal headings and gas problems in the waste.

30. However, the most important advantage gained by adopting a retreat system is lost if an attempt is made to ventilate the waste using a bleeder entry system. The airflow through the waste area is a very real hazard. In cases where a bleeder entry is considered absolutely necessary, then cognisance should be taken of the danger, and a plan of action prepared in the event of a heating. This will normally involve sealing the bleeder entries at strategic sites.

31. Mining methods applicable to Western US coals are listed below in generally increasing order of risk:-

Room and Pillar Methods	Longwall Methods
no pillar extraction	retreat single thickness extraction
pillar extraction	longwall caving method
sub-level caving	retreat multi-lift extraction

Rate of Advance

32. Within any extracted waste area adjacent to a working place there will normally be air, either deliberately induced by bleed action or entering the waste by virtue of the force of the ventilating current. In this zone the rate of airflow can be critical and any coal within this zone will tend to oxidise at an increasing rate if the process is not interrupted.

33. In practice, when a working face is operating normally any particular piece of coal passes through the zone at a rate equal to the rate of advance of the working face. It is the time taken from entering to leaving the zone that is critical. If this time is excessive, then oxidation may occur to an unacceptable degree.

34. There is, therefore, a critical rate, everything else being equal, below which the advance should not be allowed to fall. Typically, in retreat longwall methods it may be 18 ft per week and the planned production from the face should take account of this factor. This figure has been arrived at as a result of experience in the South Midlands Area of the NCB (UK). However, each case needs to be looked at in the light of its specific conditions.

35. Because of the abnormal strata conditions and frequently incomplete filling of the gob when a longwall starts from the solid, the initial rate of advance should be planned to be in excess of the relevant norm for a distance of at least 150 ft.

36. Similarly, when the face is approaching its planned stop line, the rate of advance should be increased over a similar distance immediately prior to salvaging. However, more important still, is speed in salvaging equipment and the effective sealing off of the completed face.

Pillar Size

37. Pillar size has a direct influence on the liability to spontaneous combustion. It may also be a factor in determining the preventive methods to be used in both current and disused workings. Pillar size can play a major role when controlling an active heating, particularly when relatively large areas have to be sealed off.

38. Ideally, pillars should be of adequate size to avoid crushing. The size required depends upon the strength of the coal, the depth of cover and the influence of other workings above, below or within the horizon being worked.

39. In most cases, pillars of such a size could result in a very low percentage extraction and, in practice, a compromise is usually necessary. It is desirable to design the mine layout in the planning stage in such a manner that district isolation can be easily effected. If this is done, then smaller pillar sizes can be incorporated into the individual district layout to achieve a realistic percentage extraction. If the preventive measures within the district fail to prevent or control a heating, the district as a whole can be isolated from the remainder of the mine.

Sloughing

40. Sloughing occurs to some degree on most coal surfaces. It enables leakage air to enter and travel behind the outer coal surfaces and, if this is not prevented, there is a risk of a heating developing. This type of heating is particularly dangerous as it is capable of developing into open fire very quickly. It is also difficult to detect.

41. It is not always wise to remove the loose coal as sloughing is then encouraged to continue. Where pillar sizes are critical or the risk is high, the coal should be faced and/or injected with a sealant to prevent air leakage and further sloughing, and particular attention should be paid to roof support in the coal headings.

42. The direction of pillar edges relative to the natural cleavage in the coal is an important factor. The pillar surfaces should be as near as possible at 45^0 to the cleat.

43. There is normally a gradation of sloughing from the pillar edge. The degree of sloughing depends upon the depth of cover, the coal strength, the number of planes of cleavage, the pillar size, and the effects of mining.

44. It is the latent sloughing which is potentially the most dangerous as this is not readily visible; as a consequence, it may not be treated under the heating prevention policy for the mine.

Roof Conditions

45. Poor roof conditions increase the liability to spontaneous combustion both at the working face and within the entries. Roof falls leave cavities which have to be supported and are often filled with timber. Such sites frequently feature in subsequent local heatings.

46. Bad roof conditions also lead to increased amounts of coal in waste areas.

47. Roof falls on a working face divert air into the waste and this may be the direct cause of a heating some distance from the site of the fall. This is particularly dangerous near the intake end of the face as the waste gases are more oxygen rich to begin with.

48. Secondly, breaks associated with the fall may accept air, particularly if these face into the airstream. Such breaks may allow air to a critical position within the gob area but remote from the fall.

49. Any timber used in supporting the cavity or the cavity itself, may result in a heating when the face has moved sufficiently to place the fall area at a critical position within the waste.

50. Similar considerations apply when roof falls occur in the airways. Air is deflected into breaks in the roof and sides to a greater extent than before and this may lead to an active heating. Combustible material should not be used to fill or support such a cavity in an airway where the risk is high. The exposure time of these materials is relatively great when located in an airway, and they frequently feature in any heating which subsequently develops (see Plate 6).

51. Such roadway roof falls are particularly dangerous when they occur in the proximity of the intake or return end of the working place.

Crushing

52. Crushing can be significant in two types of location - at pillar and rib edges and worked-out areas. In the first case, where a pillar is subject to crush, a situation can develop where leakage paths are created, leading both to the flow of air into the solid coal and, in some circumstances, through the solid to affect a more distant zone.

53. In the other case, loose coal is frequently present in worked-out areas - in some cases as deliberately unmined roof coal and in others as a result of accidental loss. After the mining phase, such coal may be crushed by the convergence of roof

or floor, by the grinding action of the disturbed overlying strata, or by falls of roof coal. The effect is to reduce the sizing of the coal and to create an increased surface area with consequent added risk of heating.

Leakage

54. To create the circumstances in which spontaneous combustion can occur there must be a supply of oxygen and a situation where a build up of heat is possible. This can be brought about, for example, by air leaks through fissures in solid coal and can result in shallow seated heating. This situation can occur where leakage paths exist at air crossings, in solid rib sides cracked under pressure, in and around regulators and doors and other similar locations where there is a high pressure gradient and a tendency for the air to attempt to flow through solid coal.

55. In other circumstances, where a worked-out area or gob exists, leakage paths through or around the seals or through unconsolidated packs, as in the case of advancing longwall, or through inadequately sealed bleeder systems, can result in the passage of sufficient air leading to the development of a deeper seated heating.

56. Leakage and leakage paths over coal surfaces are one of the most significant factors in the development of spontaneous combustion to a stage of active heating.

Multi-Seam Working

57. Where a multi-seam situation exists, both during the working of the first seam or subsequent seams, situations can arise with spontaneous combustion hazards for the seam currently being worked and any other seam above or below it. For example, where a seam has been worked with another unworked seam underlying it, leakage paths can be created into the lower seam, with consequent risk of heating. In other circumstances, where a seam is worked under an overlying unworked or worked seam, the later mining operations can result in fire hazards in the upper seam. Particularly vulnerable areas include air crossings, regulator sites, stoppings and any other point of high pressure difference. The effect of a second working on pillar and rib conditions in another seam can result in potentially hazardous situations because of added stress and the creation of crushed and leakage prone situations.

Coal Losses

58. Coal losses - that is leaving remnant coal in worked-out areas - is a serious heating hazard. Most gob fires result from this. In the South Midlands Area of the NCB there are, on average, six heatings of this kind each year. There is no normal mining system that can guarantee that remnants will never be left in a waste area. Most mining systems result in a significant loss of coal. The resultant situation, in which the coal is frequently likely to be crushed and finely divided and in a location where heat build-up is possible, must be considered a potential hazard.

59. In the longwall mining system, it is both impractical and hazardous to carry out an effective cleaning-up operation behind a powered support line, and changes in cutting horizon, faulting or other circumstances.

Worked-Out Areas

60. Worked-out areas are a potential source of heating. Where such areas are not stopped off, they are likely to have interruptions in the ventilation system as a result of roof falls, or lowering or floor lift, leading to deterioration in rib conditions and to the presence of loose small crushed coal - all such factors contributing to a potentially hazardous situation. Ventilation quantities are frequently below those in working areas and may fall to critically low levels where the oxygen supply is adequate, but the cooling effect is not.

61. Where worked-out areas are sealed off, a hazard can exist when there is leakage of a limited amount of air through or around stoppings. The hazard is greatest where the pressure difference across the stoppings is high and least where the stoppings are systematically balanced.

62. Flow through sealed areas results not only from differences in the mine ventilating pressure, but also from the large volumes of such areas, which result in barometric changes creating inflow and outflow situations, sufficient in some circumstances to provoke heating.

Heat from Machines

63. Normally, heat from machines is dissipated within the ventilating air stream and the temperature rise of the general body of the air is likely to be very small. In some circumstances the effect of the heat from machines is secondary in that additional air that may have to be circulated will require a higher ventilating pressure with consequent increased risk of leakage. It is possible that localised heat from, for example, a transformer may increase the coal temperature at that site to such an extent as to increase the spontaneous combustion hazard, but such circumstances are likely to be extremely rare.

Stowing

64. Stowing is carried out in a number of coalfields throughout the world specifically to seal mined-out areas completely. As such, it has proved to be an effective method of spontaneous combustion control. However, where dependence is placed upon solid stowing as the means of reducing the heating hazard, a dangerous situation can arise if the operation is not carried out to a satisfactory standard.

Methane Drainage

65. In respect to the two methane drainage systems that may have application in the Western US - boreholes from the surface or inclined boreholes from panel entries - the heating hazard, if any, can only derive from the methane drainage suction promoting a flow of air into the coal seam or a mined-out area. The hazard is more likely where the drained mixture contains less than 40% of methane. This can be indicative of the passage of a significant proportion of air through the system and such air may be travelling through zones where it can contribute to the spontaneous combustion risk. UK legislation does not allow the drainage of potentially flammable mixtures of methane and air. In fact the limit is set at 40%, which is well above the upper combustion limit of 14%. Draining a mixture containing very little air or methane, but a high proportion of carbon dioxide and nitrogen, can have the effect of drawing air into the gob, with consequent risk of heating.

Ventilation Pressure

66. Ventilation pressure has a direct and important influence on the risk of the development of active heating.

67. Increased intensity of mining, higher standards of methane dilution and, in some circumstances, reduction of airborne dust all tend to require more ventilation quantity in individual sections. As mining goes deeper, more air may be required to reduce ambient temperatures at the working face and in the return airways. These increased quantities require an attendant increase in ventilation pressure.

68. The index of flow relating pressure "H" with quantity "Q" is normally as in $H = RQ^2$ where "R" is the resistance to flow. For a given increase in pressure there is a smaller percentage increase in flow in the mine roadways. In some leakage paths, however, the airflow may be laminar as against turbulent and certainly this occurs in some regions within most extracted areas. Under these circumstances, the index relating flow and pressure may be between $H = RQ^2$ and $H = RQ$. When this applies, the percentage increase in airflow is proportionally greater in the leakage paths than in the mine airways. The flow through leakage paths, and hence the liability to spontaneous heatings, is therefore increasing to a greater extent than may be apparent.

69. Other air pressures that affect the risk of spontaneous combustion are those naturally developed by the combined effect of heat emission and gradient, and by barometric fluctuations. In an extracted area a critical flow of air may occur either in sympathy with or in opposition to the mine ventilation pressure under the influence of one or both of these factors.

70. The effect on spontaneous combustion of barometric pressure changes is confined to the waste or to voids behind stoppings. In these situations breathing takes place both in and out of the waste or void, with the attendant risk of a heating developing in the vicinity of the packside or the stopping site.

Changes in Humidity

71. Research has been carried out by a number of laboratory workers into the influence of humidity in spontaneous combustion (Ref 75 and 91).

72. In general terms, if coal adsorbs moisture from the ventilation air it will heat up due to the release of the latent heat of condensation and chemi-sorption effects. On the other hand, if the coal looses water by evaporation to the ventilation air, the reverse occurs and the coal will cool. Both effects will occur if there is any imbalance between moisture in the coal and moisture in the air.

73. The balance between the complex mining conditions that can bring about condensation or evaporation has not been fully researched, but it is becoming increasingly evident that changes in environmental moisture play a significant role in tipping the balance from adsorption and heating (leading to spontaneous combustion) and evaporation and cooling with the consequent reduction in the risk of a fire developing.

CHAPTER V

DETECTION AND MONITORING

INTRODUCTION

1. The need for early detection of an incipient heating in a mine is receiving an increasing amount of attention in all coal-mining countries.

2. The early detection of spontaneous heatings is of utmost importance, so that prompt remedial action can be taken. When a spontaneous combustion reaches the "fire stage", the difficulties of control become much more serious - not only from the hazard to safety, but also from the serious financial losses involved in equipment and output. Recent fires at mines in Europe have resulted in the loss of many millions of dollars and in one case (see Appendix "I"), the permanent closure of a large, highly-developed, modern mine.

3. Fortunately, the development of physical methods of gas analysis during the last ten years has revolutionised the approach to the analysis of mine airs. New methods, especially gas chromatography and infra-red analysers, provide a sensitivity and accuracy (both qualitatively and quantitatively) hitherto unobtainable with the traditional chemical absorption methods that had evolved during the past 100 years. Moreover, the new physical instruments operate much faster and have enabled the development of methods for the continuous monitoring of mine airs, hitherto not practicable.

4. This chapter outlines the various methods of detection which have been used, and gives a brief description of the recommended method for early detection of heatings - the tube bundle technique of continuous monitoring - which is now installed in many mines in Europe, with over 170 in the UK.

GENERAL PRINCIPLES

Carbon Monoxide

5. In recent years there has been a great increase in the sensitivity, reliability and accuracy of carbon monoxide measuring instruments which has made the direct use of carbon monoxide as a sensitive indication of spontaneous combustion much more reliable. In the past, the fact that carbon monoxide can arise in a mine from sources other than the oxidation of coal, eg in shot firing or from diesel locomotives, has given rise to difficulties as intermittent sampling fails to discriminate between carbon monoxide from heatings and from alternative sources. However, if carbon monoxide could be established as the earliest indicator of spontaneous heating - and there have been suggestions (Ref 87) that other gases such as hydrogen, ethylene or other unsaturated hydrocarbons, might provide a better indication of incipient spontaneous combustion - its continuous recording would show trends indicating danger.

6. Therefore, a comprehensive series of tests on coals of all ranks was carried out in the UK, using the paced adiabatic non-isothermal criterion to determine the quantity and timing of gases evolved during oxidation in the temperature range from ambient to $400^{0}F$. The results (Ref 93) convincingly established that carbon monoxide is the most sensitive gaseous indicator of spontaneous heating; this is a reiteration of what Graham, who carried out the fundamental work on this subject, stated some 50 years ago, but in the meantime

alternative claims had been made for other gases for which conclusive proof was lacking.

7. It has now been established that these other gases can be a good guide to the temperature reached in a heating. A typical set of curves is given on Plate 7; the same type of curves were obtained for all ranks of coal, there being - as would be expected - a shift of the curves to the right (ie to higher temperatures for the same gas emissions) for higher rank coals and vice versa. In addition, investigations have been made of a number of trace compounds (Ref 110 and 125) that appear in very small quantities during low temperature oxidation. Some 25 compounds have been identified, of which about half have been measured quantitatively. These results indicate the complicated nature of the oxidation reactions of coal, and although, in general, the rates at which all of these gases are evolved increased with rising temperature, no compound was found whose concentration increased so consistently or at as great a rate as carbon monoxide.

8. With the techniques now available for analysis of mine air, the most certain guide to incipient deep seated heating is a steady increase in the accurately measureable concentration of carbon monoxide above the mine norm, and it has been demonstrated that this can give a clear indication of trouble at temperatures at least 70^{0}F earlier than any of the suggested alternative gases. With present analytical techniques, it should be possible to detect an increase in coal temperature 20^{0}F above the ambient temperature conditions in the strata. Plate 8 shows the result of experiments in one European coalfield using several observers (Ref 110). It can be seen that "smell" does not become detectable until temperatures 70^{0}F to 90^{0}F in excess of those at which carbon monoxide has already shown a very significant increase. Since, in practice, the number of sampling points is limited, gas analysis is not as significant in the detection of shallow rib fires.

Carbon Monoxide:Oxygen
Deficiency Ratio

9. Although it was first recognised (Ref 6) as long ago as 1898 that coal exposed to air at ordinary temperatures gave rise to a little carbon monoxide, the analytical methods then available were not sensitive enough to be used for early detection of heating. In 1914, an ingenious and simple method was evolved for using the analytical data from gas analysis for detecting incipient heatings (Ref 19). In the experimental work on the oxidation of coal, the quantity of carbon monoxide in the air drawn off was compared with the quantity of oxygen consumed. The calculation was based on the fact that nitrogen is neither added to nor taken from the air concerned in the oxidation, and the ratio so determined is almost independent of subsequent dilution with fresh air.

10. The calculation is made as follows. If N_2 is the percentage of nitrogen in the heating, then the oxygen in the fresh air originally accompanying it was:-

$$O_2 = \frac{20.93}{79.04} \times N_2$$

The oxygen consumed, therefore, is:-

$$\frac{20.93}{79.04} \times N_2 - O_2 \text{ (ie \% oxygen in the air from heating)} = \Delta O_2$$

and the ratio of carbon monoxide to oxygen consumed

$$\frac{100 \times CO}{\Delta O_2} \text{ ie } CO/O_2 \text{ deficiency}$$

The normal ratio in a mine with a reasonably consistent extraction rate is 0.1 to 0.5, and any rise indicates a heating. It was found that the ratio increased with temperature and gave valuable information about incipient heatings in mines. This ratio, known as "Graham's ratio", has been used extensively for many years in certain mines where heatings were suspected, has provided valuable objective evidence of heatings as a supplement to personal observations, and has, in some cases, given the first warnings of dangerous conditions weeks before a smell was noticed. Prior to the use of tube bundle systems, practical experience made it generally accepted that regular air analysis gives enhanced confidence that management would receive due warning of the onset of an incipient heating, and that, where in regular use, the Graham ratio gave the first indications of a heating.

METHODS WITHOUT THE USE OF INSTRUMENTS

11. The development of a heating is accompanied by the progressive appearance of haze, sweating of the strata, smell, smoke and fire, unless the heating is stopped at some stage. Some of these stages do not always occur, eg the formation of haze depends on the temperature and humidity of the return air from a heating in relation to the temperature and humidity of the air with which it mixes, and, similarly, sweating of strata near a heating also depends on the temperature of the strata. Smell is more reliable, but requires trained and experienced men to recognise it with confidence at an early stage of a heating. The characteristic smell, often known as "gob stink", has not yet been identified precisely by chemical means and its recognition is a purely subjective matter. Many descriptions have been given to this smell, eg faint paraffin odour, the smell of a burning pit heap, a taint of onions or garlic, decaying vegetation, petrolic becoming acid, etc, but, in practice, it is a smell a man has to learn and apparently never forgets after experience. Thus in mines subject to heatings, an experienced underground official can obtain valuable information by "sniffing" but, unless well-trained, he can confuse the smell of new brattice cloth or lubricating oils with that of a heating. It has been shown that with modern analytical methods a much earlier warning of a heating can be obtained than by smell, which probably does not become noticeable until the coal reaches about 250^{0}F, and is only obvious at about 300^{0}F. However, the effectiveness of experienced human observation should not be under-estimated, particularly in connection with shallow seated rib-side fires.

12. When a heating is located near the roadway surface, its presence may first be detected by virtue of a rise in temperature of the strata surface. Local hotspots such as these are also often detected by an emission of smoke or haze which tends to lie in the roof of the roadway.

13. In 1941, it was suggested that the air leaking into a suspected area could be charged with some substance such as methyl bromide which would undergo a marked change of odour when in contact with heated matter; the smell of the return air would then give warning of a heating - but no trace has been found of any experimental work having been done on this method.

METHODS USING PORTABLE INSTRUMENTS

Carbon Monoxide Detectors

Stain-Tubes

14. The most commonly-used portable detectors of carbon monoxide are chemical stain-tubes; they provide a ready and relatively accurate method of measuring carbon monoxide - provided the right range is chosen, and that guard tubes are used if there is a possibility of the presence of hydrogen sulphide. Some makers of these devices incorporate guard tubes and this should be checked before use. In the absence of hand-held carbon monoxide meters, stain-tubes are used to locate the emission of carbon monoxide from sealed-off areas or across gobs. However, this type of instrument is not sufficiently accurate for the determination of the carbon monoxide:oxygen deficiency ratio.

Hand-Held Carbon Monoxide Meters

15. Recently a number of hand-held carbon monoxide meters have become commercially available. They are based on the polarographic cell or on the temperature rise of a hopcalite cell. These instruments require frequent maintenance and recalibration. As in the case of stain-tubes, their use to indicate the onset of spontaneous combustion depends on the fact that carbon monoxide is the most easily recognised indication of an incipient heating of coal.

Carbon Dioxide Detection

16. Carbon dioxide is not significant to the detection of spontaneous heating.

Oxygen Detectors

17. Various commercial instruments based on the polarographic cell are available. Their use is mainly to provide protection against gross oxygen deficiency, but they are not sufficiently accurate for the determination of the carbon monoxide:oxygen deficiency ratio and they have no relevance to the early detection of spontaneous combustion.

Temperature Measurement

18. Whilst, in theory, hand-held temperature measuring instruments could be used to detect a temperature rise in exposed coal surfaces (rib-sides, pillars, face, etc), there is no record of their having been used for this purpose, the human hand being just as sensitive and much more convenient.

Thermistors

19. Thermistors (thermally sensitive resistors) have been used (Ref 71) in a gob with the object of registering temperature rise. However, the difficulty of

placing the thermistors in the right place and the need to use very large numbers of them to cover the mine workings, has resulted in the method being abandoned. Further development of thermistor technology may increase their relevance to spontaneous combustion detection.

Infra-Red Detectors

20. It has been suggested that infra-red meters could detect a small rise in temperature on the surface of coal. Trials underground have shown that when they were made sensitive enough to register a few degrees difference on any exposed coal, the meters were affected by many stray effects, such as machines and even working men, and gave many false "alarms". Furthermore, it was not possible to use them in the places where spontaneous combustion was most likely to develop, particularly gobs behind a working face, and, although theoretically a promising approach, they were not found to be a practical solution to the problem of early detection of spontaneous heating, though they are being used successfully for other purposes underground, notably for detecting "hot spots" on machinery and failed conveyor idlers. They have application in locating leakage of warm return air from heating in mineable areas and can indirectly assist in the control process. The use of these meters is in its early stages and is likely to be expanded as instrument technology improves and underground experience is gained.

Smoke Particulates

21. The US Bureau of Mines have designed a sensitive smoke detector (Ref 129) which will detect combustion-generated "submicron" particulates and could be used for detecting incipient fires. They have stated (Ref 130) that submicron particulates appeared slightly earlier than significant carbon monoxide production, but a careful consideration of their results and published graphs showed that these results were obtained at 300°F to 400°F. It was agreed with the authors that the curves would cross at lower temperatures, and certainly below 160°F carbon monoxide would be an earlier and more reliable indicator of an incipient heating. This new smoke detector, with its greatly increased accuracy, should provide a means of early detection of fires not due to spontaneous heating.

Detector Gas Measurement

22. Other gases have been suggested from time to time, eg hydrogen cyanide has been recognised in the air in the vicinity of a slowly-propagating, low-temperature "zone of combustion", but the amount evolved is very little below 900°F. Hydrogen sulphide was stated in 1916 (Ref 21) to be evolved in the early stages of a gob fire, but for various reasons (eg because H_2S frequently occurs in mine water from interaction of acid water on pyrites), it is not likely to be useful as a detector gas.

SAMPLING POINTS

23. Positions at which samples are taken to monitor spontaneous combustion conditions must be sited strategically throughout the mine. The number of points are determined by the risk factor in each case, but in order to be certain of sampling the return air from any underground heating, one point should be sited close to the main surface fan inlet and a highly sensitive analyser should be employed for the continuous analysis of this sample.

24. Less dilution occurs at each individual section main return and consideration should be given to locating a sampling point just within each of these positions, both in active and abandoned workings.

25. The most important point is that located at the outbye end of the return of each working place. At this position, the dilution factor is still high but there is little direct leakage, since most doors are normally sited further outbye. At this control point the carbon monoxide concentration is typically at a level of between three and twenty parts per million, but this depends on the seam being worked and the quantity of ventilation air. Peaks of up to one hundred parts per million may occur, due to shotfiring and the use of diesel powered machines. These peaks are normally easily distinguished from the background norm when monitoring is continuous. Where spot sampling is done, it should take place at a time after such activities have ceased and some time has elapsed to allow normal conditions to be stabilised.

26. These three locations cover most of the relatively permanent sites within the ventilation circuit and therefore sample the general body of mine air. It may be necessary to provide additional sites, for example on the return side of stoppings, particularly where there is a large area of extracted workings involved.

27. Additional temporary sites may be selected when a heating develops. They are normally sited at suitable intervals to cover the zone in which the carbon monoxide emission is taking place. Once identified, such points are normally sampled regularly by hand-held instruments, as an aid to determining the location and the rate of development of the heating.

28. It is always advisable to establish a point within a sealed-off area. Such points are relatively free from dilution by fresh air and, when sited at the return end of an extracted or sealed area, give valuable and early information regarding conditions within the void. A proportion of the samples from such a control point should be fully analysed. Regular (daily) observation of the carbon monoxide:oxygen ratio is of great importance in these circumstances.

CONTINUOUS MONITORING

Telemetering from Instruments Underground

29. In some European countries, relaxations of the ventilation regulations are permitted provided continuous monitoring of methane is adopted. There are a number of intrinsically-safe transducers available for this purpose. The electrical signals from these instruments are normally transmitted via the pit telemetering system to the control room for processing and display. The signals may also be used for underground alert systems with provision for automatic cut-out of the electricity supply.

30. With the existence of telemetering facilities for methane, it was a natural development to adopt intrinsically-safe carbon monoxide meters underground for the detection of spontaneous combustion. The most widely used instrument in general use is the non-dispersive, infra-red, Luft-type analyser developed by Bergbau-Forschung manufactured by Maihak. This can be a single point instrument or it can be provided with up to six sample points, located up to 100 ft from the instrument, which are interrogated in sequence. The analyses are telemetered to the control room where they can be processed as required.

31. The advantage claimed for the telemetering system over the tube-bundle system is the reduction in the delay due to the sample travel time in the sampling tubes, but, in practice, this has been found insignificant. The main disadvantages of the system are high capital cost and the problems of instrument maintenance in the hostile environment underground.

Tube Bundle Equipment

32. This method consists essentially of a series of plastic tubes placed underground through which air is drawn continuously and analysed for carbon monoxide at a surface station. The system has been described in a series of papers (eg Ref 109 and 118) and full details of the design and equipment necessary are given in an NCB Handbook published in 1977 (Ref 131). This system was developed by the NCB and has been used since 1968; there are now over 170 installations of varying degrees of sophistication in the UK. Further developments are still taking place, mainly in the control, recording and alarm systems.

33. The fundamental components of a tube monitoring system are the tube (with its accessories), the pump, a sample selection unit and the analyser. The practical success of this approach has been made possible by the commercial availability of small-bore plastic tubes in an outer sheath (developed for hydraulic controls), and the development of new, accurate, sensitive, infra-red instruments for the continuous measurement of carbon monoxide. The tube bundles are similar in construction to multi-core electric cables, with polythene tubes instead of wires, layed helically in a PVC sheath which may be armoured where there is a danger of mechanical damage. Normally the bundles contain up to 19 tubes of 0.17-in or 0.25-in bore - external diameters are 0.25 in and 0.38 in respectively. Individual tubes from sampling points are brought together in junction boxes to larger bundles (2, 3, 4, 7, 12 or 19 tubes) and are identified by numbers printed along their length at about 1-in intervals.

34. The most important factor, from a practical standpoint, for the early detection of spontaneous combustion is the characteristics of the carbon monoxide analyser (see Appendix "O"). This aspect cannot be over emphasised as much of the criticism of the system, outside the UK, has arisen from the use of unsuitable analysers. At present there are no suitable instruments commercially available in the USA which will meet all the points in the specification. In Europe, the Maihak Unor 2, as modified by the NCB, and the non-dispersive infra-red instrument (ADC), designed in collaboration with the NCB specifically for continuous monitoring at mines, have given very satisfactory performance. It is recommended, therefore, that an ADC instrument or a Bendix-Maihak, modified as specified by the NCB, should be used in systems for the continuous measurement of carbon monoxide in the USA. There are suitable American instruments available for the detection of methane and oxygen deficiency; the control and subsequent recording systems and the electronic warning equipment would present no difficulty to companies producing control systems in the USA.

Experience

35. The advantage of the tube bundle system lies in the inherent simplicity of the underground equipment and the fact that all the controls and analysing instruments associated with it are on the surface where they can be conveniently serviced and are not restricted by the requirements that they should be explosion proof or intrinsically safe. Furthermore, operation of the system can be maintained under conditions when the power supply underground is cut off, in

dangerous atmospheres, eg behind stoppings, or even when there are no men underground, enabling monitoring to continue over weekends or holiday periods. Although developed and originally installed for monitoring carbon monoxide continuously, the mine air can also be passed through a chain of instruments analysing the gas for other components, eg oxygen, methane, hydrogen, ethylene, etc, which may be of interest in special circumstances.

36. It has been suggested that a disadvantage of a tube bundle system is that the sample lines must be of considerable length, resulting in a delay between the occurrence of a change in atmosphere composition at the sampling point and the subsequent indication on the readout system. With an induced pressure drop of 10 lb/in^2 there is a delay of about 20 minutes for 1 mile and 3 hours for 3 miles using 0.25-in tubing, and about half these times if 0.38-in tubing is used. However, since often days or weeks elapse between the start of a spontaneous heating and a condition which necessitates action, this sampling delay has, in practice, been found to be unimportant in the early detection of incipient spontaneous combustion.

37. In view of the work outlined in paragraphs 5 to 8, carbon monoxide was the gas chosen for continuous monitoring. The oxidation of coal underground becomes significant from a practical point of view when the temperature starts to rise. A rise in temperature increases both the rate of oxidation and the rate of carbon monoxide production. Thus, if the carbon monoxide content of a mine air is measured continuously, a persistent change of level, ie a "trend", indicates the beginning of a heating. The absolute level of carbon monoxide in a return roadway is relatively unimportant from a detection point of view, because the onset of a heating can be identified against the normal level and sources of contamination such as shot-firing or the operation of diesel engines which are intermittent in nature and will be seen on a recorded graph as humps or peaks which are easily recognised. A continuous record will supply mine management with much more definite information than can be obtained by hand sampling and laboratory analysis.

38. At a number of mines fitted with tube bundle systems heatings have occurred. So far no deep seated heating has developed at these mines that has not produced a rising trend on the carbon monoxide chart. For instance, in one case a rise of a few parts per million at the beginning of a vacation was investigated, a small heating found and controlled, and it was possible to resume work normally after the vacation period; it is probable that without the system a serious fire would have developed during the time when few men were in the mine. At Markham Main mine, in the UK, there have been 56 occasions over the past 10 years on which rising carbon monoxide concentrations have been observed. Each has been followed by remedial action which has prevented the development of any serious spontaneous combustion incident.

39. Monitoring systems proved particularly valuable during the strikes which occurred in the UK in 1972 and again in 1974. It was subsequently stated that the information provided by the tube bundle system saved the life of at least six longwall faces, and almost certainly of one mine. It has also been stated that in one UK coalfield the use of tube bundle systems has successfully reduced the number of serious incidents which hitherto had resulted in the need to seal off three to four working sections per year.

40. The financial savings of tube bundle systems are considerable as they have reduced the need to send gas sampling teams into the mine at weekend and vacation periods. At some mines with a known history of spontaneous combustion this saving is of the order of 12 to 15 man-shifts a week, at overtime rates, so that

the complete cost of the tube bundle installation has been offset in one year's operation.

41. It should also be remembered that if a man has to be sent into the mine to take a sample, the time from portal to portal is often some hours, compared with which the "time delay" of the tube bundle is negligible. The advantages of obtaining continuous analytical results from all strategic points underground cannot be matched by hand sampling; as well as detecting spontaneous combustion, these advantages include the detection of irregularities in the ventilation system, such as the failure of an auxiliary ventilation fan or the malfunction of ventilation control doors. Tube bundle systems have also given early warning of the onset of frictional fires on belt conveyors arising from the failure of idlers.

42. Further developments are taking place in the continuous monitoring field, particularly associated with digital read out presentation of information.

Shaft Monitoring

43. A development of the original tube bundle system has been the installation of shaft monitors designed to detect any type of fire which might break out underground by sampling and analysing the air from the return shaft. The analyser is confined to one sample, although particularly sensitive instruments are needed. Automatic comparison is made with the carbon monoxide content of the downcast air. This sytem is particularly valuable when a mine is inactive or unmanned, and alarm systems have been devised for this type of installation (Ref 131).

Alert Systems

44. Given the electrical outputs from the "tube bundle" gas analysis train, alert systems can be designed to meet any desired requirements. In practice, they range from visual interpretation of simple chart recorder traces to highly-sophisticated, computer-controlled, interrogation systems which may be interlocked with the mine's automatic control equipment.

45. It is usual to arrange the gas analysis cycle so that the gas from each continuously sampled underground point is analysed at 20-minute intervals and if three successive analyses show a progressive increase in carbon monoxide concentration, an alert is announced by a light signal or by a sound signal, or by both. This so called "three shot alarm" avoids false alerts that could be caused by transitory increases in the concentration of carbon monoxide from shot-firing or from diesel locomotive exhausts. In special cases it may be necessary to increase the three shot to four or five shot systems, but this is rarely necessary. Once an alert has been initiated, the system can be automatically locked on to the "abnormal" sampling point with successive interrogation of the last three analyses, the intervals between which have been reduced to 2.5 minutes. If the analyses return to normal, the alert is cancelled and the system returns to normal cycle operation. If, on the other hand, there is a continuing increase in carbon monoxide concentration, the alert is continued.

46. It is also desirable, especially in high dilution situations such as upcast shaft monitoring, to build into the system a zero drift alert to give a double check on the built-in automatic zero adjustment of the carbon monoxide analysers. Provision should also be made for the automatic injection of "span gas" into the system at four-hourly intervals to check the continuing accuracy of the analytical equipment. If the error revealed is small, it is corrected automatically. If,

however, it is greater than predetermined acceptable limits, warning is given that the analytical system requires servicing.

47. Records can, of course, be stored on tape for visual recall and print out as required.

48. In the most recent installations, the analytical records from a number of mines can be interrogated from a central laboratory to give immediate indication of any malfunction; this effectively cuts down on routine service visits and ensures maximum efficiency from the supporting technical services.

CONCLUSIONS

49. Reliable techniques are available for the detection and monitoring of spontaneous combustion. These range in complexity from human observations, through hand-held instruments and intermittent air sampling, to continuous monitoring. The system to be adopted must depend on the likelihood of spontaneous combustion and the degree of risk involved.

50. Maximum security is provided by a properly installed and maintained continuous monitoring system and whenever a significant spontaneous combustion risk exists, the system should be adopted. However, it must always be remembered that regular inspection of the workings is an essential part of every early detection programme.

CHAPTER VI

PRECAUTIONS

INTRODUCTION

1. If the hazard of spontaneous combustion is to be minimised, precautions must be taken during both the planning and operating phases.

2. Precautions which are currently proving effective are described below for underground and surface situations.

3. The fundamental approach to the prevention of spontaneous combustion underground involves the selection, at the planning stage, of the mine layout and mining methods that have the lowest possible spontaneous combustion risk. At the operating stage, working must be carried out with proper arrangements for obtaining warning of the development of a heating and there must be pre-planned facilities to enable the seriousness of the incident to be limited.

4. Surface problems, though causing certain environmental and operational difficulties, tend to be less serious than those underground.

5. It must be remembered that even with the best precautionary planning and operating procedures, circumstances can arise in which spontaneous combustion occurs. It is imperative that mine management ensure that the workings are checked with the utmost care, so that preventive action can be taken in good time.

6. The effectiveness of this approach is demonstrated by the successful working, in many parts of the world, of coalfields with a very high spontaneous combustion risk. In these cases, mining methods have been evolved which produce the lowest frequency of heating, and effective procedures are applied for the inspection of the workings, monitoring, control and combat.

DEVELOPMENT OF SPONTANEOUS COMBUSTION IN UNDERGROUND MINES

Solid Ribs

8. Heating can sometimes develop in the roof or sides of roadways driven in coal or at new working places. This is due to the occurrence of cracks and/or the sloughing of small coal, especially when this is left loosely attached to the solid coal. The ventilation air is moving slowly at the boundary layer, so while there may be sufficient oxygen to initiate the oxidation of the coal, there is insufficient air to carry away the heat generated and the heating becomes self accelerating.

9. These fires may develop relatively quickly, often in a matter of hours, and they are generally small and restricted to a few feet in depth. Because the amount of coal involved is small, perhaps only a few pounds, the quantity of carbon monoxide produced is also small. So if the hazard is to be detected, air sampling points must be carefully chosen and the sensitivity of the carbon monoxide analyser must be suitably adjusted to ensure early response. Otherwise the first indications of trouble may be smell, smoke or visible fire.

Gob Areas

10. In advance longwall mining the face starting line is left behind as the rear boundary of the gob. It is here that spontaneous combustion frequently develops, due to air leakage through the partly-consolidated gob. The path of this leakage is unpredictable and will vary with movement of broken strata in the gob and may not occur at all until the face has advanced a considerable distance and ventilation pressure across the gob has increased. The incubation period of spontaneous combustion in this situation is slow - often many weeks - and as the site may be deep seated, it may remain unrecognised until a fire has actually developed and smoke, haze, sweating and smell become obvious in the return roadway. At this stage the situation is already serious. The delay in detection can be obviated by continuous monitoring of the return air for carbon monoxide. At the first indication of a rise in the concentration of carbon monoxide, relatively simple precautions (see Chapter VII and Appendix "L") will almost certainly prevent the development of a fire situation and the probable loss of the face.

11. With retreating longwall faces air leakage across the gob may still occur, especially with bleeder systems. Since the path of the air through the gob cannot be controlled, spontaneous combustion may develop some distance back from the face. This aspect is considered in more detail under "Control of Leakage through Gob Areas".

12. If detection is left to smell or smoke, a fire situation can exist before remedial measures are taken. Once again, the value of early detection by continuous monitoring of carbon monoxide cannot be over-emphasised.

Crushed Pillars

13. The development of spontaneous combustion in crushed pillars follows the pattern for solid ribs. Sloughed coal clinging to the solid, or deep fissures caused by strata movement, permits air to penetrate into a heat insulated environment so that the rate of oxidation increases progressively. As with rib fires, such heatings can develop relatively quickly in small quantities of coal. When pillar fires are a suspected hazard, apart from the precautions described in Chapter VII, carbon monoxide monitoring points must be carefully chosen to ensure early detection of trouble.

Abandoned Areas

14. The development of fires in sealed-off areas is always a hazard. It is rarely possible to ensure that the stoppings or the surrounding strata will remain completely air-tight with the result that breathing occurs with changes in barometric pressure. The only way of checking what is happening behind the stoppings is from air samples taken from inbye (ie downstream) of them. It is therefore essential to ensure that adequate sampling arrangements are incorporated in all stoppings and that regular routine analyses of the gob gases are made. The tube bundle sampling technique is particularly suitable for this purpose.

PRECAUTIONARY TECHNIQUES UNDERGROUND

15. Having considered the places where spontaneous combustion can occur, it is now possible to consider the precautionary techniques that can be applied to minimise the associated risks.

Selection of Mining Method

16. The mining method that minimises the effect of spontaneous combustion is, generally, the one that provides the greatest intrinsic protection. For example, when working spontaneous-combustion-prone coals, methods should be adopted that minimise pillar crush, require low ventilating pressures, obviate the need for ventilating gob areas, provide adequate pillars between working sections, and reduce the amount of remnant coal to a minimum.

17. It is not possible to lay down rigid parameters governing the selection of mining method, since, in almost every case, there has to be some compromise between the desire to minimise spontaneous combustion and other relevant factors such as capital investment, productivity, compatibility with existing mine operations, etc. However, in general terms, a partial extraction method, such as room and pillar without pillar extraction, is likely to have a lower risk of spontaneous combustion than a multi-lift longwall method with bleeder ventilation which could be exceedingly hazardous.

18. It is essential to consider the potential consequences of spontaneous combustion and to recognise that, though a method may have a high theoretical recovery rate, should spontaneous combustion occur and result in the loss of a section or sections, the actual percentage extraction achieved could be lower than that obtainable from a method of mining with lower, but reliable recovery percentage.

19. For example, in working, say a 20-ft seam, the risk associated with working a 12-ft, single-lift, retreat longwall could be contrasted with a multi-lift longwall involving two or more passes or a longwall caving method designed to recover the total seam thickness in one pass. Bearing in mind the spontaneous combustion risks involved, it may be found that the one pass longwall ultimately produces the best overall percentage recovery.

20. These are, however, only general principles, and in planning and operating their mines, management must make their own judgement of the total mining system in relation to spontaneous combustion, taking into account the basic principles discussed in detail in this report.

Strata Control

21. Many heatings occur within a short distance of roadway sides. These are due to ground pressure and subsequent movement creating both leakage paths and a proportion of highly-crushed coal. It is important that an adequate support system is used, especially in high-stress locations, such as junctions, or at locations of high ventilation pressure differentials, such as at overcasts, doors and regulator sites.

22. Any system of mining, mining layout or method of support that minimises ground movement will reduce the likelihood of spontaneous combustion. In this context, particular care should be taken in designing the face end support in the case of the longwalls. Any reduction of bed separation, particularly adjacent to the intake and return ends of the face, will reduce inflow of air to the waste and will reduce the number of potential heating sites.

23. It is particularly important to support the roof adequately near the site of geological disturbances. Ingress of air over the finely ground coal frequently associated with faulting is a potential heating hazard.

24. Consideration should be given to designing roadway support systems including effective road side packs to limit convergence, so that subsequent roadway enlargement is not required. Sites of roadway enlargement, where roof is taken down, frequently expose bed separation to the kinetic energy of the main ventilation current and can lead to heating.

25. Where roadway enlargement is necessary, it is advisable to advance the working place in a direction opposing that of the ventilation airflow if the roof, floor or sides are of carbonaceous material.

26. Supports for roadways driven in high-stress areas should receive special attention. Where the ground is badly broken, injected resin could be used to improve strata control and reduce air leakage. However, careful consideration should be given before employing this technique, since information has been obtained from Germany to show that the heat of setting of resin used in this way has promoted spontaneous combustion in nearby strata.

27. The relatively recent innovation of pump packing is a major step forward in ground control associated with the longwall face. This system results in less bed separation, better airway support resulting in less convergence, and improved roof conditions at the face ends. All of these are important factors in reducing the risk of spontaneous combustion.

Stability of Openings
and Pillars

28. The stability of ribs and pillars is a significant factor which must be assessed when considering the degree of precautions to be taken against spontaneous combustion.

29. It is clearly uneconomic to design all pillars to avoid crush. Indeed it is impossible to prevent some crush at the edges of pillars of any size. The mine layout must, however, include stable pillars at strategic locations so that sections of the mine can be isolated effectively if necessary.

30. The more stable the ribs or pillars, the less routine preventive work will be required. This is particularly important in the case of pillars which have a long life. The actual size of pillars and of entries can only be determined by practical experience in the mine concerned. Major controlling factors are the strength of the coal, the depth and nature of cover and the influence of other workings above, below or within the horizon being worked. In cases where relatively large entries are required for ventilation purposes, the merits of parallel entries and the greater surface area exposed, should be considered against the provision of a lesser number of larger roadways.

31. Generally, the larger the pillars and the more stable the entries, the lower is the risk of spontaneous combustion.

Ventilation Control

General

32. The occurrence of spontaneous combustion is dependent on the oxygen supply being within a critical band range. Spontaneous combustion will not develop

where there is a sufficiently restricted air supply, or where the air supply provides adequate cooling, thus preventing any significant rise in temperature.

33. Virtually all the current methods of spontaneous combustion prevention comprise attempts to create or maintain the first condition. Any attempt to comply with the second condition in inaccessible positions, such as in the waste, on a permanent basis would create high risk. This is because of the relatively large areas of crushed material that may exist in the peripheral zones of airflow within the waste, ie in ventilation shadow areas.

34. The objective of sufficiently limiting leakage air supply to carbonaceous material can only be achieved by attention to detail, firstly in the planning stage, then when the district is being worked, and finally when the district is salvaged.

Control of Leakage
Through the Solid

35. The following points should be taken into account at the planning stage.

36. A ventilation layout that minimises pressure differences should be adopted. This normally requires the provision of sufficient airways, each of adequate cross-sectional area, to carry the planned ventilation quantities.

37. Doors and regulators should be minimised; those that are necessary for the working of the mine should be sited, as far as possible, in stone. If this is not possible, then sealing may be necessary (see Plate 9). Regulators should be designed in such a manner that opening and closing of the associated doors has the minimum effect on the static pressure level within the district. This may be achieved by means of the provision of a regulator tube(s) to carry the air quantity through the full length of the regulator site, as shown on Plate 10.

38. The number of air crossings should also be minimised, particularly when they are constructed in proximity to the seam or gob.

39. In some instances it may be necessary to seal the airway surfaces and, where the risk is high, sites of doors, regulators and air crossings may require injecting with an inert inorganic sealant.

40. All forms of sudden restrictions to airflow in the mine are a potential danger and should be avoided if possible. In this context, parking and marshalling of supplies should only take place at properly selected sites.

41. It is clearly uneconomic to attempt to coat with a sealant all the coal surfaces in the mine roadways purely as a preventive measure. There are, however, areas of relatively high risk where consideration should be given to either surface sealant coating or strata injection. Such sites include major doors, regulators and overcasts, especially those sited in key or strategic positions.

42. The ventilation pressure relationship between a newly-planned district and any workings in close proximity requires examination. This is particularly important when pillars of coal are to be left between adjacent faces.

Control of Leakage Through
Gob Areas

43. There is little doubt that when there is a high risk of spontaneous

combustion, a retreat mining system should be adopted. The safety advantages of retreating are so great that no other method of extraction should normally be considered in this type of situation.

44. Flow of air through gob areas is either a result of leakage due to differential pressure or from the impingement of the moving intake air stream on the face of the waste material.

45. Both types of airflow provide an oxygen supply that can result in heating. Therefore, the most important precaution against spontaneous combustion is to reduce or eliminate these flows.

46. Gob bleeder systems are designed to encourage the flow of fresh air into the waste, and will inevitably contribute significantly to the spontaneous combustion risk.

47. The airflow distribution associated with a level retreating longwall without bleeder ventilation is shown on Plate 11. All the air that enters the intake gate road passes the solid coal pillar and eventually reaches the face. There is a small amount of leakage through the fractured coal at the junction of the face and intake gate.

48. When the air reaches the face, it does so with considerable kinetic energy and this results in a relatively deep penetration into the intake end of the waste. A small proportion of this air entering the waste will continue to flow along the leakage paths associated with the rib side of the abandoned intake airway and may eventually traverse the original face start line.

49. There will be little or no flow through the consolidated area of the waste, but more air will flow into the waste as the main body of airflow traverses the intake end of the face. This air returns to the face air stream at an increasing rate as the return end of the face is approached. It is finally joined by any air which may have traversed the original face setting off line and has eventually returned through the leakage paths associated with the rib side of the abandoned return. This path to the original face line may well remain open to some extent for the life of the district. It gets longer and more difficult as the face retreats, but the pressure across it tends to rise as the face may accept more airflow as it travels outbye (Plate 11).

50. The two abandoned roads behind the face should be packed off at suitable intervals as the face retreats and, if necessary, the air penetration at the intake end of the face should be reduced by facing the waste off with brattice sheets for a distance of 25 ft or thereabouts from the rib side.

51. The main zone of critical air velocity exists in the waste, and when a face stops or travels slowly, a change in air quantity can move the zone.

52. Though longwall advancing has serious drawbacks, from a spontaneous combustion viewpoint, and is not generally to be recommended, an examination of the system provides valuable insight into the problems of leakage control. The airflow distribution associated with a level longwall advancing face is shown on Plate 12. All the air which enters the intake gate road passes the solid coal pillar from which the face was set off.

53. On reaching this point a small proportion of the total airflow will pass through what was the face start line direct into the return airway. As the remaining air travels inbye there will be little or no flow across the consolidated gob area between the gates. Some leakage, however, will take place through the pack and a small air current may flow parallel to the gate along the inner pack wall. The quantities involved depend on the effectiveness of the method of sealing off the face start line and the quality of the gate side packs.

54. This flow condition will exist until near the face, where neither packs nor gob are so well consolidated. At this point the rate of leakage through the pack wall will increase and some leakage across the gob will occur. Both these leakages will increase as the coalface is approached.

55. Leakage through the main gate pack relatively close to the face may well be increased locally by the effect of large machinery such as stage loaders, equipment train, etc.

56. As the air stream passes through the face, some will enter or leave the waste, particularly where the waste has not caved. The amount of airflow entering or leaving the waste is determined by such factors as extraction heights, type and density of supports, the presence or absence of flushing shields and the proximity of the face machine (Ref A14).

57. In the return gate, leakage, both into the airway through the packs and along the inner pack wall, occurs at a decreasing rate travelling outbye, until the face setting off line is approached. At this point the leakage may be considerable, depending to what extent consolidation has been retarded by the pillar edge and to what degree any sealing has been effective. It is important to note that the ventilation pressure causing this leakage will inevitably rise as the face travels further inbye.

58. In order to reduce leakage at this position in both gates, it may be necessary, initially, to remove a section of the crushed pillar corners and to face the exposed coal surface with a sealant. The excavation may then be packed with loose or bagged material, this in turn being faced with a sealant and finally the strata injected.

59. To reduce air leakage through the packs along the length of the gate roads, the most effective routine method in general use is to lag between the supports on the gob side and to fill behind with a sealant/water mix. If there are any breaks in the roof, it may be necessary to continue the work on both sides and the roof of the road in order to prevent leakage. This work must be kept up close behind the face and should be repaired as necessary. It is particularly important to keep this work up to date before the face is due to stand for any reason, such as holidays, or when approaching the planned finishing position.

60. In the unconsolidated area of gob relatively close to the face there will be a graduation of air velocity which will range from zero up to a value approaching that existing at the face. Within this range of velocities there will certainly be a number of zones in which the airflow conditions lie between the two states of equilibrium as discussed earlier. The major zone lies at some variable distance back from the face and is more deep-seated, everything else being equal, the higher the face air quantity. If the physical and chemical conditions are conducive to oxidation, the coal within these zones will oxidise and some measure of spontaneous combustion will occur with an attendant rise in temperature.

61. In the longwall face, most of the zones in which this critical leakage occurs move forward with the face progress. The actual area of combustible material across which this leakage exists, therefore, is constantly changing and normally there is not sufficient time for a dangerous rise in temperature to occur. However, when the face slows or stops moving for any reason, the same area of combustible material is exposed to the critical leakage for a longer period and a heating is more likely to develop, particularly when the face movement is retarded or arrested as a result of geological disturbances such as faulting, etc. The combination of finely-ground coal and air leakage paths associated with fault planes represents a relatively large and suitable surface for oxidation to take place.

62. In order to prevent spontaneous combustion from this cause, when a face stops or its movement is retarded, the normal precaution of making certain the roadsides are sealed as far as possible will reduce some leakage across the gob area. The leakage into and out from the waste from the face will, however, remain unaltered.

63. During the first two months of 1972, the UK coal mines were not worked because of a strike. In an attempt to move the critical zone of airflow, and thereby reduce the risk of heatings developing, it was decided to alter certain high-risk face air quantities. This was done in stages in order to prevent any new zone remaining in one position long enough to initiate a heating. The results of this exercise are shown on Plate 13 and, in each case, it can be seen that there is a drop in carbon monoxide emission as a direct result of the quantity change. The critical zone moved closer to the face with each reduction in air velocity. If high-risk faces are to stand for an extended period (four weeks or more) the action described in Ref A15 should be considered.

64. It is considered that the air quantity leakage through the waste will be reduced in greater proportion than that on the face for a given drop in district pressure gradient. This is possibly a result of the index relating flow and pressure being numerically higher on the face than within the flow areas in the waste.

Rate of Advance

65. Whatever the system of working adopted, there will be a considerable range of air velocity within the waste area. Relatively close to the working place there will be a number of zones in which the airflow conditions favour the development of spontaneous combustion. It may be important, depending on the degree of liability, to limit the time any combustible material lies within such a zone.

66. The rate of output from the face or section should be planned so that this time is always below the permissible maximum. Experience will determine the minimum rate of advance permissible in each case. The first indications that a heating is developing from this cause is a slowly rising trend in the carbon monoxide content in the return air. In longwall retreat workings in thick seams where the liability is high, the minimum rate of advance permissible has been found to be about 18 ft per week in the Warwickshire thick coal.

67. It is prudent to plan to achieve a rate of advance well in excess of the minimum determined by experience, particularly for the first and last few weeks of the life of the face. In the first instance, the effect of the solid coal pillar adjacent to the start line will tend to reduce the degree of consolidation within the extracted area. In the second case, the more rapid the rate of advance in the last

few weeks, the longer the time made available before salvage operations may be interrupted by heating. This consideration is particularly important when allocating manpower to a salvage operation in which difficulties are expected.

68. It is important to ensure that development workings are prepared to take over production on schedule. If they are late, it may be necessary to reduce the rate of progress of the production unit at the critical time. In these circumstances it may be expedient to extend the face life by extracting a proportion of the pillar originally planned to be left as support.

Stopping Off Worked-Out Areas

69. When a panel of coal has been worked out in a mine section, it is generally necessary to seal it off. Adequate stoppings to isolate it from the remainder of the workings can normally only be erected in sites that are either out of the seam, or situated within a pillar of coal substantial enough not to crush. There is little risk of a heating associated with the former, and most heatings associated with the latter may be dealt with by injection sealing the strata in the vicinity of the stopping.

Barriers or Stoppings

70. The construction of barriers or stoppings varies according to the purpose for which they are required. To prevent accidental access into workings, a construction of brick or breeze block may be sufficient.

71. Where the stopping is required to be explosion proof, it must consist of sufficient bulk material of adequate density. The site should be prepared by cutting into the roof, floor and sides to provide an adequate key. Using materials of the density of masonry, sufficient will be required to fill a length of roadway equal to one half of the sum of the roadway width and its height. Such a stopping sited in stone would normally be fireproof and its surroundings may be made relatively leakproof by injection with a suitable sealant which is stable at high temperatures (Ref A16).

72. In cases where a leakproof and explosion-proof seal is required, but there is no necessity for it to be fireproof, the most convenient method of construction is by the use of pumped plaster.

73. All loose material is removed from the site and preparation is made to key the backwall into the solid. This wall may be constructed of bagged sealant or debris, or a timber barricade, and then faced with a plaster mix. This facing must be completed to a high standard to prevent the pumped plaster, which is of thin consistency, from running away. A second wall is then built, typically 10 ft in front of the first, and initially constructed approximately 3 ft high. The void between is filled with pumped plaster and the front wall built up another yard and the process repeated.

74. Following this, further lifts are placed until the stopping is adjudged large enough relative to the size of the roadway. It is then necessary to inject the surrounding strata in order to minimise air leakage. Stoppings constructed in this manner tend to shrink, probably as a result of excess water in the mix which subsequently drains out. It is necessary to top up by further pumping at intervals as required. Typically, a stopping 10 ft thick, 10 ft wide and 8 ft high would require 26 tons of plaster and when completed would consist of 40 tons of slurry. This size of stopping can be pumped on within a working shift. It is not suitable for use

where high temperatures are likely as the plaster reverts to its powdered form when heated. This is a major disadvantage when such stoppings are constructed at sites within the solid coal and are subjected to high pressure differential in an oxygen-rich atmosphere.

75. If it is necessary for the stopping to be made fireproof, then it must be constructed from a sealant which is stable at high temperatures.

76. If it is expected that re-entry through the stoppings will be necessary, then this may be facilitated by the provision of a re-entry duct. This comprises a 3-ft-square sectional duct which is laid through the entire length of the stopping site. This duct is sealed after the stopping is completed and may be used to facilitate simultaneous closure if required. Sealing is accomplished by means of closing a properly-constructed bulk head door built into the ducting, or filling the duct with puddled and/or bagged sealant or both. Re-entry into the sealed area via this duct is relatively straight forward to achieve.

77. All stoppings should be equipped with a steel pipe approximately 3 in in diameter to enable measurements of pressure and gas samples to be taken.

78. Stoppings sited in coal pillars, especially those that are small enough to crush, or are sited in the gob, are a potential source of heatings. At such sites, air is driven into the crushed coal or gob material by the air pressures existing across the stopping. This is particularly the case at stopping sites if the panel is not balanced. It is equally the case at both intake and return sites if the stopping sites are balanced against mine pressure differences, but are under the influence of barometric fluctuation. In a seam liable to spontaneous combustion, stoppings should not be sited in such locations.

79. When it is necessary to seal off a whole mine section comprising a number of panels, the danger of spontaneous combustion in the locality of the main stopping sites is greater than in the case of a single panel. The larger void behind the stoppings when a section is sealed amplifies the effect of barometric changes. If these outer seals cannot be sited remote from the seam, then use of the following technique is suggested.

80. The seals should be constructed in the normal manner but sited so that further lightweight seals can be constructed some distance outbye. If the sites of the seals are balanced, the zone between these pairs of seals will fill with carbon dioxide, nitrogen and methane from the sealed area and, provided the zones are made large enough, whatever breathing exists round the inner seals will not be associated with an oxygen-rich atmosphere. The risk of heatings occurring round the outer seals does not exist as these are constructed as barriers to prevent unauthorised entry and are, therefore, not required to withstand any differential pressure, except possibly during a large rise or fall of barometric pressure.

81. The volume of the zones must be calculated to be large enough to accommodate sufficient gas. This is relative to the size of the sealed-off void and also to the amplitude and duration of barometric rise and fall.

82. The length of airway between the main and the outer wall or main roadway should not be treated with a sealant. If this length of airway is sealed its potential value as a pressure chamber may be lost. This is because intimate contact with any leakage paths interconnecting the sealed area with the main roadway will be blocked off.

83. This technique for sealing off a section of a mine was applied in a UK mine where the original stoppings had been sited in pillars that were believed to be adequate. However, in spite of continuous injection, the heating continued to be active. Products up to 100 ppm of carbon monoxide were recorded in the return from the sealed-off area when the barometric pressure level fell below the ambient pressure behind the seals. As this return was also the main manrider road and return airway from a production face, the situation had to be rectified.

84. Following the construction of a buffer zone, as described above, no further trouble was experienced.

Inhibitors

85. Laboratory experiments have shown that a number of chemicals, notably borates and calcium chloride, significantly inhibit the oxidation of coal, and underground experiments have been made to spray both compounds, either in solution or powder form, into the gob, on the longwall face start line or on to coal pillars to reduce the risk of spontaneous combustion.

86. It has been claimed (Ref A1) that the use of borax powder was successful in reducing the incidence of spontaneous combustion in a pyrites mine in Australia but that the cost was too high for general use.

87. Calcium chloride in the form of "Montan Powder" is used extensively in German mines for roadway consolidation and to suppress dust, and it has been found that its use also brings about the lowering of the carbon monoxide norm in the mine, suggesting that coal oxidation is being inhibited. Apart, however, from the technical problems of introducing calcium chloride powder into the wastes and other strategic locations where spontaneous combustion is likely to be initiated, it must be recognised that it produces highly-corrosive conditions, if proper precautions are not taken, and is, therefore, a hazard to electrical equipment, steel supports and to machinery generally. It may also give rise to health problems, particularly dermatitis and ulcers, and large-scale trials to spray the longwall face start line to prevent spontaneous combustion in a colliery in Europe had to be abandoned on medical grounds.

88. Calcium chloride was used for roadway consolidation in South Wales in 1945-47 but was discontinued on cost and medical grounds (Ref A2).

89. In general, therefore, the prospects for the use of known chemical inhibitors are not encouraging. So far, an exhaustive search for alternative materials has proved singularly unsuccessful.

Inspection Procedures

90. Because spontaneous combustion can be detected by physical inspection, a proper inspection routine must be established and conscientiously carried out. The routes of such inspection and the particular points to be checked must be specified by management. Such inspections will enable attention to be paid to the possibilities of smoke, smell, sweating or local temperature increases. The tell-tale signs which have to be looked for have already been described in Chapter V. The periodic taking of air samples for laboratory analysis reinforces such physical checks, and is a necessary precaution in any spontaneous-combustion-prone situation where continuous monitoring is not employed.

91. Regular inspections must be made of all potential air leakage paths, particularly where pressure differences are high, such as at overcasts, etc.

92. A formal reporting procedure should be established to ensure that any anomaly is recorded and any remedial action shown to be necessary from these inspections, is made known to management on a routine and reliable basis.

Monitoring

93. Since early warning is an essential precaution to prevent the deterioration of an incipient heating into an active fire, comprehensive monitoring is desirable, and in many cases essential, in a spontaneous-combustion-prone mine. Full details of the equipment available were given in Chapter V. In designing the monitoring system as part of a precautionary programme, the essential factors to consider are the selection of reliable gas analysis equipment, location of the central equipment pack and the definition of the remote sampling point.

94. If due attention is paid to these factors, then the remote monitoring system will forward the essential early warning that the precautions taken to date have failed to control the programme. However, absolute reliance should never be placed on remote monitoring alone and it should always be carried out as part of a comprehensive programme which must involve visual physical inspection of all relevant parts of the mine working and an independent check system of air sampling and analysis to ensure that the monitoring equipment is functioning correctly.

95. In order to obtain the maximum amount of reliable information from a monitoring system, care must be taken in establishing the carbon monoxide norm on which appreciations of the situation are made, and the effect of extraneous carbon monoxide sources, such as shot firing or diesel equipment, must be studied and appreciated.

Self Rescuers

General

96. Under practical mining conditions, all fires, including those arising from spontaneous combustion, produce carbon monoxide, carbon dioxide and result in a reduction in the oxygen content of the air. The degree to which these factors occur depends on the severity of the fire, but it must be remembered that from the point of view of the health hazard, they have a cumulative effect on the respiratory system.

97. Carbon monoxide is toxic because it interferes with the oxygen-carrying function of the blood; its presence in the blood leads to both physical and mental impairment. Figures given in text books for the physiological effect of breathing air containing carbon monoxide are misleading as they usually fail to take into account that the inevitable presence of carbon dioxide will increase the rate of breathing and hence the rate of uptake of carbon monoxide. Oxygen deficiency is also inevitable, so that the rate of oxygen exchange with the haemoglobin in the blood is reduced; both carbon dioxide and oxygen deficiency therefore seriously increase the toxicity hazard of carbon monoxide.

98. Griffin (Ref A3), discussing this problem in relation to the use of filter self rescuers, suggests that the carbon monoxide limit should be calculated as a

function of blood saturation. If this is set at between 20% and 30%, it means that at a normal lung ventilation rate of between 25 litres to 30 litres per minute, the total volume of carbon monoxide breathed should not exceed 600 ml and that a limit of 0.02% carbon monoxide should be set for men working without breathing apparatus.

99. Griffin puts the critical limiting concentration for carbon dioxide at about 4%, at which point headache, respiratory difficulty and an increasing lack of awareness of his surroundings make it unlikely that a man would be able to make the necessary mental and physical effort to escape. The German physiologist, Lehmann (Ref A4), states that the maximum carbon dioxide concentration in which life is still just possible, at least for a brief period, is between 5% and 6%.

Filter Type Self Rescuers

100. An examination of the analyses of post-fire atmospheres indicates that the ratio of carbon dioxide to carbon monoxide is unlikely to be less than 10:1. This ratio, whatever its value, will remain constant irrespective of any subsequent dilution with fresh air, so that oxygen deficiency can be calculated in terms of the percentage of carbon monoxide in the air. For example, if there is 0.5% of carbon monoxide, the percentage of carbon dioxide is unlikely to be less than 5%. This means that approximately 5.25% of oxygen in the respirable air will have been lost in the combustion process and that there will only be about 14.7% oxygen in the air breathed. Filter self rescuers cannot make good this deficiency, indeed they rely on the oxygen in the inspired air to convert the carbon monoxide to carbon dioxide; this reduction of oxygen in combustion processes is critical to the use of filter self rescuers. Griffin (loc cit) states "although it is not possible to predict with accuracy the effects of a given oxygen deficiency on a man, if the oxygen content falls to less than 16% the physiological effects of insufficient oxygen are likely to reduce a man's chance of escape".

101. If this criterion is accepted, the maximum concentration of carbon monoxide in the inspired air for which a filter self rescuer will provide life support is of the order of 0.5%. While, at first sight, this may appear to give the filter self rescuer only a small margin of safety, European experience during the last twenty years indicates that it is sufficient to give protection as escape apparatus in all but the most severe fire conditions. It also points to the value of continuous monitoring of carbon monoxide with alarms set at appropriate levels; for example, at 0.02% or when there is any sign of fire, rescuers should be worn and evacuation of the working area should proceed. It should be emphasised that they are not intended as working apparatus.

Oxygen Type Self Rescuers

102. In 1977, the USBureau of Mines questioned the use and efficacy of filter self rescuers and recommended that they should be replaced, within two years, by oxygen self rescuers that provide full life support. These self rescuers generate oxygen by the interaction of the moisture in the exhaled air on potassium superoxide and thereby give a life supporting respirable atmosphere which is independent of the external environment. Oxygen self rescuers obviate the problems of oxygen deficiency and high carbon dioxide associated with filter self rescuers and provide a better chance of survival for men enveloped in post-explosion and post-fire gases.

SURFACE COAL STOCKS

Introduction

103. As already stated, the interaction of oxygen and coal has two effects. The first, a chemical change, is oxidation, whilst the second is of a physical nature, namely disintegration or size degradation. These occur in all coals, even anthracite, but the rapidity is related to the rank of the coal. Therefore, were it not impractical, it would be preferable to leave coal in situ until it is required. In practice, however, methods of coal production, distribution and utilisation render it necessary that reserves of wrought coal should be available.

Methods of Storage

104. The whole problem of coal storage may be regarded as keeping within bounds the process of oxidation and spontaneous combustion. The principles involved are the same as for spontaneous combustion underground.

105. It is clear that coal spread out in a very thin layer will never show any temperature rise, since heat is conducted away as rapidly as it is liberated. Also, once the "active centres" on the surface of the coal have been used up very little further oxidation will take place unless the coal is broken or there is a temperature rise from an external source of heat. Therefore, up to some definite thickness of layer for each particle size of each type of coal, the temperature will rise to a maximum which is not dangerously above air temperature; for bituminous coals this is commonly taken to be about 6 ft.

106. If, however, coal is stored in such a way that the heat produced is largely conserved and the access of air is sufficient to promote oxidation, a temperature rise will take place which, in turn, accelerates materially the rate of oxidation of the coal, and so the process goes on until fire conditions supervene. Dumps most likely to go on fire are those of unconsolidated coal of ungraded sizes; the fine coal presents a large surface area for oxidation while the larger coal leaves voids which enables air to penetrate the mass and provide the oxygen to allow a fire to develop.

107. From this it follows that there are two possible methods of safe storage. The first is to ensure free ventilation through the pile so that there is never a significant build up of temperature. The second is to consolidate the mass of the pile or seal its surface, or both, so that the passage of oxygen is severely curtailed. It is only when conditions fall between these extremes that a potential spontaneous combustion situation exists.

108. The free ventilation approach is only possible with large graded coals. With raw coal and small coal it is simply not possible to obtain sufficient cooling air.

109. The method recommended, therefore, for the storage of small coal is to aim at excluding air from the heap. This is done by compacting the heap by spreading the stock in layers (approximately 2 ft thick) over the whole planned storage site for a particular heap and rolling each layer before commencing the next .

110. The main source of danger in this method is failure to consolidate the sloping sides of a dump. It is essential that the sides all round the heap should be chamfered off so that they rise from the ground to the top of the heap at an angle less than the natural angle of rest. The angle between the ground and the coal will probably lie between 15^0 and 30^0, according to the equipment used and the method of tipping and consolidation adopted. It cannot be over-stressed that it is absolutely essential for the safe storage of bituminous coal by this method that the sides should be properly consolidated.

111. A similar method should be used for raw coal, although the presence of large pieces (say up to 10 in) makes consolidation more difficult and therefore more essential. If the coal is normally crushed at the mine site (say to minus 1 in for power station use), then it is advantageous to crush prior to storage rather than stock raw material.

112. In certain cases coal is stored at the mine in vertical cylindrical bunkers or silos. These are often used in conjunction with unit train loading facilities and can hold 10,000 tons or more. Obviously the silo minimises oxygen ingress. However, where coals are very liable to spontaneous combustion, it is possible to reduce the risk still further by providing a "blanket" of nitrogen or other inert gas.

Height of Consolidated Stack

113. If the above precautions are taken in laying down the stock, height is only governed by mechanical handling problems and the planned ground area of the stock. The maximum height of a properly-consolidated heap is immaterial. It usually appears that a convenient height from the point of view of handling is about 15 ft. From the point of view of safety, the larger the heap the better because the amount of surface per ton of coal becomes less. If, however, it is necessary to lay down a stock without taking proper and complete precautions (eg lack of equipment), then the height should be limited to about 6 ft.

Temperature Measurement

114. If there is any possibility of spontaneous combustion, then it is advisable to monitor the temperature of the body of the stockpile for the first three months of storage. This can be done by driving a series of 1-in bore tubes, closed at their lower ends, into the pile to a depth of about 6 ft. A thermocouple can then be lowered down each pipe in turn and readings taken at different depths using a hand-held digital thermometer.

115. The temperature beyond which spontaneous heating develops into a fire situation varies considerably according to conditions and the type of coal, but may generally be taken as about 140^0F. The aim should always be to minimise any temperature rise because of the deterioration which occurs with heating even when there is no spontaneous combustion.

116. When critical conditions are reached, a slow and steady rise in temperature, with a flat portion at about 180^0F (when the heat absorbed by moisture evaporation balances that produced by oxidation), must be expected, followed by an accelerated temperature rise culminating in a series of small fires. A typical curve for a small (400-ton) unconsolidated heap is given on Plate 14; the time to reach 180^0F will vary but is normally between 2 and 4 months. Adequate

graphing or logging of the temperature-history of the various points in the stack will give clear warning of a dangerous state, and enable preventive action, such as re-compacting or even applying an overall impervious coating, to be taken if the heap temperature exceeds ambient temperature by 40°F (Ref 3, 16 and 61).

The Weather-Proofing of Coal Stocks

117. In very special cases, eg when the stock is to be retained for a long period or the coking properties are of especial importance, the exclusion of air can be further improved by covering the completed heap with road tar in the same way as a summer dressing is applied to roads (Ref A5). Experience has shown that road tar is an efficient and economical method and, in addition, can be used on heated heaps which, in the complete absence of air, would then stop oxidising and cool off. The sealing of a stock with tar has some added advantages, such as protection against wind losses and reduction of channelling due to heavy rain; a secondary effect, therefore, is to reduce atmospheric and river pollution to the minimum.

118. The tar covering also keeps the coal much dryer which improves the handleability of the material on recovery. For example, a 100,000-ton heap of raw gas-making coal in the UK was tarred mainly because of many complaints about dust from previous heaps on this site, which was near the North Sea coast and subject to strong winds. It was considered that the saving of coal would probably pay for the cost of tarring as well as removing the cause of complaint, and there was also a history of spontaneous heating of the same coal. When it was necessary to remove the heap after 2½ years, the surface was still in excellent condition; there was an insignificant loss in calorific value (about 0.1%), and no deterioration in caking properties (Ref 89).

119. Road tar is produced in large quantities and used in all districts, so equipment for applying it and personnel skilled in its application are available. However, some organic binders, which have been used in USA for dust-proofing coal heaps, have been tested in the NCB laboratories (eg Rezosol E1 and S411GB: Cyanamid Aerospray). Although only about 80% as effective as road tar as a seal, they could probably be used as effective alternatives, depending on availability and cost.

Common Faults in Stocking Coal

120. The most common cause of fires in coal stocks is the laying down of uncompacted small coal or raw coal in such a way that segregation occurs, the larger pieces often rolling to the outside - in other words, a failure either to ventilate thoroughly or to compact properly. In a large number of cases of heated stocks that have been inspected, the stock of coal was well consolidated on top by running a rail track or road vehicles over it, but the sides were left loose. Such a stock of bituminous coal will inevitably fire; larger coal rolling down the sides allows air to enter until it comes into contact with the consolidated centre and fires begin in this zone. Again, some stocks have had open-ended vertical pipes driven into them apparently to aid ventilation, but when heating commences these pipes act only as chimneys.

121. Other minor sources of trouble are due to an external source of heat being near the stock. Similar conditions arise when freshly-wrought coal, with its original avidity for oxygen, is put down on an old stock that is already slightly heated. It is widely believed that putting freshly-wrought coal on to old coal is a common cause of fires, but this is not a source of trouble in itself. Fires that occur in such circumstances are either due to the old coal being warm, or a zone of open texture being left where the two coals are contiguous.

Remedial Measures

122. When the critical temperature beyond which spontaneous combustion must be expected is reached, it is wrong to delay in the hope that conditions will right themselves. If preventive action is not taken, a fire is inevitable and the affected area will spread. The danger usually starts at points about 3 ft to 6 ft below the surface and near the outer edges where ventilation is sufficient to promote heating and the depth of coal serves to prevent a sufficiently rapid loss of heat. If the stock is to be retained, the only method of dealing with such conditions is to exclude air.

123. In a compacted heap the fires are likely to be very small fringe fires, and these can be dug out and the heap re-rolled. A non-compacted heap of small coal can often be saved by shaping it, rolling, and then sealing with a dressing of road tar. Apart from such methods, the only effective way of dealing with a fire is to take up the coal and use it. If the heated coal is dug out and scattered thinly (less than 1 ft thick) so that it cools, the trouble may be alleviated, but usually the removal of coal lays open fresh sides of the heap, and if - as is normal - the adjacent coal is warm or if the heated coal is not removed, the trouble soon re-occurs and spreads.

124. If a fire has started, spraying or hosing with water is completely ineffective; not enough water can be applied to wet and cool the whole heap as the water follows relatively narrow channels and because such treatment induces air currents. Attempts with water to extinguish a heap on fire permanently are useless and liable to aggravate conditions, unless a wall can be built around the stock and the complete heap flooded and immersed under water.

Losses Due to Storage

125. If a fire occurs, then the coal in the fire obviously looses all its value. However, even if there is no fire, the coal is oxidising (burning) slowly, although if the stock remains at ambient temperature the losses in calorific value are small. As the temperature of a stock increases, the rate of oxidation increases and hence the loss of heat value. One estimate of the possible losses at 70^{0}F and 160^{0}F is shown in Table I.

126. The caking properties of a coal are liable to be rapidly and extensively affected by oxidation. Although the rate of change naturally depends upon the size grading of the coal, cases have been studied where even large coal has lost much of its caking power if stored for several years. This effect becomes particularly noticeable if the stock has been allowed to increase in temperature. Some practical examples based on Free Swelling Index cokes are given in Table II, and it will be noted that there is a measurable effect in two years even when there is no rise in temperature, whilst if stored at 160^{0}F, a 1-in slack looses most of its coking properties.

SURFACE WASTE DUMPS

Introduction

127. In order for a fire to occur, it is necessary to have both combustible material and oxygen - in this case coal and air. The main cause of burning spoil heaps is spontaneous combustion brought about by the exothermic oxidation of the coal substance, which is aggravated in many cases by the presence of pyrites. This is not, however, the only cause, since fires can be started by carelessness, such as the burning of vegetation on the face of an old tip, the use of braziers by men working on the tip, or the dumping of boiler furnace ashes that have not been properly quenched.

128. The basic principles underlying oxidation in a spoil heap are the same as those applying to coal stocks. There are, however, certain additional factors that may modify the method of approach. The higher the percentage of coal in a spoil tip, the more liable it is to spontaneous combustion. Therefore, there are safety as well as energy conservation advantages in reducing this percentage.

129. An alternative to tar for sealing is to use clay, or clay plus calcuim chloride, since the addition of extra inert matter is unimportant in this context and has the additional advantage of reducing air pollution from fines.

130. If these factors simplify spoil tip management, there is one which makes it more difficult. A spoil tip, unlike a coal stockpile, is a permanent thing and it is a major expense if it has to be dug out or moved. This means that it is necessary to be even more sure that spontaneous combustion will not occur.

Method of Waste Dumping to Avoid Fires

131. It follows from the basic principles that in order to avoid spoil tip fires either coaly material or air should be excluded, as far as possible, from the tip. It is almost impossible to exclude coaly material from tips of washery shales and mine dirt, but the amounts can be minimised by good housekeeping.

132. The main effort in laying down spoil must therefore be to effect the exclusion of air. Much of the compacting will be done by the vehicles which bring the waste material to the site running on top of the heap, but extra rolling will be necessary, particularly on the sides. The actual design of the heap will depend upon the site, but the principles of layering and compacting, if properly carried out, will not only minimise the possibility of spontaneous combustion, but will also make the heap more stable.

133. Wherever spoil is tipped from a height, not only will it not be compacted, but much of the large material will roll to the foot of the heap and produce conditions conducive to spontaneous heating. Similar conditions are produced when material is tipped from lorries or rail traffic on top of a heap giving high, loose sides.

134. Finally, although this will not always be necessary if the layering and compacting is well carried out, the sides can be covered with a 3-in to 6-in layer of clay to reduce further any air infiltration into the heap.

Remedial Measures

135. When a fire becomes extensive in a spoil tip, it becomes potentially dangerous and objectionable. It can be dangerous because of internal collapse or because the fire approaches buildings or railway lines. The fumes produced by a burning tip are a continual source of complaint for people living in the neighbourhood; and may also be an offence under local clean air regulations.

136. Combat measures once a fire has started in a large spoil heap are difficult and expensive, and frequently unsuccessful. Very often the best that can be done is to control and reduce its nuisance value.

137. Water, except by total flooding, is useless. In general, water is applied on the surface by sprays or by applying jets of water to the seat of the fire. The use of sprays will keep down surface fires, but the spread of fire in the heap is not retarded. Some heaps have been sprayed weekly for over 30 years and are still on fire. When jets of water are applied to the seat of a fire, deep fissures are formed in the material of which the heap is composed, and instead of putting out the fire, these fissures provide an inlet for air and so allow the fire to grow beneath the surface and spread over a much wider area. It has also been found that the use of this method causes explosions to take place in a heap.

138. If water must be used because of special circumstances, sprays are probably the best way of applying it, although this is very unlikely to give lasting results. An important consideration is that if sufficient water is applied to a heap to have any effect on a fire, it is often sufficient to raise the moisture content of parts of the heap to a flow condition and cause movement of the material, which can be a very serious hazard. Another method sometimes used for applying water is to dig large holes - lagoons - on the top of a heap and fill them with water in the hope that the water will percolate through the heap and put out the fires; but in a short time the bottom of the lagoon becomes sealed by disintegrating shales, and there is a great danger of the water causing instability in part of the heap. Another disadvantage of using water is that it will leach out products of pyrites oxidation giving a ferruginous very acid effluent which pollutes local streams unless it is given an expensive treatment.

139. The only practical approach is to try to exclude air from the heap by laying on an impervious cover, usually of clay or wet sand. If a heap could be properly sealed it would ultimately cool down, but the immense reservoir of heat usually dries and cracks the covering, which therefore needs regular attention. Rather more success has been obtained with the use of limestone and limestone dust slurries. If limestone dust is laid on a heap to a depth of about 9 in it makes a reasonably effective seal against air getting to the fire and, at the same time, acts as a filter for the fumes from the fire which were previously passing to the atmosphere; this is a palliative and not a cure, but it is better and has less drawbacks than treatment with water.

140. Suspect spoil heaps must be constantly watched, particularly after rain storms which can cause deep channelling of the sides, permitting the re-entry of air and the consequent resurgence of the fire.

141. Considerable care should be taken in surveying burning spoil heaps, since fire zones can be hidden below thin crusts of apparently solid ground, and there have been many cases of persons falling through this surface crust. Rescue services and breathing apparatus should be available at all times.

CHAPTER VII

COMBATING ACTIVE HEATING

INTRODUCTION

1. The steps taken to combat an active heating depend on many factors and as no two heatings are identical, expertise can only be obtained by combat experience.

2. An early start to combat action increases the possibility of success and it is vital that all underground personnel, particularly those on afternoon and night duty, when senior management are not normally present, are aware of the action they must take when the presence of a heating is first suspected.

3. In this event, the miner concerned should first notify the mine control centre. If open flame is seen an attempt should be made to summon assistance and to fight the fire with extinguishers, rock dust or other non-combustible material. All personnel must be withdrawn from the return side of the incident. Water must not be used if the coal is actually on fire as this may produce water gas and the risk of an explosion. The mine control centre should notify the most senior official at the mine who should arrange for an immediate inspection of the site in order to assess the magnitude of the heating and any remedial measures to be taken.

4. Where the rate of development of the heating is slow, underground operations may be left undisturbed until a more convenient time. In more severe circumstances, men may have to be withdrawn from production teams for fire combat duty. In the case of a very rapid deterioration, it may be necessary to evacuate the section in which the heating occurs or the whole mine.

5. The nature of the action taken to combat heating depends on the circumstances and, in particular, its accessibility and the vulnerability of the rest of the mine. These factors, carbon monoxide and combustible gas temperatures and concentrations, explosion risk, limited visibility due to smoke or haze, or high air temperatures due to direct heat emission, will all influence the action to be taken. Consideration must be given to the rate of change of any of these factors and to the availability of manpower and materials, since this may determine the length of time required to carry out remedial measures.

6. Whenever combat work is in progress, the rate of development of the heating must be closely monitored. Generally, up to six sample points will be located at strategic positions, with one on the intake side as a reference. Where full analysis is required, samples will have to be transported to a laboratory.

7. Although readings from hand-held instruments may be adequate for minor incidents, where available, mobile gas analysis facilities are preferable and samples should be taken at least half hourly while the situation is critical. This interval may be increased when the situation improves.

8. It is essential to maintain a continuous check on carbon monoxide in the vicinity of all fire fighters as toxic and explosive gases can "back" against the ventilation current. In practice, the limiting factors with a deep-seated heating are high concentrations of carbon monoxide, lack of visibility due to smoke, or the risk of an explosion. Rescue teams are as vunerable to the latter two as workers not wearing breathing apparatus.

9. Shallow-seated heatings are frequently characterised in later stages by smoke and high air temperatures, which limit fire-fighting operations. Once such limits are reached, fighting the fire near the source must be abandoned. The situation then resolves itself into one of constructing seals at previously prepared sites further outbye and sealing the heating off remotely.

10. In the UK, a level of carbon monoxide of 250 ppm is considered the limit for work without breathing apparatus in the general ventilation, and can be tolerated by workmen for up to six hours, depending on their duties. The more onerous physical tasks may require a two-hour changeover system to be operated. In the USA, MESA, schedule 22, stipulates that the maximum concentration of carbon monoxide should not exceed 100 ppm.

11. It must not be forgotten that carboxy-haemoglobin, arising from the absorption of carbon monoxide through the lungs, requires hours in fresh air before it is eliminated. Men exposed to carbon monoxide must be given adequate time to recover between working shifts.

12. Filter self rescuers must never be worn for active fire fighting. They are provided for escape purposes only.

13. A careful watch must be kept on the barometric pressure. Any indication of rapid fall must be notified immediately to the incident controller and should be followed by still greater precautions against increases of noxious or explosive gases from the gob.

METHODS OF COMBATING HEATINGS

14. The three methods for combating active heatings are:-

(i) digging out,

(ii) flooding with water,

(iii) ventilation techniques.

The most widely-used and important techniques are those in the third category associated with ventilation control.

15. The methods are detailed below.

Digging Out

16. This method is confined to heatings that are relatively small and judged by temperature (above 100^0F) of the surrounding strata to be close to the roadway surface.

17. In the UK, the extent of this type of heating is typically a sphere of about 3 ft in diameter of material above 120^0F, including about 1 ft^3 of incandescent material.

18. An adequate supply of sealant must be made available at the site, together with an adequate supply of water.

19. Sufficient manpower must be organised for continuous work at the site until the job is completed, and normally five men would make up a team.

20. All personnel in the district on the return side of the heating should be withdrawn. Adequate communication should be established between the heating site, the mine control room and any persons working on the return side of the heating elsewhere in the mine.

21. If necessary, the location of the heating should be determined by drilling for hot material. When the location is fixed, the surface area of the roadway for 30 ft either side of the site must be thoroughly dampened with water and rock dusted.

22. Excavation of the site should then be commenced about 3 ft upwind of the location. Picks and shovels should be used and the newly-exposed coal surfaces should be constantly dampened and cooled with a fine mist water spray. As the centre of the heating is approached, the coal is invariably crushed and conditions can become very hot and dusty. When the incandescent material is reached, great care must be taken to cool the periphery of the hot material first, progressively approaching the centre, thereby avoiding the risk of the formation of water gas. This is important because water gas, being a mixture of carbon monoxide and hydrogen, is both toxic and potentially explosive.

23. The percentage of carbon monoxide and the concentration of smoke and steam downstream of the heating normally increase during the digging out process. The risk of the hot material breaking out into open flame is high and it is essential that an adequate supply of dry non-flammable dust is readily available at this stage in the operation.

24. The hot material must be thoroughly cooled and dampened as it is removed and the operation should continue until all the hot material above 120°F has been removed.

25. Time should be allowed, typically a shift, for the completed excavation and the surrounding strata to cool. At this point, the exposed surfaces should be surface sealed.

Flooding with Water

26. Combating by means of flooding with water is an accepted technique in suitable circumstances. There are two methods which may be used: one quenches the fire by slowly submerging the heated material under water, the other utilises water and local gradients to prevent oxygen reaching the heating site.

27. The first method may be used when gradients are favourable, for example to combat a heating in workings which lie entirely to the dip. It may be necessary to construct new dams or to convert existing seals into dams if these are sited below the resultant water level. Since heating activity is stopped and the heated material reduced to ambient temperature by the cooling effect of the water, it may seem attractive to pump out the water and regain access to equipment and coal reserves. In practice, however, when oxygen is admitted over the wetted coal surfaces, the coal frequently oxidises and heating may redevelop rapidly.

28. The second method does not have this disadvantage and provides an air-tight seal that is generally easily removable. However, it can only be employed when gradients are suitable, for example, where there is a low point in the airway or airways associated with the heating. The low point must be such that the water reaches the roof of the airway at a level at least 3 ft or more before it runs over the brink. Filling such a site with water effectively stops airflow to the heating site.

29. It may be necessary to prevent an explosive atmosphere building up by equipping seals with access tunnels through which ventilation can pass. The water barrier is then constructed by running the water through pipes in the seals until samples indicate an air-proof seal has been effected.

Ventilation Techniques

30. The most widely-used methods of combating active heatings are based on the control of the ventilation system. The detailed procedures adopted depend on the circumstance of each heating, but all are based on the need to deprive the heating zone of oxygen supply. The ventilation techniques include increasing rate of advance to move the critical oxygen zone away from the heating, sealing leakage paths, controlling ventilation pressure to control airflows, sealing off and flooding with nitrogen. Details of the individual techniques are given below.

Increasing Rate of Advance

31. Within the extracted area in proximity to the working face there will be a "critical" zone of airflow (see Chapter VI and Plates 11 and 12).

32. At the first indication of a heating occurring in an extracted area, it is advisable to increase the rate of advance as much as practicable. This will tend to reduce the exposure of the heated material to "critical" airflow conditions, and to bury it in the waste.

Minimising Leakage

33. Frequently, heatings occur in situations too remote from the roadside to be dug out. Such sites are often areas of high ventilation pressure gradient, such as exist at some seals and most aircrossings, doors and regulators.

34. Most heatings of this type can be combated by the direct application of a sealant. This may either be injected into the strata or applied as a coating to the strata surface, or frequently a combination of both techniques.

(i) Surface Sealing

Where the pressure differences associated with a heating are small or where the area of ground to be sealed is relatively large, it may be advisable to apply a surface coating of sealant (Appendix "P") to the strata. This can be done either by hand application or by spraying. Both methods, particularly spraying, are rapid and enable large surface areas of roadway to be sealed in a relatively short time. In moving ground, the coating has to be constantly refaced if the seal is to remain effective.

Where the airway surface is smooth, it is necessary to provide a support for the coating. This normally takes the form of wire mesh which is fastened to the surface prior to sealant application.

A coating of sealant such as this may be used as a temporary measure to limit the heating activity while the more permanent injection operation is completed.

Heatings in development entries often occur in the roof and, where lagging is used, can be difficult to locate and combat because of their position. The smoke and products of combustion lie close to the roof and may be hidden by the lagging. They may eventually apppear some distance from the heating site, either upstream or downstream depending on roadway gradient.

The heating should be located by drilling holes in the roof at intervals along the roadway and observing the direction of travel of the smoke. The lagging in the vicinity should then be made good and finally plastered with sealant. A thick mix of sealant pumped above the lagging will then remain in position. When this platform has been established, thinner mixes can be pumped and the area injected solid until the heating is extinguished.

(ii) Strata Injection

This is accomplished by drilling a number of holes, varying between 3 ft and 30 ft long, into the strata in which leakage paths are to be sealed. The holes are drilled in two sections, the first $2\frac{1}{2}$ in in diameter and typically 5 ft long. A standpipe is inserted into this section comprising a 6-ft length of 2-in diameter screwed pipe. A thick mix of sealant is then pumped into the pipe until the hole, including the annular space around the pipe, is filled. After this has solidified, the pipe is drilled out to $1\frac{3}{4}$ in diameter and the hole extended to its final length.

A thin mix of sealant is then pumped in until the pipe will not accept further material. If the hole does not tighten up and the sealant is running away, it may be necessary to leave the sealant to set hard without further pumping. Pumping can then be resumed after redrilling and the process should be repeated until the hole finally goes solid. To enable the pumping to be continuous, work should be done on about four or five pre-drilled holes.

It may be necessary to drill a considerable number of holes to consolidate sufficient strata to isolate the heating. During the drilling process the presence of hot drill cuttings or warm rods may give a useful indication as to the exact position of the heating, though regard must be given to the heat from the exothermic reaction of drying sealant when this observation is made.

In a typical combat situation, between forty and eighty 28-lb bags of sealant would be injected into each hole and it might be necessary to pump several times on a hole to seal it adequately. Any hole accepting more than 200 bags of sealant should be abandoned as abortive.

Pressure Control

35. If surface sealing or injection are not applicable or are ineffective, the ventilating pressure across the heating zone must be reduced or balanced. This can either be accomplished by raising the lower pressure side of the heating site or by lowering the pressure associated with the intake side. In either case the tendency for air to flow through the heating zone will be reduced or eliminated and the supply of oxygen to the heated material curtailed. The technique by which this is done will depend on the circumstances of the heating. The following examples illustrate various methods:-

(i) Aircrossings

Because of the high pressure difference, aircrossings are potential heating sites. If a heating develops and normal sealing or injection does not resolve the situation and more time is needed for intensive injection, it may be necessary to balance two airways at the site. In these circumstances, the pressure between the airways can be reduced or removed completely either by use of a fan (Plate 15a) or bypassing the air through an adequately-sized duct (Plate 15b).

(ii) Room and Pillar

Accessible fires in room and pillar workings can generally be dealt with by means of digging out, surface sealing or strata injection. Inaccessible fires, for example in de-pillared areas, require the adoption of the techniques described below for retreat work gob areas.

(iii) Retreat Work Gob Areas

General:

When a heating occurs in the waste of a retreat working, the carbon monoxide normally appears first in the return third of the face length. When heating activity increases, emission can be detected progressively nearer the intake end.

This pattern suggests that most gob heatings tend to occur closer to the intake entry, where there is a higher oxygen content, than to the return, where there is normally less oxygen.

Gradients play an important role in the development of gob heatings. The interaction of the pressures due to buoyancy and pressures due to ventilation can cause a resultant flow in the waste area. As a heating becomes more intense, it is increasingly able to motivate its own oxygen supply. This derives from the increased buoyancy forces produced by the rising temperature.

The measures described in Chapter VI for precautionary action can also be applied to combat active heating. In general, most depend for their effectiveness on being initiated at an early stage in the development of heating activity.

Suppression By Gob Gases:

Gob gases in waste areas without bleeder ventilation containing a deficiency of oxygen may be used to limit the level of activity or the rate of development of an active heating. The technique depends for its effectiveness on application at an early stage in the development of heating activity.

If the waste gases contain a high proportion of methane or a very high percentage of nitrogen, they will be lighter than air. Where workings are retreating to the dip, such a waste gas fringe may be brought close to the waste edge by lowering the face air velocity and/or screening off the waste from the scouring effect of the airstream. There will be a higher than normal emission of gas from the waste under the influence of a falling barometer or rapid caving conditions.

Where the waste gases contain a high proportion of carbon dioxide and are heavier than air, the technique may be used in a similar manner for workings retreating to the rise.

In layouts with gradients along the working face line, it is sometimes possible to arrange the forces causing air movement in the waste to work in opposition to each other. Descensional ventilation of such a working will place any buoyancy pressure existing due to heat or a predominance of naturally lighter than air gases in opposition to the forces producing ventilation.

When considering the use of this technique, attention must be paid to the gradients and the gas analysis of the waste.

The flow of air through the district may need to be adjusted to produce the required result. Within the limits imposed by methane percentages and other environmental constraints, the optimum air quantity will be that which produces the lowest quantity of carbon monoxide at the return sample point.

Gob Pressurisation:

This method of combating a gob heating is very effective and is easily applied. In this system, the return paths for the products of combustion are filled with air from the return end of the workings by means of a suitably-sited fan and duct line. This method was used in the incident described in Appendix "L".

(iv) Within Sealed Areas

General:

Heating associated with sealed-off areas may develop after the seals are constructed or be the reason for which the seals are erected. The site can be either within the abandoned area or near one of the seals.

Techniques:

If the area cannot be permanently flooded with water then, whether the heating is inside the sealed area or near one of the seals, the ventilation pressure across the sealed area should be balanced as far as practicable. All sealing sites bounding the enclosed void should be treated by coating with a sealant and by sealant injection.

Heatings Associated with Sealing Sites:

It the heating activity is known to be associated with one or other of the seals, and this may be verified by sampling at points 30 ft or so inside and outside each seal, or by observation of elevated strata temperatures, it may be possible to locate its position and pump direct on to it by use of suitably-placed injection boreholes. If, in spite of these measures, the heating activity is not reduced to an acceptable degree, then the buffer zone technique described in Chapter VI is recommended.

The high level of heating activity in such a location is illustrated on Plate 16, with carbon monoxide concentrations in excess of 500 ppm and carbon monoxide:oxygen deficiency ratios above 1.0. This technique for sealing off a section of a mine was applied in a UK mine where the original seals had been sited in pillars that were believed to be adequate. However, in spite of continuous pressure injection, the heating continued to be active. Products up to 100 ppm of carbon monoxide were recorded in the return from the sealed-off area when the barometric pressure level fell below the ambient pressure behind the seals. After a "buffer" zone was established, the heating was successfully combated.

Deep-seated Heatings Within a
Sealed Area:

Heating activity occurring within a sealed area and remote from the seals is frequently difficult to suppress effectively and permanently. The techniques available are sealing by surface coating and injection, combined with pressure balancing. Both techniques are relatively simple and effective when the number of entries into the abandoned area is limited. Where the abandoned area is bounded on one or more sides by gob or by ineffective pillars, adequate sealing becomes increasingly difficult. If multiple entries are involved, the pressure balancing becomes more complex.

Under such circumstances, the ambient pressure within the sealed-off area should be established at a level approximating to that existing at the major sources of intake leakage. In practice, provided the site of a single chamber is carefully chosen, a combination of chambers should not be necessary. Other factors being equal, the chamber should be erected at a site where the application of conventional sealants is least likely to be effective.

Heating activity within an abandoned area is particularly sensitive to changes in air pressure distribution in the surrounding roadways. Experience shows that heatings which have been dormant for periods of months, and in a few instances years, have been reactivated by relatively minor changes in relevant ambient pressures.

In view of the probable long life of pressure chambers associated with this type of situation, balancing should, as far as possible, be effected using ambient air pressures existing underground. This ensures the balance being to some degree self-compensating against ventilation changes, and makes it independent of power supply failure or equipment breakdown.

Provided sufficient room has been left outbye of one or more of the seals, it should be possible to erect a pressure chamber (Ref A16) as shown on Plate 17. This will enable the pressure within the sealed-off district to be raised or lowered to minimise the airflow through it.

Such facilities as means of sampling behind the original seals are retained, either by extending the pipes out through the chamber wall or by providing means of access into the chamber.

Pressure chambers constructed in this manner are normally better placed at the low pressure side of the district. This is the site at which the carbon monoxide appears and more immediate control of the emission can be maintained from this position.

Occasionally the chamber will require to be erected at the intake or high pressure side of the district. This will be the case when access to the return side is not possible until the chamber is operational.

There are two types of pressure chamber. The first, a static type, is illustrated on Plate 17. This comprises a length of roadway in which there are two seals, one is normally explosion proof, whilst the other may be a lightweight timber barricade. The pressure within this chamber may be controlled by the mine ventilation system or by means of auxiliary fans. Normally, the pressure is adjusted until the pressure across the original seal is zero, as indicated by the gauge. Occasionally, pressures considerably in excess of this are necessary, depending on the number, position and length of the associated leakage paths. The shorter the length of the chamber, the more likelihood there is of a higher pressure requirement. The second type of balance chamber is of the "flow through" type. This is for use in an airway in which the normal ventilating current of air is required to flow. The circumstances and use of this chamber are described in Appendix "L".

Sealing-Off

36. Sealing-off as a combat action involves either the reinforcement of existing seals or the construction of new ones. The purpose of the operation is to isolate the seat of the fire from an oxygen supply, to bring about a build-up of an extinctive atmosphere in the sealed area, to prevent access and to isolate the remainder of the mine from the effects of any explosion.

37. Where sealing-off is carried out under emergency conditions, the maintenance of a safe environment at the sealing site and the timing of the closure of the seals are of paramount importance. Because the construction of seals in emergency conditions can be hazardous and the situation is frequently unpredictable, it is generally prudent to select and prepare back-up sealing sites outbye of the original seals, in case the original sites have to be abandoned.

38. The construction of an emergency seal involves essentially the same technique as sealing-off of a worked-out section in normal circumstances, though the rate at which the seal has to be constructed and the environmental conditions under which the work takes place often make the task more onerous. Full details are given in Chapter VI and the incident described in Appendix "M".

39. Intake seals are generally easy to site but return seals involve more complex considerations. The most significant factors in site selection for a return seal are:-

(i) Satisfactory environmental conditions. However, since circumstances frequently deteriorate while the seal is being constructed, consideration must be given to the time it will take to construct and the extent of predicted deterioration and its effects. Where possible a location within some 100 ft of a fresh air base should be chosen.

(ii) Suitable strata conditions for effective sealing.

(iii) Adequate access for construction materials.

(iv) Communication with the incident control centre.

40. Effective control of construction work is essential and the site should be under the supervision of a senior mine official in contact with the Incident Controller. A sampling procedure should be initiated and arrangements made for the transmission of the samples for analysis. Progress of seal construction should be reported at regular intervals and a record kept on the mine surface.

41. It is frequently desirable to ventilate the sealing sites to enable them to be constructed in fresh-air conditions. This presents no problems on the intake side, but at the return site the atmosphere may contain a high level of carbon monoxide, and/or a deficiency in oxygen. The environment may prevent work without breathing apparatus and, consequently, progress in building the return seal may be retarded or it may even have to be abandoned and other sites selected, possibly much further outbye.

42. Sealing sites are normally selected near a crosscut between intake and return. This facilitates supplies handling and provides ready access to a fresh air base. However, under some circumstances, poor environmental conditions can exist at the return seal shown on Plate 18.

43. The environment can be improved by reversing the pressure over the return seal site (see Plate 19). This can be achieved by extending the ducting, which is installed through the seal site, to a point in the main return several feet outbye of the intake crosscut. A shuttering board or Kennedy barrier is then erected over the ducting at a position in the return beyond the crosscut. The doors in the separation crosscut are then fully opened. The pressure across the return site will then reverse and fresh, smoke-free and relatively cool air will be drawn inbye over the site.

44. In very adverse circumstances, where seals have to be constructed by men using breathing apparatus, the appropriate rescue procedures must be implemented.

45. When sealing-off, the timing of the completion of the seals is critical. Generally, to ensure that an explosive situation does not develop at the heating site, ventilation must be maintained through the section. This involves circulating air through the intake seal and out via the return seal, until the pre-determined closure time is reached. Both seals must then be closed and sealed simultaneously, under the direction of the Incident Controller. For this purpose, therefore, there must be a precise plan and effective communications during the final sealing. This phase is assisted by incorporating explosion-proof access tunnels in each seal.

46. The final phase of any sealing-off operation is to monitor the change in atmosphere behind the seals by air sampling. These samples must be related to the Coward "explosive triangle" (Ref A10, A11, A12 and A13) and appropriate action taken to safeguard life in the event of the development of explosive mixtures. This applies even though explosion-proof seals have been built. The sealing off can be considered finalised when the air analyses show that heating has ceased and an extinctive atmosphere has been established.

Nitrogen

47. Heatings have been controlled in Europe by suppression with nitrogen gas. The technique is illustrated in Appendix "F". The incident described was a successful application of the technique, but it should be noted that it utilised the locally favourable circumstances for the supply of liquid nitrogen and the evaporation of more than 5 million ft^3 of nitrogen. Such circumstances clearly only prevail in a few locations and reduce the possibility of wide application of the technique.

ADVANCE EMERGENCY PLANNING AND TRAINING

48. At any mine with a spontaneous combustion risk, a "heating prevention programme" should be set up. Sufficient supervisors and workmen must be allocated to implement the programme and adequate training must be given in all its aspects. In the event of an emergency developing from a heating incident, the combat work is generally similar to preventive work, but this has to be completed more quickly, and possibly under arduous conditions.

49. The training of rescue teams is not within the scope of this report, but all personnel likely to be involved with combating active spontaneous combustion should receive adequate and regular training in the use of preventive techniques, such as surface sealing, strata injection and construction of seals.

50. Whenever seals are erected, details of the position, date, materials used, and the seal size should be entered into a record book specially prepared for the purpose and this record must be kept for the life of the mine. The exact site of each seal, together with its identification number, should also be marked on a plan made for that purpose.

51. Under emergency conditions, it is essential that sufficient personnel are available who have been trained in the construction of pumped seals. Each seal construction site should be under the personal supervision of a senior official of Mine Superintendent status. A surface control room should be established from which an Incident Controller, of at least Mine Superintendent status, and generally

more senior, should direct operations. In this room also would be other senior management, government mines inspectors and technical specialists that are considered necessary. A typical organisation chart is shown on Plate 20.

52. In order to control an incident effectively, adequate air sampling procedures must be set up and gas analysis facilities provided.

53. When a serious fire occurs underground, the first priority is to ensure the safety of all personnel. High on the priority rating is an efficient gas sampling and analysis service, since the information provided will play an important part in the strategy for combating the fire. The better the service, the more effective the fire-fighting plans will be.

54. In Western Europe, Russia and Japan, a comprehensive gas analysis service is generally provided on a routine basis by mine or regional laboratories equipped with at least one mobile unit, on call 24 hours a day, every day of the year. These mobile laboratories are entirely self-supporting and can operate independently of external services; they are linked into the emergency communications system by radio and line telephone.

55. On arriving at an incident, it is the responsibility of the scientist in charge of the laboratory to consult with the Incident Controller to establish a gas sampling programme and thereafter to brief the leaders of the rescue teams on where and how the samples are to be taken and to provide all the sampling equipment necessary. The taking of gas samples should be part of the basic training of all rescue personnel.

56. While every incident poses its own specific problems, it is desirable in its early stages to achieve the maximum possible sampling frequency that the situation permits; as analytical data become available, the sampling programme can be adjusted to meet the prevailing conditions revealed. In many European mines the availability of tube-bundle systems now greatly facilitates sampling and additional sampling points can be linked into the system using the emergency tubing carried by the mobile laboratory. Experience has also shown the value of having a standby multi-cored tube bundle installed in the shaft for use in such an emergency.

57. Mobile laboratories should be equipped with all the necessary auxiliary apparatus, pumps, condensation traps, etc, for linking into the shaft tube bundle. Should the incident develop to a stage when seals have to be installed, provision for sampling through them must be made as these will provide the only means of assessing what is happening behind the seals and subsequent action will depend almost entirely on the gas analysis data obtained in this way. The provision of adequate sampling facilities through seals, especially when balanced seals are used to prevent air leakage into the heating area, cannot be over-emphasised.

58. The minimum gas analysis data required are carbon monoxide, carbon dioxide, oxygen, methane and hydrogen. From these analyses the carbon monoxide:oxygen deficiency ratio and the potential explosibility of the atmosphere can be calculated. Mobile laboratories should be equipped with mini-computer or programmed calculator facilities for carrying out these and the other routine calculations required.

59. The analytical equipment of the mobile laboratories is generally the same as that used in the regional or mine laboratories - non-dispersive infra-red analysers for carbon monoxide, carbon dioxide, methane and hydrogen, para-magnetic analyser for oxygen and gas chromatographs for ethylene, ethane and higher hydrocarbons. Analysers may also be provided for oxides of nitrogen and hydrogen-sulphide.

60. The use of mobile laboratory facilities is regarded as a temporary expedient and they must be released as soon as possible in case they should be needed elsewhere. Under the emergency planning procedures in force in the UK, for example, every mine must have a suitable room that can be converted into a gas analysis laboratory in an emergency. It is a general rule that this room should be equipped and operational within seven days of the beginning of the incident in order to release the mobile laboratory and its associated staff for standby duty at base.

61. To equip the semi-permanent laboratory at the mine, gas analysis equipment could be provided from a pool held at a regional centre for this purpose, as experience indicates that a full gas analysis service will be required throughout the initial emergency and the subsequent recovery period. This period may extend to some weeks or more as the information provided is critical to any plans for re-opening the seals or indeed in deciding that the area affected must be subject to long-term abandonment. As soon as conditions allow, analysis can be resumed at the permanent laboratories.

CHAPTER VIII

US MINING CONDITIONS

INTRODUCTION

1. This chapter reviews the coal geology and surveys the current coal mining industry of the four Rocky Mountain States of Colorado, Wyoming, Utah and New Mexico. The characteristics of the coal and its geological setting are discussed with special reference to the hazards of spontaneous combustion. Hazards of spontaneous combustion, as related to underground mining, are also reviewed, with special reference to eight mines visited during the project. The analytical results of fifteen selected samples collected during the project are presented and their significance to the liability of the coals to self-ignition is discussed.

MINING GEOLOGY

Geological Setting

2. The coals of Colorado, Wyoming, Utah and New Mexico occur in sediments of Cretaceous to early Tertiary age. Seams of commercial thickness are commonly found within the first 100 ft of a non-marine section above a marine sequence of sandstones and shales. The coal-bearing sequence was deposited along the western margins of an ancient sea covering the Western Interior of the North American continent, some 95 million to 50 million years ago. The sedimentation was disrupted by block faulting during the Laramide earth movements (late Cretaceous to Paleocene), giving rise to a series of uplifted blocks which formed areas of positive relief separated by intermontane basins.

3. Details of the geology and coal characteristics found in the four States are given in Appendix "Q".

Location and Reserves

4. The principal coal-bearing areas of the four States are shown on Plates 21 to 25 and are listed in Table III, with statistics on their location, age and rank.

5. Total in-situ underground coal reserves for the four States amount to some 49,000 million tons and are tabulated below:-

	Sub-bituminous	Bituminous	Anthracite	Total
	10^6 tons	10^6 tons	10^6 tons	10^6 tons
Wyoming	24,967	4,524	-	29,491
Colorado	4,745	9,226	28	13,999
Utah	-	3,780	-	3,780
New Mexico	607	1,527	2	2,136
Total	30,319	19,057	30	49,406

USBM, IC 8678, 1974.

6. Wyoming has some 60% of the known underground coal reserves, located mainly in the Powder River and Green River basins. The second largest concentration of reserves is found in the Uinta and Green River basins of Colorado. Reserves in Utah and New Mexico are small and amount to only 8% and 4% of the total respectively.

7. In-situ underground reserves listed by rank, sulphur content and seam thickness for each county and state are found in USBM, IC 8678, 1974. Further detailed reserve figures are also available in the Keystone Coal Industry Manual, 1977.

Coal Characteristics

Rank, Oxygen Content and Heating Values

8. Liability of coals to spontaneous combustion decreases with increasing rank of coal. Both oxygen content and dry, ash-free calorific value of the coal, which are indirect measures of rank, can be related to the liability of coals to self-ignition.

9. The rank of coals found in the four States varies from lignite to anthracite (most commonly sub-bituminous to high volatile bituminous). Cretaceous coals, which were formed on the coastal plains bordering the Mesozoic sea, are generally of higher rank and better quality than the Tertiary coals found in the restricted intermontane basins.

10. Some two-thirds of the in-situ underground reserves are sub-bituminous and, in general, will be more liable to spontaneous combustion because of their greater oxygen content than the remaining one-third which are bituminous in rank. Anthracite, the coal rank which has the least potential for spontaneous combustion because of its low oxygen content, is relatively insignificant in terms of reserves (less than 0.1% of the total). Rank of coal tends to increase with increasing depth of burial (Hilt's Rule) so that coals found at depth in the centre of a structural basin are often of a higher rank than those found on the basin margins. However, this trend has less impact on the rank than the localised effects of igneous intrusions and structural complications which are found on the margins of many of the coal-bearing basins (eg Carbondale field of Colorado). Metamorphism of the coals in structurally complex areas frequently increases the rank of coals from sub-bituminous and the lower ranking bituminous grades to medium and high volatile coals with coking properties (eg Crested Butte field of Colorado) or even to semi-anthracite and anthracite (eg Cerrillos field of New Mexico).

11. Oxygen contents may be as high as 18% to 24% (dry, ash-free basis) for sub-bituminous coals with heating values on the order of 8,500 Btu/lb to 13,000 Btu/lb. They may be as low as 8% to 16% for the high and medium volatile bituminous coals with heating values on the order of 14,000 Btu/lb to 16,000 Btu/lb. Heating values for most Western States coals lie in the range of 11,000 Btu/lb to 15,000 Btu/lb. Some of the lower ranking sub-bituminous coals have heating values as low as 9,000 Btu/lb.

Moisture, Ash and Sulphur

12. Coals of the Western States are typified by low ash, moisture and both organic and pyritic sulphur contents, making them ideal for steam generation and metallurgical purposes.

13. Moisture content, on an as-received basis, commonly averages between 10% and 15%. In some fields, poorer quality or lower rank coals may have a moisture content as high as 35%. The relationship between moisture content and spontaneous combustion of coal is complex, and no conclusions can be drawn from the available data.

14. Ash content, on an as-received basis, commonly averages between 6% and 10%. In some fields, poorer quality coals may have an ash content as high as 29%. The relationship between ash content and spontaneous combustion of coal is also complex, because the ash contains both accelerators and retarders of oxidation (see Chapter II). The silica and alumina (aluminosilicate mineral) content of coal ash has a retarding effect on oxidation, while magnesia, ferric oxide and lime (carbonate minerals) have an accelerating effect. The percentage of retarding and accelerating species within the ash from each coalfield varies. Data from Wyoming coalfields show that the percentage of SiO_2 plus Al_2O_3 can vary from 25% to 85% while that of MgO plus Fe_2O_3 plus CaO varies from 10% to 45%.

15. The sulphur content of Western States coals commonly averages between 0.2% and 0.9%. Ninety-nine per cent of Colorado and Wyoming coal resources have sulphur values less than 1% and about half the tonnage has values less than 0.7%. Poor quality coals from some of the smaller fields have sulphur contents as high as 5%, but such tonnages are relatively insignificant. Coals from Utah and New Mexico tend to have slightly higher sulphur contents (0.5% to 1%).

16. The ratio of pyritic sulphur to organic and sulphate sulphur is variable. In Colorado, pyritic sulphur forms a high percentage of the total sulphur content, while in Wyoming and New Mexico some 70% of the total sulphur is in the organic form. The organic sulphur content does not affect the spontaneous combustion of coals, thus the hazard of self-ignition is minimised in the Wyoming and New Mexico coals. The sulphide form is thought to play a secondary role in increasing the probability of spontaneous combustion, suggesting that the Colorado coals may be slightly more susceptible to self-oxidation.

Petrography

17. The proportions of the lithotypes, fusain, vitrain, clarain and durain are thought to be significant factors in the liability of coals to spontaneous combustion. Air is able to migrate through the more porous fusain layers and supply oxygen to the more reactive lithotypes, such as durain.

18. Data on the petrography of Western States coals are limited. However, the majority of coal seams investigated appear to comprise alternating layers of clarain and durain in approximately equal quantities. Only two of the eight sample sites investigated in the project contained remarkable quantities of fusain (even then less than 10%). The fusain was found intercalated with durain bands.

Methane Content

19. Methane emission rates in the mines visited during the field survey ranged from very low (Mine No 1) to very high (Mine No 4). The methane percentage has little bearing on the susceptibility of Western States coals to spontaneous combustion though it may initially retard oxidation as it inhibits the diffusion of oxygen into the coal, but high methane emission and active heating together could create a hazardous situation.

Physical Properties of Coal

20. Available data on the hardness and friability of Western States coals are limited. Soft, friable and fractured coals, which air can easily permeate, have a higher probability of spontaneous combustion than massive unfractured coals. Friability of coals, with the exception of anthracite, tends to increase with rank, but the correlation is not good. Bituminous coals of higher rank tend to produce more fines in mining and handling with the result that greater surface area is exposed to oxidation, and consequently the likelihood of spontaneous combustion is greater.

21. It appears that the majority of undisturbed seams have relatively hard coal with Hardgrove indices less than 60. The Hardgrove grindability indices of coals from Wyoming vary from 41 to 87. The averages for the reported coalfields lie generally between 45 and 51 (Ref A17).

22. Coals of Wyoming contain one to four fracture sets, although only one or two of these sets are generally well developed.

23. Fracturing of the coal is likely to be more prevalent in structurally disturbed areas (ie near faults, as seen in the Hanna field of Wyoming). The possibilities of spontaneous combustion are greater in such seams than in structurally undisturbed and less fractured seams.

Geological Characteristics

Sedimentary Features

24. The coal seams exhibit a large range of sedimentary features which affect mining conditions and indirectly contribute to the possibilities of spontaneous combustion.

25. The majority of underground in-situ reserves occur in thick, gently dipping, regular seams with thicknesses in the order of 5 ft to 15 ft. However, some of the smaller, sub-economic coal-bearing basins, such as the Kolob field of Utah and the Dakota field of the San Juan region in Colorado, are typified by thin, discontinuous, poor quality coal seams high in ash and sulphur content. A few basins have unusually thin seams, such as the Goshen Hole field of Wyoming where the seams are less than 2½ ft thick. In Utah and New Mexico, the seams are thinner and more lenticular than in Wyoming and Colorado. The long direction of the coal lenses in New Mexico is parallel to the Mesozoic shorelines for a distance of 1 mile to 30 miles. The lenses extend for relatively short distances (½ mile to 5 miles) perpendicular to the ancient shorelines. In Wyoming, the seams frequently have exceptional thicknesses ideal for strip mining. A few seams attain thicknesses of some 200 ft (eg the Healy seam at Lake De Smet in the western Powder River region). (Ref Keystone Coal Industry Manual, 1977).

26. Coal-bearing stratigraphic sections often contain upwards of 15 seams, although only one to three are economically attractive for extraction in any one area. Rider seams lying close to the roof of workable seams are commonly present in many fields. These seams can be a source of spontaneous combustion in locations where they are fractured or collapsed.

27. Shorelines along which the coal deposits formed were subject to repeated shifting as the ancient sea advanced and retreated across the region in Cretaceous to Paleocene times. This shifting of shoreline has resulted in a complicated interdigitation of marine and terrestrial sediments, and irregularities in extent of the coal seams that are still imperfectly understood. As a consequence, many seams contain shale partings, especially the thicker seams in Wyoming where partings are commonly 1 ft to 2 ft thick but on occasion may be as thick as 15 ft. In some fields (eg Toadlenad field on the west side of the San Juan River region in New Mexico), the shale partings may be sufficiently thick to prevent economic extraction of the coal (Ref A18).

28. The conditions of variable deposition have also given rise to splits and coalescing of seams to form abnormal thicknesses, as well as rolls and washouts which cause rapid changes in thickness. Lenticular seams, such as those found in the Kaiparowits Plateau field of Utah, may pinch out and be replaced by other seams at slightly different stratigraphic positions. In other places, two mineable seams will overlap with a very narrow separation.

29. Roof and floor conditions also vary considerably. In strong strata, support is provided by roof bolts, although under some conditions these are not necessary. In exceptional cases, soft clay and shale rocks require more intensive support as in the Coalville field of Utah where the soft shale floor heaves during recovery of coal pillars.

30. Sedimentary anomalies in the seams create difficult extraction problems and may result in sections of coal being abandoned; these abandoned coal sections are potential sites for spontaneous combustion.

Thickness

31. The coals of the Western States are thick and, as a consequence, coal is frequently left on the roof and/or floor by present extraction techniques. (Four of the eight mines visited extract only part of the seam section.) Extraction heights rarely exceed 8 ft to 9 ft and in some mines as much as 15 ft of floor coal or 4 ft of roof coal is left, creating potential spontaneous combustion risks.

32. Data on seam thickness, as given in the Keystone Coal Industry Manual, 1977, have been analysed. The following thickness parameters have been estimated:-

	Colorado	Wyoming	Utah	New Mexico
	ft	ft	ft	ft
Median	10	10 to 12*	6½	6
Lower quartile	5	*	5	4½
Upper quartile	12	*	9	8
Lower decile	4	*	3½	3½
Upper decile	18	*	12	11

*Poor data base, not analysed. Most seams are between 5 ft and 22 ft thick.

33. The data indicate that a large percentage of the known seams have thicknesses in excess of the generally accepted maximum mining height of 8 ft to 9 ft. Spontaneous combustion caused by incomplete extraction of the seam should be less of a hazard in Utah and New Mexico where some 50% of the seams are less than 9 ft in thickness. In Wyoming and Colorado, which contain 88% of the in-situ underground reserves, the median seam thickness is considerably greater than the current maximum extraction height.

Structural Features

34. A large portion of the in-situ underground coal reserves occurs in regular, gently dipping (0^0 to 15^0) strata found in broad structural basins separated by high mountain ranges. The thickness of the sedimentary succession increases towards the centre of each basin; overburden thickness may exceed 6,000 ft in the deepest parts of the deeper structural basins.

35. Many of the basins are asymmetric in shape, with upturned beds (20^0 to 90^0) along the mountain front on the western flank and more gently dipping beds (0^0 to 20^0) on the eastern margins (eg Uinta basin, Colorado; Powder River basin, Wyoming). Margins of some basins (eg Piceance basin, Colorado), especially some of the smaller basins, are extensively affected by folds, faults and igneous intrusions. In such localities, seams have high and variable dips, are often overturned, and the coal rank may be locally increased. Faulting is an important factor in such fields as the Hanna field, Wyoming and the Book Cliffs field, Utah, where faults have displacements varying from a few inches to 600 ft. In the Harmony field of Utah, the strata have been extensively deformed and forcibly intruded by igneous rocks so that the seams are locally thickened and thinned. More unusual is the presence of igneous rocks in the centre of a basin, such as in the Raton basin where Tertiary igneous stocks, dykes, sills and laccoliths have pierced and disrupted the coal-bearing strata. These structural irregularities create difficult extraction problems and may result in coal being abandoned; the abandoned coal presents potential sites for spontaneous combustion.

Geothermal Gradient

36. The temperature of strata commonly increases at the rate of 1^0F to 2^0F per 50 ft to 100 ft over the usual range of coal mining depths (zero to 3,000 ft). Vulnerability of coals to self-ignition increases with increasing depth of cover, as the rate of oxidation doubles for every 18^0F rise in temperature. The gradient in some mines could be higher than average values for the North American continent because the coalfields occur in tectonically disturbed areas.

Weathering and Burning of Outcrops

37. Exposure of seams in outcrops causes extensive degradation of some coals resulting from loss of bed moisture to the atmosphere. The resultant weathering of outcrops, characteristic of sub-bituminous coals, is common in many of the fields and may be extensive, as seen in the South Park field and Tongue Mesa field of Colorado.

38. Many seams have burnt outcrops resulting from fires set by natural causes. Surface coal may be burnt for several hundreds of feet behind the outcrop, leaving a residue of hard, dull red clinker. Though hazards arising from spontaneous combustion of the outcrop coal are relatively unimportant, as pillars of

coal are left at the surface in order to isolate the weathered and burnt coal from the underground workings, the burning serves as a clear indication of the coal's vulnerability to self-ignition.

UNDERGROUND MINING

Mining Survey

39. Current coal production from the four States was in the order of 36 million tpa in 1976, of which two-thirds was from surface mining. An estimate of the 1976 production by State, for both surface and underground mining, based on data from the USBM and the Keystone Coal Industry Manual, 1977, is given below:-

	Underground	Surface	Total
	10^6 tons	10^6 tons	10^6 tons
Colorado	3.3	7.5	10.8
New Mexico	0.8	8.5	9.3
Wyoming	0.5	7.5	8.0
Utah	7.9	-	7.9
Total	12.5	23.5	36.0

40. Underground production comes from 43 major producers (Plates 22 to 25), which account for 12.5 million tons (see Table IV). This table also gives information on manpower employed, seam thickness and coal analyses for the various mines. A summary of the mining statistics is given below:-

Underground Mines

	Number of Mines	Annual Production	In-situ Reserves
	(Principal Producers)	10^3 tons	10^6 tons
Utah	22	7,871	3,780
Colorado	17	3,292	13,999
New Mexico	1	830	2,136
Wyoming	3	514	29,491
Total	43	12,507	49,406

Source: Production estimates - Keystone Coal Industry Manual, 1977 (1976 figures)

Reserves - USBM, IC 8678, 1974

41. Although Utah has the largest number of mines in the four States (51%) and produces the largest output (63%), it has the second least favourable reserve position (8% of the total underground in-situ reserves). The greatest potential in terms of reserves for underground development lies in Wyoming which, although accounting for only 4% of the total output, contains 60% of the total reserves.

42. At present, the principal producing coalfields are in the Uinta region. The Colorado portion of this region contains eleven mines. The Castlegate/Emery and Book Cliffs fields of the Uinta region in Utah contain fifteen and seven mines, respectively.

43. More than 56 million tons of additional underground production capacity is planned for the period 1976 to 1985 (see Table V) and is summarised below:-

	Number of Projected Mines	Additional Annual Capacity
		10^6 tons
Utah	18	28.80
Colorado	23	23.85
Wyoming	4	+3.50
New Mexico	No projections available	
Total	45	+56.15

44. With the installation of this new capacity, annual production from underground mines in the four States will total 65 million to 75 million tons by 1985.

Field Visits

45. Eight mines in the four States were visited during the project. Details of their geology, mining statistics, and history related to spontaneous combustion are given in Appendices "R" to "Y". The locations of the visited mines are given below:-

Mine No 1	Yampa field	Colorado
Mine No 2	Hanna field	Wyoming
Mine No 3	Rock Springs field	Wyoming
Mine No 4	Carbondale field	Colorado
Mine No 5	Uinta region	Utah
Mine No 6	Emery field	Utah
Mine No 7	Mesa region	New Mexico and Colorado
Mine No 8	Weld field	Colorado

46. Production from the eight underground drift mines varies from 150,000 to 1,100,000 tpa (average 500,000 tpa). Only one mine (No 5) exclusively uses the longwall method of mining. Two mines (No 4 and 7) have single longwall faces as well as room and pillar workings, although at least two others have plans to implement longwall faces in the future. Most development work and room and pillar extraction is carried out by continuous miners. One mine (No 6) also uses conventional equipment in part of its room and pillar workings. Shearers are used on longwall faces.

47. Conveyors are used for coal transport from longwall faces. Combinations of shuttle cars, front-end loaders and conveyors are used for coal haulage from room and pillar workings.

48. Coal-bearing sections exploited by the mines commonly contain upwards of seven seams, although it is unusual for more than one seam to be mined.

49. Seam thicknesses vary from 4 ft to 24 ft and at least five of the mines leave roof and/or floor coal during extraction. Coal recovery may be as low as 17% (Mine No 6).

50. Cover varies from a few tens of feet to 3,000 ft but commonly is less than 700 ft. Several of the mines plan to extend their workings to areas where the cover is between 1,400 ft and 2,000 ft (No 2, 5 and 7). Seam gradients vary from zero to 25%, but the majority of workings lie in the range of 5% to 15%, with higher gradients restricted to structurally disturbed areas. About one quarter of the mines have workings in which faulting is present and affects the mine layouts (notably in Mine No 2). Bumps are a significant mining hazard in some mines (eg Mine No 4).

51. In most cases the roof is sufficiently strong so that entries require only open roof bolting plans for support. Steel mats and additional steel or timber support are used locally in areas where the roof conditions are poor. Thickness of seams has an indirect effect upon roof conditions. Although the standard width of entries varies from 12 ft to 20 ft, it is difficult in practice to maintain these spans in the thicker seams, and pillar sloughing can become a problem. Increasing depth of cover can result in the crushing and sloughing of pillars, especially in the central portion of the exposed rib. The majority of currently working mines have a depth of cover of less than 700 ft, but cover depths will increase in the future as mining continues down dip in order to exploit deeper reserves in the centres of the coal-bearing basins.

52. Water presents a mining problem in four of the eight mines visited and is worst in Mine No 5, where 2 million gallons per day are pumped from the workings. Water is present either in aquifers overlying the worked seam or, in the case of Mine No 2, in faults intersecting the seam.

53. Ventilation pressures are commonly less than 6-in water gauge; the mines are equipped with one or two main fans handling air quantities of between 82,000 ft^3/min and 500,000 ft^3/min. Four of the mines have had no underground fires due to spontaneous combustion. Incidents appear to have been largely restricted to mines working coal seams with high oxygen contents (ie Mines No 2, 3, 5, 6 and 8). Mine No 5 has experienced the greatest number of incidents - seven in the past 27 years. Mine No 2 lost part of its workings in the past from a fire.

Self-ignition of the outcrop coal and surface stockpiles have been more common than underground fires. For example, at Mine No 3, production is cut back to prevent a build-up of the surface coal stocks should there be a delay in the arrival of the unit train.

Mining Conditions

54. Underground locations where spontaneous combustion may occur include:-

(i) working place,

(ii) support pillars,

(iii) remnant coal left in the roof and floor,

(iv) coal left in disturbed areas,

(v) waste coal left in the gob after caving,

(vi) rider seams lying above the worked seam,

(vii) fractured coal.

Working Place

55. Risks of self-ignition in working places are small, provided these are being advanced at normal rates. The risk of spontaneous combustion will increase if working places are left idle for any length of time.

Support Pillars

56. Between 45% and 65% of the coal can be left as pillars during room and pillar mining. Sites of weathering and sloughing resulting from degradation of the coal due to high stress conditions in the pillars, are possible loci for self-heating. Although most of the mines practise pillar recovery, such recovery is never complete, thus giving rise to potential hazardous conditions, especially in abandoned workings. The hazard is reduced along main airways, except where they are clad in timber support and planking, as the air flow will reduce the build-up of heat.

Remnant Coal

57. Extraction heights are rarely greater than 8 ft to 9 ft and, as a consequence, in some mines working thick seams, more than of 15 ft of floor coal is left in the floor and upwards of 4 ft of coal is left in the roof. Even in seams with thicknesses less than the commonly accepted maximum extraction thickness, coal is often left either to support a weak roof or because the roof coal is of poor quality. Unmined roof and floor coal, as seen in Mines No 1, 2, 4, 6 and 8 are potential sites for spontaneous combustion.

Disturbed Areas

58. Coal is frequently left in geologically disturbed areas where extraction is difficult or uneconomic. Coal may be left because of sedimentary features such as rolls, bumps (as in Mine No 4), wash-outs, poor roof and floor conditions, or

structural features such as faults (as in Mines No 2 and 3) and igneous intrusions. The hazard of self-ignition of such unmined coal may be compounded by extensive fracturing, which increases permeability and thus exposes more coal surface on which oxidation may take place.

Waste Coal

59. Coal left through the incomplete extraction of pillars, as seen in all the mines visited, is also a potential site for spontaneous combustion. The hazard is aggravated by the commonly fractured and pulverised nature of the partially-extracted pillars, resulting either directly from the pillar robbing operation or from crushing of the coal due to high stress concentrations in the centre of the pillar.

Rider Seams

60. Thin and uneconomic seams in the roof may be exposed by caving, both behind longwall faces and during pillar recovery in room and pillar operations. Blocks of the overlying seam may fall into the gob, thus giving rise to potential sites for spontaneous combustion.

Fractured Coal

61. Leakage of air can occur through fractured coals and increase the liability to spontaneous combustion. Fracturing can be due to natural causes, as found in tectonically disturbed areas. It can also be a result of mining operations where seams are mined near the surface, thus creating channelways for air leakage from the surface or where a second seam is mined in close proximity to a previously worked seam.

Ventilation

62. Besides a suitably vulnerable coal site, underground occurrences of spontaneous combustion require a steady supply of oxygen and an environment that favours heat accumulation. The hazards of spontaneous combustion in potentially dangerous sites can be reduced, either by preventing air from reaching the coal (as required in abandoned areas), or by designing a ventilation system to ensure that the rate of heat dissipation to the airflow is greater than the rate of heat production in the coal (as required in working areas).

63. Current legislation applicable to Western US mines makes provision for bleeder airways in order to attempt ventilation of the waste areas. Although in theory such a practice can reduce the build-up of heat in remnant coal left in the waste areas, it is commonly found in practice that a constant airflow cannot be maintained through all parts of the waste because of irregular paths of the airflow in the abandoned areas. Spontaneous combustion can start in partially ventilated coal-bearing waste areas and will be aggravated by the airflow generated by the bleeder ventilation system.

64. Both forcing and exhausting axial flow fans are used for main mine ventilation, operating at pressures not greater than 6-in water gauge, which is generally lower than in Europe. Mine resistances, and hence ventilation pressures, are small as a result of the system of multiple entry development and large openings used for room and pillar workings in thick seams. Low ventilation pressures do reduce the possibility of air leakage into waste areas, provided that no bleeder ventilation airways exist and that abandoned areas are properly isolated from the main ventilation circuit.

65. Fire hazards resulting from spontaneous combustion can be further aggravated by high humidity in the airflow within a mine. Condensation of water vapour on coal surfaces can cause an increase in temperature in the coal by release of latent heat of vapourisation as the water changes from vapour to liquid. Although there are some exceptions, normal humidity in the mines of the Rocky Mountain States rarely exceeds 15% (in contrast to 60% or even 70% in European mines); absorption of water vapour is minimal.

Statutory Requirements

66. Details of Federal and State regulations relating directly or indirectly to the prevention and containment of fires arising from spontaneous combustion are given in Appendix "Z".

67. Federal legislation is covered in the Federal Coal Mine Health and Safety Act of 1969. Its accompanying regulations are included in the Code of Federal Regulations, Title 30, Mineral Resources.

68. State legislation related to spontaneous combustion is found in:-

Colorado:	Coal Mining Laws of the State of Colorado,
New Mexico:	New Mexico Mine Safety Code for All Mines,
Wyoming:	The Mineral and Mining Laws of Wyoming, Title 30,
Utah:	Miscellaneous sections of the State Law pertaining to Mining Activity, Coal Mines.

69. Existing legislation covers the spontaneous combustion situation by virtue of requirements relating to inspections, ventilation, methane control, reporting of fires, etc, and it is not envisaged that specific legislation will be required to cover spontaneous combustion. Certain relaxations of current requirements, such as bleeder ventilation, may be necessary to reduce the spontaneous combustion hazard.

Spontaneous Combustion Experience

70. The ability of coals of the Western States to self-ignite has been known for many years. Many reports are available which record the outbreak of fire at the surface outcrop and indicate the extent to which seams have been burned back over many years.

71. Reported underground incidents have been few in number and mainly associated with larger operations. The exact number of fires caused by spontaneous combustion is unknown because current legislation requires only those fires not extinguished in 30 minutes and/or causing injury or loss of life to be reported.

72. Notable on the list of major incidents arising from self-ignition are those of the Sunnyside mine in Carbon County, Utah, where seven heatings and fires have occurred over the past 27 years, and those of the Somerset mine in Gunnison County, Colorado. Fires arising from spontaneous combustion since 1971 in the Somerset mine are described in Appendix "K".

73. A large number of spontaneous-ignition incidents occurring on the surface have been reported. Heatings have occurred in stockpiles, in waste heaps, and during coal transit in rail cars. No major incidents, however, have been reported, and outbreaks have been quickly brought under control by digging out the coal and quenching it with water. Incubation periods have been estimated at four weeks to three months in stockpiles. Where coal is to be stockpiled over long periods, compaction has generally been a successful preventive measure.

LABORATORY TESTING

Sample Collection and Preparation

74. Forty-five samples were collected (see Table VI) from the eight mines visited. Between three and four samples were taken from each seam, representing different horizons roughly equally spaced from roof to floor. The samples comprised about 4-in to 6-in cubes of coal and each represents about a 6-in thickness of a seam.

75. Each sample was sealed in a plastic bag, which was placed in an air tight sample tin and sent to the consultants' laboratory. On arrival, all the samples were inspected; most of them still consisted of one or two pieces, although a few had broken down to small coal and were not considered for oxidation tests. Fifteen samples (one from each seam sampled) were chosen for analysis and testing for oxidation characteristics by the paced, adiabatic, non-isothermal criterion (PANIC) developed by the NCB. The outside "skin" was trimmed off, the rest of the sample was crushed in nitrogen to 30-60 BSS mesh for oxidation tests, and an aliquot was analysed. In three cases a second section from a seam was fully tested to make sure that there was no significant variation between different parts of a seam. The sample of "bone" coal from Mine No 4, which contained over 40% ash, was analysed but not tested for its oxidation characteristics.

Analytical Results

76. The results of the proximate analyses are given in Table VII, and the results of the ultimate analyses for carbon, oxygen, hydrogen, carbon dioxide, nitrogen and sulphur in Table VIII. In three cases, two samples from a seam were tested; the results indicated that the coal in any one seam was consistent as regards fundamental properties (ie coking, calorific value, rank and oxidation characteristics).

77. Six of the fifteen coals analysed were either high volatile C bituminous or sub-bituminous A in rank, with very poor or no agglomerating characteristics; three were high volatile B bituminous; five were high volatile A bituminous; and the remaining one was medium volatile bituminous coals. The volatile matter (dry, mineral-matter-free basis) varied from 22.1% to 48% (average 39% for the fifteen samples). The calorific value (moisture, mineral-matter-free basis) varied from 11,470 Btu/lb to 16,440 Btu/lb (average 13,740 Btu/lb for the fifteen samples).

78. As-received moisture of the fifteen analysed samples varied between 22% and 0.2% and between 10.8% and 0.6% on an air-dried basis.

79. The oxygen contents, which are of particular importance from the point of view of spontaneous combustion, varied from 2.7% to 18.0% on the dry, ash-free basis, but ten of the coals had oxygen contents over 10%, six over 15%, and only five had less than 10% oxygen.

80. Sulphur content varied between 4.34% and 0.31%; eleven of the samples had a sulphur content less than 1%, and six a sulphur content equal to or less than 0.5%.

81. Chlorine content varied between 0.02% and 0.05% (average 0.03% for the fifteen samples).

Oxidation Tests

82. The emission of carbon monoxide during oxidation testing is given in Table IX. Plate 26 gives the curves for carbon monoxide emission between 80°F and 250°F; these curves, identified by sample number, are given on three graphs for clarity because of overlapping. On the third graph each curve represents several samples, because the curves for these samples are practically co-incident.

83. The results for methane emission are given in Table X. Table XI shows the temperatures at which there are indications of a change in the type of reaction.

Potential Detector Gases

84. Plate 27 illustrates the temperatures at which the possible detector gases attain various concentrations. The curves for carbon monoxide have been shown on separate axes to those for hydrogen, ethlene and propylene purely for clarity.

85. Carbon monoxide is the first gas to show a significant increase (Table IX and Plate 26). The first increase occurs at 100°F to 120°F for low rank coals and at 150°F to 165°F for high rank coals. In every case the carbon monoxide in the oxidation gases exceeds 100 ppm by 210°F and thereafter increases very rapidly. Table IX shows that the pattern of evolution of carbon monoxide related to temperature and gas quantity and coal rank, corresponds very closely with the results obtained for British coals. As in Britain, this is the obvious gas to use for the early detection of spontaneous heating; carbon monoxide is the basis of the method given in Chapter V. In all cases carbon monoxide exceeded 100 ppm before the next potential detector gas attained 10 ppm.

86. Hydrogen, at a level of a few parts per million, is first measurable in most samples at 200°F to 220°F. This gas reaches 10 ppm at temperatures varying from 220°F for high volatile coals up to 250°F to 265°F for low volatile coals.

87. Ethylene is first detected at a level of 0.5 ppm at temperatures varying from 175°F to 230°F, and reaches 10 ppm at about 300°F. Both hydrogen and ethylene would be useful temperature indicators, but would not give the essential early detection provided by carbon monoxide.

Methane

88. Methane results are given in Table X. Although this gas is always present in coal, it is of no use as a detector gas because it is not associated with oxidation at temperatures below 104°F. It will be noted from Table X that methane shows no marked increase as temperature rises from 86°F to 212°F. Whereas for some low rank coals, the methane evolved is only about 10 ppm, the higher rank coals give much greater quantities, and samples 12 and 13 give amounts exceeding 3,400 ppm (0.34%) between 122°F and 176°F. This may be important for safety reasons and possible methane drainage schemes, but is of no value for detection of spontaneous heating.

Oxidation Reactions

89. Table XI indicates changes in oxidation mechanism at about 100°F and 160°F. It is at present assumed that between ambient temperatures and 100°F, any oxidation is due to internal molecular rearrangement; from 100°F to 160°F, the oxidation reaction occurs at active centres on the macro-surface; above 160°F, the coal gradually becomes more porous and the reaction takes place on micro-surfaces. The results obtained on the fourteen American coal samples were very similar to those obtained with British coals of the same rank.

CONCLUSIONS

90. The most important factors favouring spontaneous combustion of the Rocky Mountain States coal are:-

(i) Their relatively high oxygen content, as indicated by their sub-bituminous to bituminous rank.

(ii) Remnant coal left in unrecovered pillars inherent in the commonly-practised mining method of room and pillar.

(iii) Coal left on the roof and floor in seams thicker than the commonly-accepted maximum extraction height of 8 ft to 9 ft.

(iv) Use of bleeder ventilation airways that results in unsatisfactory ventilation of pockets of coal in the waste; these pockets can become sites for self-ignition.

(v) Localised extensive fracturing of the coal due to natural and artificial causes, resulting in air leakage through the high surface area of such coal.

91. Nevertheless, reported incidents of spontaneous combustion have been few, which may be due to:-

(i) Well-maintained multiple-entry roads that permit low ventilation pressures within the mines.

(ii) Generally shallow control.

(iii) Low relative humidity of mine airflow, which reduces the heat build-up on coal surfaces arising from condensation of water vapour.

92. The results of PANIC tests on the fourteen samples of Western US coals show that their oxidation characteristics are very similar to European and Australian coals of the same ranks that have been examined in the UK. Tables IX and X show the various levels of carbon monoxide and methane for different temperatures. However, certain Western US coals are slightly more reactive to oxygen than the equivalent British coals. This is illustrated on Plate 27 where samples No 1, 2, 3 and 6 (at 10 ppm of carbon monoxide) are to the left of the corresponding rank British coals, indicating that the build-up of carbon monoxide due to oxidation occurs slightly faster with these US coals than the British coals. This trend, and it is no more than a trend, occurs throughout the range of samples tested and confirms that as with British and European coal generally, carbon monoxide is the most sensitive indicator of the onset of incipient spontaneous combustion. The results also show that there are critical changes in the oxidation reaction at about 100°F and 160°F.

93. It may confidently be concluded, therefore, that the early-warning systems based on the rate of increase of carbon monoxide concentration in the mine air used in Europe could be applied with equal success to Western US deep mines.

CHAPTER IX

CONTROL OF SPONTANEOUS COMBUSTION UNDER WESTERN US CONDITIONS

INTRODUCTION

1. Chapters I to VII have considered spontaneous combustion on a global basis, and Chapter VIII has considered the geological and mining background of the Western US. It is now possible to itemise those specific aspects which are likely to be of particular importance to the Western US. Obviously, much will be a repetition of what has already been discussed, but there are advantages in being able to combine the various aspects into one chapter.

2. Chapter X then considers five simulated examples that have been chosen to illustrate the range of conditions which are likely to be met in the Western US, and explains the precautionary and combat techniques that should be employed.

PRESENT SITUATION

3. There have been few reported serious spontaneous combustion incidents in Western US underground mines. The most serious reported occurrences have been at Somerset mine, Colorado, which had to be sealed off and temporarily closed, and a number of incidents at the Sunnyside mine, Utah and at Hanna No 1 mine, Wyoming.

4. There are many examples of burning outcrops in the Paonia, Hanna, Rock Springs and other areas. These occurrences serve to indicate the inherent possibility of spontaneous combustion, though they have not themselves caused serious disruptions to underground working.

5. In view of the chemical and mineralogical characteristics of the Western US coals (see Chapter VIII), it is perhaps surprising that there have been so few spontaneous combustion problems. In general, the coals are of a type that is prone to self heating and, in other parts of the world, it would be likely that many spontaneous combustion incidents would have developed. However, when current methods of mining Western US coals are considered, along with certain environmental factors, the reasons for the low incidence of spontaneous combustion becomes clearer.

6. To date, the most widely-used method of mining Western US coals is room and pillar, often without pillar extraction. This system provides a multiple entry layout, with many low resistance roadways and low ventilating pressures. High methane emission is not common and ventilating quantities are modest. In general, cover is not heavy and strata pressures are not severe. Crushing is infrequent. All these mining factors tend to minimise the risk of spontaneous combustion.

7. In addition, the humidity of the air in the Western US coalfields is lower than in many coalfields. It is probable that this significantly contributes to the diminution of the spontaneous combustion risk.

FUTURE TRENDS

8. As underground mining activity in the Western US expands, deeper reserves will be mined as shallower reserves are worked out and, in line with the policy for conservation of natural resources, increased percentage extraction will become more significant. The consequence of these factors will be deeper mines, higher strata pressure, more crush, greater methane emission, higher ventilating requirements and higher ventilating pressures. Mining methods that result in areas of complete extraction will be introduced. The overall effect will be to increase significantly the risk of spontaneous combustion.

9. In the future, the most widely used methods of working Western US deep mineable reserves are likely to be:-

(i) room and pillar (with/without pillar extraction),

(ii) longwall single lift (advance/retreat),

(iii) longwall multi lift (advance/retreat, top/bottom slicing),

(iv) longwall caving,

(v) sub-level caving.

10. More intensive methods of mining are likely to include variations of the longwall system, designed to recover roof or floor coal unmineable by conventional methods. These systems are likely to have a high production potential and will involve large capital investments. Unless full regard is paid to the spontaneous combustion risk, both lives and capital will be at risk.

ASSESSMENT OF RISK

11. In establishing a new mine, or extending an existing one, it is necessary to assess the degree of risk of spontaneous combustion and the need for precautionary and combat action. The following are the important factors to be considered.

(i) Previous spontaneous combustion occurrences in the seam being worked.

(ii) The results of laboratory tests on samples of the coal using the paced adiabatic criterion (PANIC). This technique has been described in Chapter III, paragraphs 17 to 19.

(iii) Determination of key coal characteristics and mining factors (RASCAL). This method is described in Appendix "N".

12. It should be emphasised that in no circumstances should a favourable indication from any one factor be considered sufficient to guarantee immunity. It is essentially to err towards caution.

13. The true degree of risk can only be assessed given actual operating experience with a specific system in a specific environment.

SELECTION OF MINING METHOD

14. Traditionally, mining methods have been dependent on balancing the conflicting factors of safe operation against minimum production costs. There is now a third criterion, which is receiving increasing emphasis in the US, that of maximum resource conservation. This will encourage the use of advanced extraction techniques in place of simple room and pillar operations. While the low capital investment required in the latter method may mean that it has lower production costs, it may be objected to as being wasteful of resources.

15. Whatever conservationists may say, a simple, low-percentage recovery system with low spontaneous combustion risk that works may recover more reserves than a sophisticated system with apparently higher percentage recovery if the latter involves regular abandonment of faces or areas due to spontaneous combustion.

VENTILATION CONTROL

16. The various methods of ventilation control will have a significant impact on Western US underground mining methods.

Control of Leakage through Fractured Strata

17. Appendix "P" describes the use of sealants and sealant coatings. Although this is based on UK experience, there is a suitable proprietary sealant "Mandoseal" marketed in the US. The associated equipment may be assembled from readily-available components or purchased direct.

Control of Leakage through Gob Areas

18. It cannot be stressed too highly that in a spontaneous-combustion-risk situation the use of any gob bleeder systems is unacceptable. It is impossible to control the pattern of bleeder air flow and there is inevitably a risk of a heating developing. In practice, it cannot be guaranteed that the flow of air throughout a gob will maintain uniformly a sufficiently low temperature to prevent spontaneous combustion. Whatever the quantity circulated, there will be a probability that interruptions in flow paths by roof falls or differential compaction will cause a limited air flow to pass through some part of the gob where the combination of finely divided coal, critical oxygen supply and heat build-up will lead to the development of a heating. This would then be exacerbated by the main flow of bleeder air.

19. Satisfactory ventilation techniques for controlling methane in gob areas, without bleeder ventilation, have been developed and in a spontaneous-combustion-risk situation there can be little justification for adopting the bleeder system.

20. Other precautions against gob leakage, such as reduction of air penetration at the intake end of longwalls and regular sealing of entries behind the face, are relevant to the Western US situation.

Rate of Advance

21. Only by practical experience will the minimum safe rate of advance be defined. Until this is done, it would be prudent to assume a higher figure than the European and adopt a minimum weekly advance of, say, 20 ft. But this can vary from seam to seam and section to section.

Monitoring and Inspection

22. In any Western US mine where spontaneous combustion has occurred in the past, or a new method of mining with a spontaneous combustion risk is introduced, or the coal characteristics indicate it as liable to spontaneous combustion, continuous monitoring should be adopted. This is a most reliable way of obtaining an early warning of deteriorating circumstances and provides a higher degree of protection than that obtained from individual samples.

23. Equipment is available in Europe that is proven and reliable and has a demonstrated record of success in indicating the early stages of spontaneous combustion.

24. The tests carried out on samples of Western US coal (Chapter VIII, paragraph 74) show that the indications that will arise from spontaneous combustion in Western US situations are comparable to those obtained in Europe and that existing technology is readily transferable.

25. Nevertheless, although this report stresses the importance of air sampling and monitoring, this must not be used as a substitute for regular inspection of the workings. Neither man nor instrument are infallible and they should be considered as being complementary rather than alternatives.

COMBAT TECHNIQUES

26. If precautions fail, then it is necessary to resort to combat. There are three principal methods that can be used, none of which is special to the US. To recapitulate, they consist of digging out, flooding with water and the use of ventilation techniques.

Digging Out

27. The procedure for digging out shallow heatings is described in Chapter VII, paragraphs 16 to 25. The equipment and materials necessary for its application are readily available.

Flooding with Water

28. The technique is described in Chapter VII, paragraphs 26 to 29. Provided the specific conditions of gradient, etc, exist, flooding can be utilised either as a means of quenching the heating directly or as a means of creating an air-tight seal to deprive a heating of oxygen.

Ventilation Techniques

29. The most important combat techniques are those associated with the ventilation system. They involve increasing the rate of advance, minimising air leakage, ventilation pressure control, and sealing-off.

30. The first two employ techniques similar to those used in the precaution mode and do not require further comment here.

31. Several variations of the application of pressure control techniques are described in Chapter VII, paragraph 35. In appropriate circumstances they can be adopted in Western US situations. To apply these techniques safely it is essential that mine managements are familiar with the principles involved, the hazards associated with carbon monoxide and other explosive and toxic gases and the need for systematic and reliable air sampling and analysis.

32. Where managerial "know-how" is adequate, pressure control techniques can be applied, but it must be stressed that incorrect application of these techniques can have the most serious consequences. Mine management should, where possible, discuss the application of these techniques with MESA and industry specialists familiar with their application.

33. In order to provide expert assistance while experience is gained by Western US mine operators, consideration should be given to establishing a working arrangement with, say, an organisation like the UK National Coal Board, who could be asked to provide the assistance of spontaneous combustion control experts to be flown to the site of an emergency.

34. Where other combat action is inappropriate or is ineffective, sealing-off will be necessary. Details of the design, construction and supervision of sealing-off in a combat situation are provided in Chapter VII, paragraphs 36 to 46. The materials and equipment required are readily available.

SELF-RESCUERS

35. Current US legislation already requires the provision of self-rescuers. Introduction of self-contained oxygen self-rescuers could provide additional protection of value in the event of serious spontaneous combustion incidents.

EMERGENCY PLANNING AND TRAINING

36. The emergency planning and training reviewed in Chapter VII, paragraphs 48 to 61 has relevance to the Western US situation. Particular attention is drawn to the need for setting up heating prevention programmes, training of rescue and non-rescue personnel in spontaneous combustion combat procedures and the provision of high level supervision both underground and on the surface of any spontaneous combustion incident.

37. It must also be emphasised that reliable air sampling and gas analysis is essential for the safe combat of spontaneous combustion incidents and that analysis facilities must be available either at individual mines or on a regional basis, capable of being brought quickly to emergency status. The Western US industry should consider how these necessary facilities can best be established.

38. This is administratively straight-forward in countries where the mines are nationalised. In the US it either requires some form of State or Federal control, as is done for certain other emergency services, or a "mutual aid" system established by the major operations.

COAL STOCKS

39. The most significant problem in coal stockpiles is that of size. With mines producing up to 5 million tpa and unit train loading facilities of over 2,000 tph, compacting all stockpiles in 6-ft layers becomes increasingly onerous.

40. The object, therefore, should be to make sure that the majority of the stockpiles are "turned round" in a time which prevents the development of spontaneous combustion and minimises the need for compaction.

41. If it is necessary to maintain long-term strategic stockpiles, these should be treated specially by a combination of compaction and surface sealing.

CHAPTER X

EXAMPLES OF PRECAUTIONARY AND COMBAT TECHNIQUES IN WESTERN US CONDITIONS

INTRODUCTION

1. It has already been stressed that it is vital to take spontaneous combustion into account when deciding on mining method and practices, both in the planning and operating phases.

2. Previous chapters have described precautionary and combat techniques and identified those which appear most likely to be relevant to the Western US.

3. This chapter is intended to be more specific in that it examines five mining methods that are in use, or contemplated for introduction, in the Western US. It is emphasised that the inclusion of a method of mining does not necessarily imply its endorsement. The examples have been selected specifically to illustrate spontaneous combustion prevention and control in Western US conditions.

4. In each case the precautionary and combat procedures are specified for the circumstances described; these, with suitable modifications, can be applied to a range of mining environments.

5. To assist the reader who may only be concerned with one method, each example is set out in full, even though many techniques are common to all the examples.

6. The examples provide a basis that will enable codes of practice for spontaneous combustion prevention and combat to be evolved for individual mining operations.

EXAMPLE 1 - LONGWALL

7. This is a simulated example of a retreating longwall operation in a multi-seam situation. The single-entry layout does not involve bleeder ventilation of the gob, and methane is controlled by drainage and a modified return-entry ventilation system, known as "back return" (see Plates 28 and 29).

(i) Mining Factors

Cover	1,200 ft
Gradients	1 in 6 along the face dipping to the return
	1 in 10 dipping along the line of retreat
Seam thickness	8 ft
Entry dimensions	14 ft x 8 ft
Mined thickness	8 ft

Roof strata	Shale
Floor strata	Shale
Strata temperature	64^0 F
Faulting	None
Rider seams	Yes
Panel dimensions	420 ft x 2,000 ft
Section development	2 single entries
Longwall length	400 ft
Longwall machine	Shearer
Longwall supports	6-leg chocks
Fire barrier	Yes
Caving characteristics	Well fragmented
Coal losses	Negligible
Crush	Yes, on entries and "back return" pillar
Planned tons/shift	860
Planned face advance/ shift	7 ft
Shifts/week	10

(ii) Ventilation Factors

Methane emission	170 ft^3/min 95 ft^3/ton
Methane drainage	Yes, in return, upholes and downholes at 45-ft intervals
Average methane percentage at the entrance to the return entry	0.34%
Air quantity	22,500 ft^3/min
Face velocity	370 ft/min (average)
Airflow pattern	Single intake. Single return

Bleeder ventilation	No
Air humidity	40%

(iii) Coal Characteristics

Rank	Weakly coking
Oxygen	8.5%
Moisture	3.0%
Sulphur (inorganic)	0.7%
Ash	6.0%
Calorific value	12,500 Btu/lb
Hardness	Medium hard
RASCAL Index	15 (at risk)

Precautionary Techniques

Planning Phase

8. A single-entry layout is illustrated on Plate 28, which reduces the risk of ribside heatings and leakage around crosscut seals normally associated with multiple entries.

9. The panel should be ventilated without the use of aircrossings, avoiding a possible source of heating and providing a separate ventilating circuit to the extent that no two faces share the main return airway. This has the effect of keeping ventilation pressures and velocities to the minimum, reducing the number of connection roads through pillars and, in the event of a serious heating, allowing the problem to be contained by sealing off the affected face without interfering with adjacent faces.

10. The face length should be such that a rate of advance is achievable that enables the "critical velocity zone" (see Chapter VI) in the gob to move fast enough to minimise the risk of a gob heating developing.

11. No bleeder airways should be used behind the face. They would be likely to induce heating in the gob area. As an alternative to bleeder airways for use in gassy conditions, where a build-up of methane is likely to occur at the return end of the face, a "back return" system (see Plate 29) would induce the flow of methane away from the face line (Ref 132). The methane drainage range in the return airway should be broken at intervals coinciding with the building of seals, and a valve should be inserted in advance of the next seal to be built, so that, if necessary, suction can be applied to drain-off surplus gas accumulating behind the seal; also methane drainage holes should be drilled in the roof and/or floor and coupled to the methane range. Since the pressure differential between the intake and point (A) is less than that between the intake and point (B), gob gases would tend to flow towards (B) and thereby reduce pollution at (A).

12. The face starting line should be a single entry of sufficient dimensions to install the face equipment. This single entry would reduce the risk of heatings at a vulnerable point, compared with multiple-entry drivages.

13. The face should be planned to start production and have an uninterrupted run, without interference by holidays, etc, in order to achieve early consolidation of the gob area outbye the starting line. Solid seals (see Plates 29 and 30(A)), let into the rib, should be erected at each end of the longwall starting line, as soon as the face has moved away, to minimise possible airflow through this vulnerable area. To reduce delays to face advance during start-up, equipment should be of proven design wherever possible and personnel should be trained to a high standard.

14. The final approach of the longwall to its finishing line should be unhindered and at an increased rate of advance. Salvaging of equipment should be scheduled to proceed rapidly in order that the permanent seals can be constructed without delay.

15. The replacement longwall development should be timed to receive the transferred face equipment from the previous production face as soon as it ceases production in order to facilitate rapid sealing off of the panel.

16. A substantial barrier pillar should be left after every third face. This will facilitate erection of seals in ground not likely to crush, and will limit the size of the interconnected gob, so reducing the heating risk arising from breathing of the gob atmosphere following changes in barometric pressure.

17. Preparatory seals should be planned (see Plate 30 (B)); these will become permanent seals when the district has been salvaged. A light seal should be erected at the entrance to the entries (see Plate 30 (C)) to prevent access to a potentially irrespirable atmosphere. The distance between (B) and (C) should be at least 15 ft to 30 ft to allow for the construction of a balance chamber should this become necessary.

Operating Phase

18. Seals should be built behind the intake/face junction at 200-ft-maximum intervals to prevent leakage through the unconsolidated gob (see Plate 30 (D)). Seals should also be built in the returns at intervals to control leakage and also to facilitate drainage of methane from the gob (see Plate 30 (E)).

19. A brattice should be erected from the intake entries for 25 ft along the face (see Plate 30 (F)). This would deflect the intake air and reduce the tendency of airflow to enter the waste at this position.

20. The shearer should not be unnecessarily parked at the intake end of the face for lengthy periods. Such an obstruction would increase the tendency for air to be diverted into the gob.

21. Preparatory sites for seals should be constructed for use in emergency and to facilitate quick closure of the section on completion of mining at the points indicated at (B) on Plate 30. They should be sited within the main entry pillar at a sufficient distance from the face finishing line to minimise damage by strata movement and far enough from the main entry to allow the construction of a pressure chamber if required, and, if possible, in a section of the coal seam least liable to spontaneous combustion. Materials for seal construction should be stored at convenient points on the outbye side of the prepared sites.

22. Regulators should be located as far outbye as practicable, and should be of the double airlock type with all the regulated air flowing through a duct (see Chapter VII, paragraph 35 (i)).

23. Separation doors should be constructed as double airlocks and enough distance allowed between doors to accommodate material trains. Fractured coal and strata in the vicinity of doors and aircrossings should be surface coated and/or injected.

24. Bulky items of equipment and stockpiles of materials should be located out of the main airflow to prevent diversion of air from the normal ventilation course.

25. Firefighting equipment should be installed and maintained in intake and return entries and the main airways.

26. Continuous monitoring of mine air and methane drainage should be adopted, where necessary, to provide routine mine air samples and warning of potentially dangerous conditions. A check sample at each of the sampling points (see Plate 30 (G)) should be taken at weekly intervals by manual means. At monthly intervals a standard calibrating carbon monoxide mixture should be fed into the mine air monitoring system at each sampling point to provide a check for pipe leakage.

27. The methane drainage installation should be properly instrumented and controlled and over-drainage avoided to minimise the induction of oxygen into the gob.

28. Routine inspection of the section should be carried out (see Chapter VI, paragraphs 90 to 92).

29. The procedure described in Chapter VII, paragraphs 48 et seq, should be followed in the event of a heating being detected.

Combating a Spontaneous Combustion Heating

30. Three sites of heatings are possible:-

(i) in a rib or pillar edge in the entry system (the rate of development of this type of heating may be extremely rapid),

(ii) in the gob or entries behind the active longwall,

(iii) in gob or entries of a previously worked adjacent panel.

Heatings at any of these locations will be indicated by a rise in carbon monoxide content at the sampling points located at the outbye end of the face return entries and/or detected by physical observation of smell, haze or condensation.

Rib or Pillar Heatings

31. Method of combat:-

(i) If the heating is accessible and shallow enough, then removal of the heated coal can be carried out (see Chapter VII). Before making a decision to dig out, the suspected area should be probed with drillholes to verify the position and depth of the heating.

(ii) The roadway surface may be coated with a sealant (see Chapter VII). This method may be effective on its own or may be used as a temporary measure whilst digging out is progressing or strata injection is taking place.

Heating in Gob Behind the Active Longwall

32. This type of heating is indicated by an increase in carbon monoxide content at the return sampling point and high carbon monoxide percentages at the return end of the face while the intake sample remains clear.

33. Method of combat:-

(i) The intake and return entry seals (see Plates 30 (D) and (E)) should be reinforced.

(ii) If possible, the rate of advance should be increased to move the zone of critical airflow and/or bury the area of active heating (see Chapter VI and Plate 11).

(iii) An auxiliary fan and ducting (see Plate 30 (H)) should be installed through the return entry seal immediately behind the face and the pressure behind the seal increased until the carbon monoxide emission is reduced to an acceptable level. The duct system will require extension as the face retreats and the ducting should be broken after retreating 300 ft. Thereafter the ducting should comprise a short length through the most recently-erected seal. At monthly intervals the fan should be switched off and the sampling point monitored until it is apparent that the heating activity remains at an acceptable level.

Heating in Adjacent Panel

34. A heating in this location is indicated by an increase in carbon monoxide at the sampling point (see Plate 30 (G)). In order to determine the location of the heating, samples should be taken at points along the return entry.

35. If the samples fail to show a reduction anywhere along the entry and a sample at the intake end of the face is normal, this indicates that the spontaneous combustion is in the working longwall gob and should be dealt with as described in paragraph 33.

36. If the carbon monoxide samples taken at intervals along the entry drop to a normal level, a check should be made from that point outbye to establish if there is a ribside heating. This may be located by careful inspection for signs of heat, sweating or smell, and should be dealt with as described in paragraph 31.

37. If no ribside heating can be located, the gob side of the return entry should be examined to determine the point of the carbon monoxide emission. This location should then be surface-coated or injected.

38. Method of combat:-

(i) The existing seals at No 1 return entries (see Plate 28 (I)) should be improved by spraying/plastering and injection as it is likely that this is the point at which oxygen is gaining access to the heating. The pressure causing the flow through the old gob must be reduced. This may be achieved by constructing a static pressure chamber at the site of the outbye seals of No 1 panel. The pressure reduction in this chamber should be adjusted until the carbon monoxide content, as indicated at the No 2 panel sampling point (see Plate 30 (G)), is marginally above normal. This would avoid the possibility of the air flow reversing across the heating.

(ii) If these measures do not result in a reduction in carbon monoxide at the control sampling point, a flow-through type pressure chamber (see Plate 30 (J)) should be installed in the No 2 return. This additional chamber should extend over a length of roadway somewhat greater than that over which carbon monoxide emission is taking place. This measure is a last resort and, if unsuccessful, it may be necessary to seal off the district.

EXAMPLE 2 - ROOM AND PILLAR

39. This is a simulated example of a continuous miner room and pillar operation. Conditions are those anticipated for a mining method using continuous miners for development and pillar extraction in an 11-ft seam.

(i) Mining Factors

Cover	400 ft
Seam gradient	2^0
Seam thickness	11 ft
Entry height	11 ft
Mined thickness	11 ft
Roof strata	Shale/sandstone
Floor strata	Sandstone
Strata temperature	75^0F
Faulting	None
Rider seams	None
Panel dimensions	3,000 ft x 850 ft
Section development	3 entry, 20 ft x 11 ft on 196-ft centres
Crosscuts	150-ft centres x 20 ft wide
Fire barrier	130 ft wide

Caving characteristics	Blocky
Coal losses	In caved gob and fenders estimated 20%
Crush	Yes, in pillars and stumps
Planned section, tons/shift	500
Shifts/week	10

(ii) Ventilation Factors

Methane emission	208 ft^3/min 200 ft^3/ton
Methane drainage	No
Section air quantity	80,000 ft^3/min
Face velocity	180 ft/min
Airflow pattern	Two intakes. Single return
Bleeder ventilation	No
Air humidity	25%

(iii) Coal Characteristics

Rank	High volatile - bituminous
Oxygen	10.7%
Moisture	4.0%
Sulphur (inorganic)	0.4%
Ash	6.0%
Calorific value	13,500 Btu/lb
Hardness	Medium hard
RASCAL Index	24.4 (high risk)

Precautionary Techniques

40. The risk of heating is considerable at crosscut seals and in the gob. Because of the mobility of equipment, losses resulting from gob heatings may be small, but crosscut heatings at the outbye end of entries, where the differential air pressure is highest, could lead to the loss of substantial reserves as well as equipment.

Planning Phase

41. A triple-entry drivage system is illustrated on Plate 31. To minimise the risk of roadside heatings, twin or single entries are desirable, and every effort should be made to obtain authorisation for this system. Where multiple entries are driven, the crosscuts should be at a maximum distance apart consistent with good mining practice. This will reduce the total area of exposed airway surfaces and the number of junctions. It will also reduce potential leakage around the crosscut seals.

42. The panel should be ventilated with the minimum use of aircrossings and doors, thus reducing the number of possible sources of heating. This will provide separate ventilating circuits, which keep ventilation pressures and velocities to the minimum, reduce the number of connecting roads through pillars and, in the event of a serious heating, allow the problem to be contained by sealing off the affected area without interfering with adjacent areas.

43. The panel width should be such that a rate of advance is achievable that enables the "critical velocity zone" (see Chapter VI) in the gob to move fast enough to minimise the risk of a gob heating developing.

44. No bleeder airways should be utilised. They would be likely to induce spontaneous heatings in the depillared area.

45. The panel should be sub-divided into smaller sections and a 30-ft fire barrier should be left between sub-sections to further isolate potentially hazardous zones.

46. The panel should be planned to start production and have an uninterrupted run, without interference by holidays, etc, in order to achieve early consolidation of the gob area outbye the starting line. It is possible that the roof strata will "hang up" and may not cave fully until the face has retreated a considerable distance.

47. The final approach of the pillar extraction line to its finishing line should be unhindered and at an increased rate of advance. Salvaging of equipment should be scheduled to proceed rapidly in order that the permanent seals can be constructed without delay.

48. The replacement panel development should be timed to receive the transferred section equipment from the previous production section as it ceases production in order to facilitate rapid sealing off of the panel.

Operating Phase

49. Seals should be built in the panel intake entries at 130-ft-maximum intervals to reduce leakage through the unconsolidated gob (see Plate 32 (A)). Similar seals should be built in the returns at 130-ft intervals to control leakage. These seals will isolate each sub-section as soon as coal recovery is completed.

50. Preparatory sites for seals should be constructed for use in emergency and to facilitate quick closure of the section on completion of mining at the points indicated at (B) on Plate 32. They should be sited within the main entry pillar, at a sufficient distance from the depillaring finishing line to minimise damage by strata movement. Materials for seal construction should be stored at convenient points on the outbye side of the prepared sites.

51. Regulators should be located as far outbye as practicable, and should be of the double airlock type with all the regulated air flowing through a duct and the doors fully closed.

52. Separation doors should be constructed as double airlocks and sited in entries with a reduced number of crosscuts to allow sufficient distance between doors to accommodate materials trains. Fractured coal and strata in the vicinity of doors should be surface coated and/or injected.

53. Bulky items of equipment and stockpiles of materials should be located out of the main airflow to prevent diversion of air from the normal ventilation course.

54. Firefighting equipment should be installed and maintained in intake and return entries and the main airways.

55. Continuous monitoring of mine air should be adopted, where necessary, to provide routine mine air samples and warning of potentially dangerous conditions. A check sample at each of the sampling points (see Plate 32 (C)) should be taken at weekly intervals by manual means. At monthly intervals a standard calibrating carbon monoxide mixture should be fed into the mine air monitoring system at each sampling point to provide a check for pipe leakage.

56. Routine inspection of the section should be carried out (see Chapter VI, paragraphs 90 to 92).

57. The procedure described in Chapter VII, paragraph 48 et seq, should be followed in the event of a heating being detected.

Combating a Spontaneous Combustion Heating

58. Four sites of heatings are possible:-

(i) in a rib or pillar edge in the entry system (the rate of development of this type of heating may be extremely rapid),

(ii) in the gob or entries behind the active face workings,

(iii) in the gob or entries of a sealed sub-section,

(iv) in the gob or entries of a previously worked adjacent panel.

Heatings at any of these locations will be indicated by a rise in carbon monoxide content at sampling points located at the outbye end of face return entries and/or detected by physical observation of smell, haze or condensation.

Rib or Pillar Heatings

59. This type of heating is likely to occur around seals between intake and return entries. The risk is greater further outbye because of higher pressure differentials and because the potential loss of reserves is greater.

60. Method of combat:-

(i) If the heating is accessible and shallow enough, then removal of the heated coal can be carried out (see Chapter VII). Before making a decision to dig out, the suspected area should be probed with drillholes to verify the position and depth of the heating.

(ii) The roadway surface may be coated with a sealant (see Chapter VII). This method may be effective on its own or may be used as a temporary measure whilst digging out is progressing or strata injection is taking place.

Heating in Gob of a Working Sub-Section

61. This type of heating (see Plate 32 (D)) is detected by an increase in carbon monoxide content at the return sampling point and the appearance of relatively high carbon monoxide percentages at the return end of the gob area.

62. Method of combat:-

(i) Remedial action is to speed up the rate of extraction in order to bury the active heating zone (Chapter VI).

(ii) If this does not have the desired effect, the face equipment should be withdrawn outbye of the affected area and seals (see Plate 32 (D1)) should be erected at a location to isolate the heating but keep coal reserve losses to the minimum.

Heating in a Sealed-Off Sub-Section

63. This type of heating (see Plate 32 (E)) is detected by a rise in carbon monoxide at the sampling point and high carbon monoxide samples at the return seal (see Plate 32 (A)) to the sub-section.

64. Method of combat:-

(i) The seals (see Plate 32 (A)) must be faced with a sealant and the strata around the seals injected and, if necessary, a pressure chamber erected at the return seal.

Heating in Adjacent Panel

65. A heating in this location is indicated by an increase in carbon monoxide at the sampling point (see Plate 32 (C)). In order to determine the location of the heating, samples should be taken at points along the return entries.

66. If the carbon monoxide samples taken at intervals along the entry drop to a normal level, a check should be made from that point outbye to establish if there is a ribside heating. This may be located by careful inspection for signs of heat, sweating or smell, and should be dealt with as described in paragraph 60.

67. Method of combat:-

(i) The existing seals at No 1 Panel entries (see Plate 32 (F)) should be improved by spraying/plastering and injection as it is likely that this is the point at which oxygen is gaining access to the heating. The pressure causing the flow through the old gob must be reduced. This may be achieved by constructing a static pressure chamber (see Plate 32 (H)) at the site of the outbye seals of No 1 panel. The pressure in this chamber should be adjusted until the carbon monoxide content, as indicated at the No 2 panel sampling point, is marginally above normal. This would avoid the possibility of the air flow reversing across the heating.

(ii) If these measures do not result in a reduction in carbon monoxide at the control sampling point, a flow-through type pressure chamber (see Plate 32 (G)) should be installed in the No 2 return. This additional chamber should extend over a length of roadway somewhat greater than that over which carbon monoxide emission is taking place. This measure is a last resort and, if unsuccessful, it may be necessary to seal off the district.

EXAMPLE 3 - SUB-LEVEL CAVING BY PILLAR EXTRACTION

68. This is a simulated example for sub-level caving by pillar extraction. Conditions are based on those anticipated for a mine near Somerset, Colorado, working the B seam. Ref Contract No J0265009 - Design and Feasibility Study of a Method for Underground Mining of Thick Seam Western Coal.

(i) Mining Factors

Cover	500 ft to 2,000 ft
Seam gradient	4^0
Seam thickness	22 ft
Entry height	8 ft
Mined thickness	22 ft
Roof strata	Shale/sandstone
Floor strata	Shale
Strata temperature	75^0F
Faulting	None
Rider seams	None
Panel dimensions	4,750 ft x 510 ft
Section development	2 entry, 20 ft x 8 ft on 40-ft centres
Crosscuts	80-ft centres x 18 ft wide
Rooms	400 ft long

Pillar size	20 ft x 62 ft
Fire barrier	50 ft wide
Caving characteristics	Blocky
Coal losses	In caved gob and fenders estimated 30%
Crush	Yes, in pillars and fenders
Planned section, tons/shift	530
Planned face advance/ shift	3 ft
Shifts/week	10

(ii) <u>Ventilation Factors</u>

Methane emission	130 ft^3/min 115 ft^3/ton
Methane drainage	No
Average methane percentage at the entrance to the return entry	0.26%
Section air quantity	100,000 ft^3/min
Face velocity	120 ft/min
Airflow pattern	Single intake. Single return
Bleeder ventilation	No
Air humidity	65%

(iii) <u>Coal Characteristics</u>

Rank	High volatile B bituminous
Oxygen	11.4%
Moisture	5.0%
Sulphur (inorganic)	0.5%
Ash	7.5%

Calorific value	13,000 Btu/lb
Hardness	Medium hard
RASCAL Index	31.9 (high risk)

Precautionary Techniques

69. There is considerable risk of heatings associated with crosscut seals and within the gob area. Because of equipment mobility, the loss arising from a gob heating is small compared with a longwall situation, but a heating at an outbye crosscut seal could result in the loss of the panel.

Planning Phase

70. A twin-entry drivage system is illustrated on Plate 33 that reduces the risk of roadside heatings compared with multiple entries. Crosscuts should be at a maximum distance apart consistent with good mining practice. This will reduce the total area of exposed airway surfaces and sloughing at junctions. It will also reduce the potential leakage around the crosscut seals.

71. The panel should be ventilated with the minimum number of air crossings and doors, thus reducing the number of possible sources of heating. This will provide an independent ventilating circuit for each side of the mine, reduce the number of air crossings and connecting roads through pillars and, in the event of a serious heating, allow the problem to be contained by sealing off the affected area without interfering with adjacent areas.

72. The panel width should be such that a rate of advance is achievable that enables the "critical velocity zone" (see Chapter VI) in the gob to move fast enough to minimise the risk of a gob heating developing.

73. No bleeder airways should be utilised behind the face. They would be likely to induce spontaneous heatings in the gob area.

74. The workings should be planned to start production and have an uninterrupted run, without interference by holidays, etc, in order to achieve early consolidation of the gob area outbye the starting line. It is possible that the roof strata will "hang up" and may not cave fully until the workings have retreated a considerable distance. To reduce delays to regular advance during start-up, equipment should be of proven design wherever possible and personnel should be trained to a high standard.

75. The final approach of the workings to the finishing line should be unhindered and at an increased rate of advance where practicable. Salvaging of equipment should be scheduled to proceed rapidly in order that the permanent seals can be constructed without delay.

76. The replacement development should be timed to receive the transferred face equipment from the previous production panel as soon as it ceases production in order to facilitate rapid sealing off of the panel.

77. A substantial barrier pillar should be left after every third face. This will facilitate erection of seals in ground not likely to crush, and will limit the size of the interconnected gob, so reducing the heating risk arising from breathing of the gob atmosphere following changes in barometric pressure.

Operating Phase

78. Materials, as described in Chapter VI, should be kept within 300 ft of the working place to facilitate sealing off in the vicinity of the working place in the event of a relatively minor incident.

79. Outbye preparatory sites for seals (see Plate 34 (A)) should be constructed for use in emergency and to facilitate quick closure of the section on completion of mining. They should be sited within the main entry pillar, at a sufficient distance from the face finishing line to minimise damage by strata movement, and if possible in a section of the coal seam least liable to spontaneous combustion. Materials for seal construction should be stored at convenient points on the outbye side of the prepared site.

80. Regulators should be located as far outbye as practicable, and should be of the double airlock type with all the regulated air flowing through a duct and the doors fully closed.

81. Separation doors should be constructed as double airlocks and sited in entries with a reduced number of crosscuts to allow sufficient distance between doors to accommodate materials trains. Fractured coal and strata in the vicinity of doors should be surface coated and/or injected.

82. Bulky items of equipment and stockpiles of materials should be located out of the main airflow to prevent diversion of air from the normal ventilation course.

83. Firefighting equipment should be installed and maintained in intake and return entries and the main airways.

84. Continuous monitoring of mine air should be adopted to provide routine mine air samples and warning of potentially dangerous conditions. A check sample at each of the sampling points (see Plate 34 (B)) should be taken at weekly intervals by manual means. At monthly intervals a standard calibrating carbon monoxide mixture should be fed into the mine air monitoring system at each sampling point to provide a check for pipe leakage.

85. Routine inspection of the section should be carried out (see Chapter VI, paragraphs 90 to 92).

86. The procedure described in Chapter VII, paragraphs 48 et seq, should be followed in the event of a heating being detected.

Combating a Spontaneous Combustion Heating

87. Three sites of heatings are possible:-

(i) in a rib or pillar edge in the entry system (the rate of development of this type of heating may be extremely rapid),

(ii) in the gob or entries behind the active face workings,

(iii) in the gob or entries of a previously worked adjacent panel.

Heatings at any of these locations will be indicated by a rise in carbon monoxide content at sampling points located at the outbye end of face return entries (see Plate 34 (B)) and/or detected by physical observation of smell, haze or condensation.

Rib or Pillar Heatings

88. This type of heating is likely to occur around the site of the crosscut seals due to intake/return pressure differentials. The risk is greater further outbye because of higher pressure differentials and because the potential loss of reserves is greater.

89. Method of combat:-

(i) If the heating is accessible and shallow enough, then removal of the heated coal can be carried out (see Chapter VII). Before making a decision to dig out, the suspected area should be probed with drillholes to verify the position and depth of the heating.

90. The roadway surface may be coated with a sealant (see Chapter VII). This method may be effective on its own or may be used as a temporary measure whilst digging out is progressing or strata injection is taking place.

Heating in Gob Behind
Working Section

91. This type of heating is detected by an increase in carbon monoxide content at the return sampling point and the appearance of relatively high carbon monoxide percentages at the return end of the face.

92. Method of combat:-

(i) Investigations should be made to ensure that the heating is not associated with the adjacent gob or pillar as described in paragraph 93.

(ii) If possible, the rate of advance should be increased to move the zone of critical airflow and/or bury the area of active heating (see Chapter VI and Plate 11).

(iii) If this does not have the desired effect, the face equipment should be withdrawn outbye of the affected area and seals (see Plate 34 (C)) should be erected at a location to isolate the heating but keep coal reserve losses to the minimum.

Heating in Adjacent Panel

93. A heating in this location can arise in one of two ways. The first is air leakage resulting from the ventilation pressure difference between the active workings and the adjacent abandoned gob. The products of combustion may appear at the face of the main seals (see Plate 34 (D)) of the abandoned panel.

94. The second is caused by "breathing" as a result of barometric fluctuations. In this case the carbon monoxide may appear in the gob at the active workings and may ultimately be detected at the sampling point or it may appear, as before, at the main seals of the abandoned gob.

95. Method of combat:-

(i) If the heating products appear at the face of the seals of the abandoned gob, the seals should be improved by sealant spraying and injection. If this does not eliminate the heating activity, it will be necessary either to construct a balance chamber to minimise the ventilation pressure differences, or to construct a buffer zone at the site of these seals to accommodate barometric fluctuation.

(ii) Should the products appear at the active district sampling point via the gob, then breathing is occurring across or through the barrier pillar under the influence of barometric fluctuations. In these circumstances the rate of advance of the active working should be increased in an attempt to bury the heated material and restrict the oxygen supply. Should this be unsuccessful and the heating activity continues to rise, the two main entries will have to be sealed off inbye. Production should re-commence leaving a wider barrier pillar against both the adjacent gob and the newly-abandoned workings.

EXAMPLE 4 - LONGWALL CAVING

96. This is a simulated example of a longwall caving operation. Conditions assumed are similar to those anticipated for a mine near Paonia, Colorado, where an application of the longwall caving method is being appraised. Ref USBM Report OFR 1339(1)-77 and 133a(2)-77.

(i) Mining Factors

Cover	1,000 ft
Seam gradient	4^0
Seam thickness	22 ft
Sheared thickness	10 ft
Mined thickness	22 ft
Roof strata	Shale/sandstone
Floor strata	Shale
Strata temperature	62^0F
Faulting	None
Rider seams	None

Panel dimensions	600 ft x 3,000 ft
Section development	3 entry, 10 ft x 16 ft
Longwall length	408 ft
Longwall conveyors	Heavy-duty, armoured
Longwall machine	Shearer
Longwall supports	Modified shields
Caving characteristics	Blocky
Coal losses	In caved gob estimated 20%
Crush	Yes, in chain pillars, main entries and gob
Planned tons/shift	2,500
Planned face advance/ shift	7½ ft
Shifts/week	10
Output/week	25,000 tons

(ii) Ventilation Factors

Methane emission	600 ft^3/min 115 ft^3/ton
Methane drainage	Yes - upholes and gob
Drained methane	200 ft^3/min
Average methane percentage in general body	0.5%
Section air quantity	80,000 ft^3/min
Face velocity	700 ft/min
Airflow pattern	Two intakes, one low velocity belt entry, three returns
Bleeder ventilation	No
Air humidity	45%

(iii) Coal Characteristics

Rank	High volatile B bituminous
Oxygen	10.8%
Moisture	5.0%
Sulphur (inorganic)	0.5%
Ash	7.5%
Calorific value	13,000 Btu/lb
Hardness	Friable
RASCAL Index	25.5 (high risk)

Precautionary Techniques

Planning Phase

97. Though the system is illustrated with triple-entry drivages (see Plate 35), to minimise the risk of roadside heatings, and to make each panel a self-contained unit, fire-barriers and single entries are desirable and every effort should be made to obtain authorisation for this system. Where multiple entries are driven, the crosscuts should be at a maximum distance apart consistent with good mining practice. This will reduce the total area of exposed airway surfaces and sloughing at junctions. It will also reduce the potential leakage around the crosscut seals.

98. The panel should be ventilated with the minimum number of aircrossings and doors, thus reducing the number of possible sources of heating, and be provided with a separate ventilating circuit so that no two faces share the main return airway. This condition can be met by one face producing the complete output of the mine or by other faces being developed off separate sets of main entries. This has the effect of keeping ventilation pressures and velocities to the minimum, reducing connection roads through pillars and, in the event of a serious heating, allowing the problem to be contained by sealing off the affected face without interfering with adjacent faces.

99. The face length should be such that a rate of advance is achievable that enables the "critical velocity zone" (see Chapter VI) in the gob to move fast enough to minimise the risk of a gob heating developing.

100. No bleeder airways should be used behind the face. They would be likely to induce heating in the gob area.

101. The face starting line should be a single entry of sufficient dimensions to install the face equipment. This single entry would reduce the risk of heatings at a vulnerable point, compared with multiple-entry drivages.

102. The face should be planned to start production and have an uninterrupted run, without interference by holidays, etc, in order to achieve early consolidation of the gob area outbye the starting line. To reduce delays to face advance during start-up, equipment should be of proven design wherever possible and personnel should be trained to a high standard. It is possible the top coal will "hang up" and may not cave fully until the face has retreated about 400 ft. Solid seals (see Plate 36(A)), let into the rib, should be erected at each end of the longwall starting line, as soon as the face has moved away, to minimise possible airflow through this vunerable area.

103. The final approach of the longwall to its finishing line should be unhindered and at an increased rate of advance. Salvaging of equipment should be scheduled to proceed rapidly in order that the permanent seals can be constructed without delay.

104. The replacement longwall development should be timed to receive the transferred face equipment from the previous production face as soon as it ceases production in order to facilitate rapid sealing off of the panel.

105. A substantial barrier pillar should be left after every third face. This will facilitate erection of seals in ground not likely to crush, and will limit the size of the interconnected gob, so reducing the heating risk arising from breathing of the gob atmosphere following changes in barometric pressure.

106. Return airways should be connected to intakes at intervals not exceeding 3,000 ft in order to provide access to fresh air.

107. Preparatory seals should be planned (see Plate 36 (B)); these will become permanent seals when the district has been salvaged. A light seal should be erected at the entrance to the entries (see Plate 36 (C)) to prevent access to a potentially irrespirable atmosphere. The distance between (B) and (C) should be at least 15 ft to 30 ft to allow for the construction of a balance chamber should this become necessary.

Operating Phase

108. Seals (see Plate 36 (D)) should be built behind the intake/face junction at 150-ft-maximum intervals to minimise leakage through the unconsolidated gob. Seals should also be built in the returns at similar intervals to control leakage and also to facilitate drainage of methane from the gob, should this be necessary.

109. A brattice should be erected from the intake entries for 25 ft along the face (see Plate 36 (E)). This would deflect the intake air and reduce the tendency of airflow to enter the waste at this position.

110. The power loader should not be unnecessarily parked at the intake end of the face for lengthy periods. Such an obstruction would increase the tendency for air to be diverted into the gob.

111. Preparatory sites for seals should be constructed for use in emergency and to facilitate quick closure of the section on completion of mining, at the points indicated at (B) on Plate 36. They should be sited within the main entry pillar at a sufficient distance from the face finishing line to minimise damage by strata movement and far enough away from the main entry to allow the construction of a

pressure chamber if required, and, if possible, in a section of the coal seam least liable to spontaneous combustion. Materials for seal construction should be stored at convenient points on the outbye side of the prepared sites.

112. Regulators should be located as far outbye as practicable, and should be of the double airlock type with all the regulated air flowing through a duct and the doors fully closed.

113. Separation doors should be constructed as double airlocks and enough distance allowed between doors to accommodate materials trains (see Plate 36 (F)). Fractured coal and strata in the vicinity of doors and aircrossing should be surface coated and/or injected.

114. Bulky items of equipment and stockpiles of materials should be located out of the main airflow to prevent diversion of air from the normal ventilation course.

115. Firefighting equipment should be installed and maintained in intake and return entries and the main airways.

116. Continuous monitoring of mine air and methane drainage should be adopted to provide routine mine air samples and warning of potentially dangerous conditions. A check sample at each of the sampling points (see Plate 36 (G)) should be taken at weekly intervals by manual means. At monthly intervals a standard calibrating carbon monoxide mixture should be fed into the mine air monitoring system at each sampling point to provide a check for pipe leakage.

117. The methane drainage installation should be properly instrumented and controlled and over-drainage avoided to minimise the induction of oxygen into the gob.

118. Routine inspection of the section should be carried out (see Chapter VI, paragraphs 90 to 92).

119. The procedure laid down in Chapter VII, paragraphs 48 et seq, should be followed in the event of a heating being detected.

Combating a Spontaneous Combustion Heating

120. Three sites of heatings are possible:-

(i) in a rib or pillar edge in the entry system (the rate of development of this type of heating may be extremely rapid),

(ii) in the gob or entries behind the active longwall,

(iii) in gob or entries of a previously-worked adjacent panel.

Heatings at any of these locations will be indicated by a rise in carbon monoxide content at the sampling point located at the outbye end of the face return entries and/or detected by physical observation of smell, haze or condensation.

Rib or Pillar Heatings

121. Method of combat:-

(i) If the heating is accessible and shallow enough, then removal of the heated coal can be carried out (see Chapter VII). Before making a decision to dig out, the suspected area should be probed with drillholes to verify the position and depth of the heating.

(ii) The roadway surface may be coated with a sealant (see Chapter VII). This method may be effective on its own or may be used as a temporary measure whilst digging out is progressing or strata injection is taking place.

Heating in Gob Behind the Active Longwall

122. This type of heating is indicated by an increase in carbon monoxide content at the return sampling point and high carbon monoxide percentages at the return end of the face while the intake sample remains clear.

123. Method of combat:-

(i) The intake and return entry seals (see Plate 36 (D)) should be reinforced.

(ii) If possible, the rate of advance should be increased to move the zone of critical airflow and/or bury the area of active heating (see Chapter VI and Plate 11).

(iii) An auxiliary fan and ducting (see Plate 36 (H)) should be installed through a return entry seal immediately behind the face and the pressure behind the seal increased until the carbon monoxide emission is reduced to an acceptable level. The duct system will require extension as the face retreats and the ducting should be broken after retreating 300 ft. Thereafter the ducting should comprise a short length through the most recently erected seal. At monthly invervals the fan should be switched off and the sampling point monitored until it is apparent that the heating activity remains at an acceptable level.

Heating in Adjacent Panel

124. A heating in this location is indicated by an increase in carbon monoxide at the sampling point (see Plate 36 (G)). In order to determine the location of the heating, samples should be taken at points along the return entries.

125. If the samples fail to show a reduction anywhere along the entries and a sample at the intake end of the face is normal, this indicates that the spontaneous combustion is in the working longwall gob and should be dealt with as described in paragraph 123.

126. If the carbon monoxide samples taken at intervals along the entries drop to a normal level, a check should be made from that point outbye to establish if there is a ribside heating. This may be located by careful inspection for signs of heat, sweating or smell, and should be dealt with as described in paragraph 121.

127. If no ribside heating can be located, the gob side of the return entry should be examined to determine the point of the carbon monoxide emission. This location should then be surface-coated or injected.

128. Method of combat:-

(i) The existing seals at No 1 return entries (see Plate 36 (B)) should be improved by spraying/plastering and injection as it is likely that this is the point at which oxygen is gaining access to the heating. The pressure causing the flow through the old gob must be reduced. This may be achieved by constructing a static pressure chamber at the site of the outbye seals of No 1 panel (see Plate 36 (I)). The pressure reduction in this chamber should be adjusted until the carbon monoxide content, as indicated at the No 2 panel sampling point (see Plate 36 (G)), is marginally above normal. This would avoid the possibility of the air flow reversing across the heating.

(ii) If these measures do not result in a reduction in carbon monoxide at the control sampling point, a flow-through type pressure chamber (see Plate 36 (J)) should be installed in the No 2 return. This additional chamber should extend over a length of roadway greater than that from which carbon monoxide emission is taking place. This measure is a last resort and, if unsuccessful, it may be necessary to seal off the district.

EXAMPLE 5 - MULTI-LIFT LONGWALL SYSTEM FOR THICK SEAM COAL

129. This is a simulated example of a multi-lift longwall mining method applicable to mining coal seams 12 ft or more in thickness. Conditions are based on those anticipated for a site near Emery, Utah, where an application of the multi-lift longwall method is being appraised. However, the hazards of this method of working, where there is a risk of spontaneous combustion, are great and it is recommended that alternatives be considered. Ref USBM Report OFR 135-77 and NTIS (PB272460 A/S).

(i) Mining Factors

Cover	350 ft to 500 ft
Seam gradient	4°
Seam thickness	20 ft
Sheared thickness	7 ft x 2 ft
Mined thickness	14 ft
Roof strata	Coal/shale/sandstone
Floor strata	Shale/sandstone
Strata temperature	50°F
Faulting	None

Rider seam	Yes
Panel dimensions	2,820 ft x 952 ft
Section development	Upper/lower lift - 2 x 2 entries
Longwall length	Upper lift - 570 ft Lower lift - 400 ft
Longwall conveyors	AFC
Longwall machine	Shearer
Longwall supports	Chock shield
Caving characteristics	Blocky
Coal losses	Roof coal, floor and middle coal
Crush	Yes, at pillar edges and middle, floor and top coal
Planned face, tons/shift	Upper lift - 1,200 Lower lift - 1,000
Planned face advance/shift	Upper lift - 7½ ft Lower lift - 9 ft
Shifts/week	Upper lift - 15 Lower lift - 15
Output/week	Upper lift - 18,000 tons Lower lift - 15,000 tons

(ii) Ventilation Factors

Methane emission	140 ft^3/min 56 ft^3/ton
Methane drainage	No
Air quantity	30,000 ft^3/min
Face velocity	600 ft/min
Airflow pattern	Twin intakes. Twin returns
Bleeder ventilation	No
Air humidity	35%

(iii) Coal Characteristics

Rank	Sub-bituminous
Oxygen	16.8%
Moisture	2.39%
Sulphur (inorganic)	0.75%
Ash	7.4%
Calorific value	11,800 Btu/lb
Hardness	Hard
RASCAL Index	42.5 (high risk)

Precautionary Techniques

Planning Phase

130. Any roof coal left represents a serious hazard likely to promote spontaneous combustion. In this method of working, the floor coal left after extracting the upper lift becomes the roof coal of the lower lift. This, combined with any already crushed roof coal left in the gob of the upper lift, further increases the hazard.

131. Ideally, each panel should be isolated from its neighbour by barrier pillars but if the system of twin or multiple-entry drivages necessitates the use of retained roadways, additional precautions need to be taken as described later.

132. The system is illustrated with twin-entry drivage development. To minimise the risk of roadside heatings and leakage between upper and lower drivages, single entries are desirable and every effort should be made to obtain authorisation for this system.

133. Ventilation of the gob is not recommended since it is inevitable with such a system that slow-moving critical zones of airflow will be created within the gob area.

134. To further reduce the risk of air leakage across the gob, it is desirable to plan the layout without connections through to a set of parallel main entries and without bleeder airways, although a back return system of return ventilation may be used in gassy seams (see Plate 37).

135. The face length should be such that a rate of advance is achievable that enables the "critical velocity zone" (see Chapter VI) in the gob to move fast enough to minimise the risk of a gob heating developing.

136. The face starting line should be a single entry of sufficient dimensions to install the face equipment. This single entry would reduce the risk of heatings at a vulnerable point, compared with multiple-entry drivages.

137. The face should be planned to start production and have an uninterrupted run, without interference by holidays, etc, in order to achieve early consolidation of the gob area outbye the starting line. To reduce delays to face advance during start-up, equipment should be of proven design wherever possible and personnel should be trained to a high standard. It is possible the top coal will "hang up" and may not cave fully until the face has retreated about 400 ft. Solid seals (see Plate 38 (A)), let into the rib, should be erected at each end of the longwall starting line, as soon as the face has moved away, to minimise possible airflow through this vulnerable area.

138. The final approach of the longwall to its finishing line (see Plate 38 (B)) should be unhindered and at an increased rate of advance. Salvaging of equipment should be scheduled to proceed rapidly in order that the permanent seals can be constructed without delay.

139. The replacement longwall development should be timed to receive the transferred face equipment from the previous production face as soon as it ceases production, in order to facilitate rapid sealing off of the panel.

140. A substantial barrier pillar should be left after every third face. This will facilitate erection of seals in ground not likely to crush, and will limit the size of the interconnected gob, so reducing the heating risk arising from breathing of the gob atmosphere following changes in barometric pressure.

141. Return airways should be connected to intakes at intervals not exceeding 3,000 ft in order to provide access to fresh air.

142. Preparatory seals should be planned (see Plate 38 (C); these will become permanent seals when the district has been salvaged. Light seals should be erected (see Plate 38 (D)) to prevent access to a potentially irrespirable atmosphere. The distance between (C) and (D) should be at least 15 ft to 30 ft to allow for the construction of a balance chamber should this become necessary.

143. Consideration must be given to an adequate system of support and systematic roadside sealing methods where the lower lift crosscuts pass beneath the upper lift entries (see Plate 38 (E)).

Operating Phase

144. Seals should be built behind the intake/face junctions at 200-ft-maximum intervals to minimise leakage through the unconsolidated gob. Seals should also be built in the returns at similar intervals to control leakage and also to facilitate drainage of methane from the gob, should this be necessary (see Plate 38 (F)).

145. A brattice should be erected from the intake entries for 25 ft along the face (see Plate 38 (G)). This would deflect the intake air and reduce the tendency of airflow to enter the waste at this position.

146. The power loader should not be unnecessarily parked at the intake end of the face for lengthy periods. Such an obstruction would increase the tendency for air to be diverted into the gob.

147. Preparatory sites for seals should be constructed for use in emergency and to facilitate quick closure of the section on completion of mining, at the points indicated at (C) on Plate 38. They should be sited within the main entry pillar at a

sufficient distance from the face finishing line to minimise damage by strata movement and far enough away from the main entry to allow the construction of a pressure chamber if required, and, if possible, in a section of the coal seam least liable to spontaneous combustion. Materials for seal construction should be stored at convenient points on the outbye side of the prepared sites.

148. The airway surfaces in the lower lift crosscuts should be coated with a sealant in an attempt to reduce air leakage associated with the upper lift entries.

149. Regulators should be located as far outbye as practicable, and should be of the double airlock type with all the regulated air flowing through a duct and the doors fully closed.

150. Separation doors should be constructed as double airlocks and enough distance allowed between doors to accommodate materials trains. Fractured coal and strata in the vicinity of doors and air crossings should be surface coated and/or injected.

151. Bulky items of equipment and stockpiles of materials should be located out of the main airflow to prevent diversion of air from the normal ventilation course.

152. Firefighting equipment should be installed and maintained in intake and return entries and the main airways.

153. Continuous monitoring of mine air should be adopted to provide routine mine air samples and warning of potentially dangerous conditions. A check sample at each of the sampling points (see Plate 38 (H)) should be taken at weekly intervals by manual means. At monthly intervals a standard calibrating carbon monoxide mixture should be fed into the mine air monitoring system at each sampling point to provide a check for pipe leakage.

154. Routine inspection of the section should be carried out (see Chapter VI, paragraphs 90 to 92).

155. The procedure laid down in Chapter VII, paragraphs 48 et seq, should be followed in the event of a heating being detected.

Combating a Spontaneous Combustion Heating

156. Three sites of heatings are possible:-

(i) in a rib or pillar edge in the entry system (the rate of development of this type of heating may be extremely rapid),

(ii) in the gob or entries behind the active longwall,

(iii) in gob or entries of a previously-worked adjacent panel.

Heatings at any of these locations will be indicated by a rise in carbon monoxide content at the sampling point located at the outbye end of the face return entries and/or detected by physical observation of smell, haze or condensation.

Rib or Pillar Heatings

157. Method of combat:-

(i) If the heating is accessible and shallow enough, then removal of the heated coal can be carried out (see Chapter VII). Before making a decision to dig out, the suspected area should be probed with drillholes to verify the position and depth of the heating.

(ii) The roadway surface may be coated with a sealant (see Chapter VII). This method may be effective on its own or may be used as a temporary measure whilst digging out is progressing or strata injection is taking place.

Heating in Gob Behind the Active Longwall

158. This type of heating is indicated by an increase in carbon monoxide content at the return sampling point and high carbon monoxide percentages at the return end of the face while the intake sample remains clear.

159. Method of combat:-

(i) The intake and return entry seals (see Plate 38 (F)) should be reinforced.

(ii) If possible, the rate of advance should be increased to move the zone of critical airflow and/or bury the area of active heating (see Chapter VI and Plate 11).

(iii) An auxiliary fan and ducting (see Plate 38 (I)) should be installed through the return entry seal immediately behind the face and the pressure behind the seal increased until the carbon monoxide emission is reduced to an acceptable level. The duct system will require extension as the face retreats and the ducting should be broken after retreating 300 ft. Thereafter the ducting should comprise a short length through the most recently erected seal. At monthly intervals the fan should be switched off and the sampling point monitored until it is apparent that the heating activity remains at an acceptable level.

Heating in Gob or Entries of Previously Worked Adjacent Panels

160. A heating in this location is indicated by an increase in carbon monoxide at the sampling point (see Plate 37 (A)). In order to determine the location of the heating, samples should be taken at points along the return entries.

161. If the samples fail to show a reduction anywhere along the entries and a sample at the intake end of the face is normal, this indicates that the spontaneous combustion is in the working longwall gob and should be dealt with as described in paragraph 159.

162. If the carbon monoxide samples taken at intervals along the entries drop to normal level, a check should be made from that point outbye to establish if there

is a ribside heating. This may be located by careful inspection for signs of heat, sweating or smell, and should be dealt with as described in paragraph 157.

163. If no ribside heating can be located, the nearby crosscuts adjacent to the old gob should be examined to determine the point of the carbon monoxide emission. Having located this, if the strata is sufficiently competent, substantial seals should be built between the pillars to isolate the old gob road. These seals should be faced with a sealant to tie in with the roof, floor and sides.

164. Method of combat:-

(i) The existing seals at No 1 return entries (see Plate 37 (B)) should be improved by spraying/plastering and injection as it is likely that this is the point at which oxygen is gaining access to the heating. The pressure causing the flow through the old gob may need to be reduced. This may be achieved by constructing a static pressure chamber at the site of the outbye seals of No 1 panel (see Plate 37 (B)). The pressure reduction in this chamber should be adjusted until the carbon monoxide content, as indicated at the No 2 panel sampling point (see Plate 37 (A)) is marginally above normal. This would avoid the possibility of the air flow reversing across the heating.

(ii) If these measures do not result in a reduction in carbon monoxide at the control sampling point, a flow-through type pressure chamber (see Plate 37 (C)) should be installed in the No 2 return. This additional chamber should extend over a length of roadway greater than that from which carbon monoxide emission is taking place. This measure is a last resort and, if unsuccessful, it may be necessary to seal off the district.

Heating in Gob or Entries of Previously Worked Upper Panel in Front of the Active Longwall

165. A heating in this location can be detected by an increase in carbon monoxide at the control sampling point (see Plate 38 (H)). In order to identify the area over which carbon monoxide emission is taking place, local spot samples should be taken along the return entries.

166. Method of combat:-

(i) After locating the affected area of roadway, this should be sprayed with a sealant to reduce air leakage. It may also be necessary to seal the surfaces of the intake entries. If this action does not effect a reduction in carbon monoxide content, it may be necessary to install a flow-through type pressure chamber in the return entries (see Chapter VII). The pressure will need to be adjusted until the carbon monoxide content is reduced to a figure marginally above normal.

(ii) Once it is considered that the sealant applied to the return airway is effective, consideration should be given to over-pressurising the chamber with the objective of identifying the points of leakage in the intake (see Chapter VII) which should then be coated with a sealant and if necessary injected.

(iii) It may be found necessary to give attention to the outer seals of the upper airways. The airflow pattern across the upper seam workings may be usefully influenced by means of a pressure chamber at one or both of these sites.

CHAPTER XI

RESEARCH AND DEVELOPMENT

GENERAL

1. Although considerable research and development work has been, and is being, carried out into aspects of spontaneous combustion, there are a number of fields where further work is required. The list below is not intended to be all-embracing but it does give an indication of the scope to be covered.

RESEARCH

Oxidation Reaction Below 100^{0}F

2 The complexity of the oxidation reactions occurring in newly-mined coal requires no emphasis, but from the practical mining point of view of combating spontaneous combustion and providing information for its early detection, the reactions above 100^{0}F are sufficiently understood, although they still present certain problems of considerable academic interest. It is in the critical temperature range from ambient to 100^{0}F, however, that essential knowledge is lacking.

3. It would appear from the work already done that the reactions taking place in this range are not strictly speaking oxidation reactions, with the expected heat release that occurs when oxygen reacts with carbon to produce carbon-monoxide. Indeed, it is suspected that the reactions that release carbon-monoxide below 100^{0}F may well be endothermic in character. This means that factors other than oxidation are responsible for the first stage in the initiation of spontaneous combustion.

4. Research is therefore needed to determine what these reactions may be, as it appears that if these could be explained, they would provide practical information of great value in preventing spontaneous combustion at its earliest possible stage.

Standard Laboratory Method to Determine the Liability of Coals to Spontaneous Combustion

5. There is a need to establish a relatively simple laboratory test to determine the liability of coals to spontaneous combustion. The test must be capable of application to large numbers of samples on a day-to-day routine basis, not only to provide information during the development of new seams, but also to provide a continuing check on the coal during normal mining extraction.

6. The established adiabatic oxidation experimental procedure is not practical for routine use as it takes too long to carry out and the apparatus required is too complex for use in a mine laboratory. Moreover, the practice of starting these tests at temperatures above 100^{0}F in order to reduce the time delay almost certainly gives misleading results as it is the reactions occurring between ambient and 100^{0}F that are, in practice, critical to the initiation of spontaneous combustion. It appears that the most useful test at present available is the temperature programmed non-adiabatic test (PANIC) described earlier in this report. It has

been used successfully by the UK National Coal Board in the survey of all British coals and continues to provide essential information on which to base precautionary action during the extraction of coal.

7. It is recommended, therefore, that research should be directed to standardising the test, with the object of making it internationally acceptable. If this could be achieved it would give a method for direct comparison of coals from whatever source and a comparative basis of reference between work in various countries in the field of spontaneous combustion.

Physical Examination of the
Petrographical Constituents of Coal

8. All laboratory "chemical oxidation" tests on coal require fundamental changes in its physical condition and this has undoubtedly given rise to misunderstandings as to the nature of the reactions taking place in massive coal as it occurs in the seam.

9. It is suggested that research on the oxidation of the intact surface of the coal should be attempted. The most promising method would appear to be to follow the oxidation of the freshly-exposed surface of coal specimens under the infra-red microscope.

10. Preliminary experiments have already given useful information but further work is required to establish the techniques necessary for routine examination. If the method proves generally applicable, it would provide a simple means of assessing the liability of coals to spontaneous combustion, similar to that used for the petrographic assessment of coking properties.

Role of Humidity in the Early
Stages of Spontaneous Combustion

11. Further work is required on the thermal effects of the interchange of moisture between atmospheric moisture and coal in the mine. The fact that artificially-dried coal adsorbs atmospheric moisture with consequential rise in temperature has not been related to practical mining conditions. The laboratory techniques for carrying out the research have been well established, but the problems of sampling and sample preparation have not been sufficiently recognised, with the result that much of the work that has been done to date on this subject is of academic interest only.

12. Research should be concentrated on sampling and sample preparation techniques that will ensure the direct comparison of laboratory results with conditions that are likely to occur underground. The inter-relationship of free and inherent moisture in coal is a highly complex and controversial subject, becoming even more so when considered in the context of their equilibrium with environmental moisture. The nature of the adsorption-absorption reactions is closely related to the micro-structure of the coal and its real and apparent surface area, still further complicated by its heterogenous petrographic structure. The problems of representative sampling and subsequent preparation for laboratory experimentation present serious difficulties and they cannot be ignored if the research is to be of any practical value to the mining engineer.

DEVELOPMENT

Infra-Red Probes

13. It is likely that the value of the new generation of infra-red probes now becoming available has been under-estimated because of the lack of systematic evaluation under practical mine conditions. While not strictly research, a programme to establish the characteristics and performance of these devices, and their possible use in detecting and locating incipient spontaneous combustion, should be undertaken.

Mining Methods and Practices

14. It has been stressed that the most reliable guide to spontaneous combustion risk, prevention and combat technique applicability, is practical experience in an active mining situation. The most important phase for Western US underground mining is now the introduction on a trial basis of those new mining methods and practices judged relevant to future needs. The detailed plans for implementation and the operating procedures adopted should embrace the spontaneous combustion considerations set out in this report, and the work done in the fields of prevention and combat should be fully recorded and evaluated to enable the contents of this report to be up-dated in the light of this field experience.

15. Further investigations should include the following topics with specific reference to Western US needs:-

Mining Practice

(i) the implications of single-entry development,

(ii) alternatives to bleeder ventilation,

(iii) application of methane drainage,

(iv) ongoing appraisal of spontaneous combustion aspects of trials of new underground mining methods,

Early Detection

(v) the application of continuous monitoring of

(a) carbon monoxide in the parts-per-million range,

(b) the changes in temperature pattern of ventilation,

(vi) development of PANIC and RASCAL techniques,

Training

(vii) training programmes in spontaneous combustion precautions and combat,

Legislation

(viii) a review of legislative requirements affecting spontaneous combustion control.

APPENDIX "A"

FATALITIES IN UK COAL MINES CAUSED BY EXPLOSIONS OR FIRES INITIATED BY SPONTANEOUS COMBUSTION

Date	Mine	Type of Incident	Number Killed
1869	Rainford	Fire	9
1889	Mossfield	Explosion	64
1889	Mauricewood	Fire	63
1898	Whitwick	Fire	35
1901	Talk-o'-th'-Hill	Explosion	4
1911	Bignall Hill	Explosion	6
1912	Cadeby Main	Explosion	88
1923	Maltby Main	Explosion	27
1925	Birchenwood	Explosion	7
1931	Bentley	Explosion	45
1934	Gresford	Explosion	265
1940	Mossfield	Explosion	11
1959	Bickershaw	Explosion	19
1967	Michael	Fire	9

APPENDIX "B"

SELECTED BIBLIOGRAPHY ON OXIDATION, STORAGE AND SPONTANEOUS COMBUSTION OF COAL

1 Plot, R. — History of Staffordshire, 1686
Spontaneous Combustion in Heaps

2 Richters, E. — Dingler's Polytech. J., 1868-70, 190, 398; 193, 51; 195, 315, 449
Oxidation of Coal

3 Rothwell, R.L. — Trans. Am. Inst. Min. Eng., 1873, 2, 150
Storage

4 Royal Commission Report — HMSO, 1876
Spontaneous Combustion in Ships

5 Fayol, H. — Bull. Soc. Ind. Minerale, 1879, 2nd ser. 8, pt. 3
Deterioration and Spontaneous Combustion

6 Haldane, J.S. and Meachen, F. — Trans. Inst. Min. Eng., 1898, 16, 457
Oxidation and Spontaneous Combustion

7 Chambers, W.H. — Trans. Inst. Min. Eng., 1899, 18, 154
Notes on Gob Fires

8 Fischer, F. — Z. Angew Chem., 1899, 12, 564
Storage - Deterioration

9 Dennstedt and Bunz. R. — Zeit. Angew. Chem., 1908, 21, 1821; 25, 1825
Spontaneous Combustion

10 Tessenden, E.A. and Wharton, J.R. — Bull. Univ. of Mo. Eng. Series, 1908, 1
Causes of Fires

11 Parr, S.W. and Wheeler, W.F. — Univ. Ill. Eng. Exp. Sta. Bull. 38, 1909
Degradation

12 Galle, E. — Zeut. f. Bakt. u. Parasiten, 1910, 28, 461
Spontaneous Combustion

13 Parr, S.W. and Kressmann, F.W. — Univ. Ill. Bull., 1910, 8, No 16, 33
Spontaneous Combustion

14	White, A.H. and Baker, P.	USBM Bull. 6, 1911 *Degradation*
15	Harger, J.	Trans. Inst. Min. Eng., 1912, 44, 318 *Gob Fires*
16	Porter, H.C. and Ovitz, F.K.	USBM Tech. Paper 16, 1912; Ind. Eng. Chem., 1912, 4, 5 *Deterioration in Storage*
17	Winmill, T.F.	Trans. Inst. Min. Eng., 1913, 46, 563 *Absorption of Oxygen*
18	Departmental Committee on Spontaneous Combustion in Coal Mines,	(Cmd. 7218) 1914
19	Graham, J.I.	Trans. Inst. Min. Eng., 1914, 48, 521 *Absorption of Oxygen by Coal*
20	Porter, H.C. and Ralston, O.C.	USBM Tech. Paper 65, 1914 *Oxidation of Coal*
21	Drakeley, T.J.	J. Chem. Soc., 1916, 109, 723 *Influence of Iron Pyrites*
22	Graham, J.I.	Trans. Inst. Min. Eng., 1916, 52, 349 *Absorption of Oxygen by Coal*
23	Winmill, T.F.	Trans. Inst. Min. Eng., 1916, 51, 493 and 510 *Effect of Particle Size on Adsorption*
24	Winmill, T.F.	Trans. Inst. Min. Eng., 1916, 51, 500 *Oxidation of Iron Pyrites*
25	Katz, S.H. and Porter, H.C.	USBM Tech. Paper 172, 1917 *Effects of Moisture on Stored Coal*
26	Tideswell, F.V. and Wheeler, R.V.	J. Chem. Soc., 1920, 117, 794 *Oxidation of Banded Constituents*

27 Briggs, H. Iron and Coal Tr. Rev., 1922, 105, 715
Heat Produced by Crushing

28 Graham, J.I. Fuel, 1922, 1, 54
Mine Air and Spontaneous Combustion

29 Stopes, M.C. and Wheeler, R.V. Fuel, 1923, 2, 29
Effect of Coal Structure and Composition

30 Coles, G. and Graham, J.I. Fuel, 1924, 3, 384
Influence of Preheating

31 Storrow, J. and Graham, J.I. Trans. Inst. Min. Eng., 1924, 68, 408
Use of Gas Analysis in Detection

32 Davis, J.D. and Byrne, J.F. Ind. Eng. Chem., 1925, 17, 125
Adiabatic Calorimeter

33 Graham, J.I. and Jones, T.D. Trans. Inst. Min. Eng., 1925, 69, 413
Spontaneous Combustion in South Wales

34 Morgan, C.E. Trans. Inst. Min. Eng., 1925, 71, 1
Detection by Gas Analysis

35 Davis, J.D. and Byrne, J.F. Ind. Eng. Chem., 1926, 18, 233
Influence of Moisture

36 Li, S.H. and Parr, S.W. Ind. Eng. Chem., 1926, 18, 1299
Oxidation of Pyrites

37 Maynard, T.C. Trans. Inst. Min. Eng., 1927, 73, 169
Reopening a District after Spontaneous Combustion

38 Fucsh, W. Brennst. Chemie, 1927, 8, 20
Bacteria Action

39 Graham, J.I. and Morgan, C. Trans. Inst. Min. Eng., 1927, 73, 258
Effect of Barometric Pressure

40 Rosin, P. Braunkohle, 1928, 27, 241
Causes and Suppression (Brown Coal)

41 Graham, J.I. Trans. Inst. Min. Eng., 1929, 79, 92
Gaseous Products of Fires and Heatings

42 Rose, H.J. and Sebastian, J.J.S. Fuel, 1932, 11, 284
Oxidation at 80°C

43 Winter, H. — Gluckhauf, 1931, 67, 401
Early Detection

44 Haldane, J.S. and Makgill, R. — Trans. Inst. Min. Eng., 1933, 85, 172
CO Formation

45 Coles, G. and Graham, J.I. — Fuel, 1933, 12, 304
Influence of Preheating

46 Mason, T. and Tideswell, F.V. — S.M.R.E. Reports 75 and 76
Gob Fires

47 Mason, T.N. and Tideswell, F.V. — Trans. Inst. Min. Eng., 1934, 87, 243
Experimental Gob Fires

48 Kreulen, J.W. — Fuel, 1934, 13, 55
Ignition Temperatures

49 Pohl, H. — Kohle u. Erze, 1936, 33, 421
Effect of Petrography

50 Holmes, C.D. and Davis, J.D. — Ind. Eng. Chem., 1936, 28, 484
Adiabatic Oxidation

51 Sebastian and Mayers — Ind. Eng. Chem., 1937, 29, 1118
Ignition Temperatures

52 Cabolet, P. — Gluckauf, 1939, 75, 953, 971, 984
Origin and Prevention of Fires

53 Bredenbruch, E. — Gluckauf, 1940, 76, 115
Combating Coal Seam Fires

54 Scarf, F., Hall, D.A. and Yearsley, C.W. — Trans. Inst. Min. Eng., 1940, 100, 88
Storage in Heaps

55 Notzold, E. — Gluckauf, 1940, 76, 381
Petrography and Spontaneous Combustion

56 Schmidt, L. and Elder, J. — Ind. Eng. Chem., 1940, 32, 249
Rates of Oxidation Coking Coals

57 Coward, H.F. — Trans. Inst. Min. Eng., 1941, 101, 229
Ignition of Firedamp

58 Willett, H.L. — Trans. Inst. Min. Eng., 1942, 102, 249
Prevention in Yorkshire

59 Scott, G.S. — USBM Bull. 455, 1944
Anthracite Mine Fires

60 Elder, J.D. et al — USBM Tech. Paper 681, 1945
Relative Tendencies of Coals

61 Lowry, H.H. (ed) — Chemistry of Coal Utilisation, 1945, 627
Storage Effect on Coal Properties

62 Skotochinski, A.A. — Akad. Sci. U.S.S.R., 1947
Influence of Humidity

63 Lehmann, G. — Gluckauf, 1951, 87, 439
Combating Mine Fires

64 Willett, H.L. — Trans. Ind. Min. Eng., 1951, 111, 629
Gas Analysis Behind Stoppings

65 Willett, H.L. — Proc. Nat. Ass. Coll. Mgrs., 1952, 49, 222
Recovery Operations

66 Mehta, M. and others — J. Scient. Ind. Res., 1952, 11B, 418
Oxidation of Indian Coals

67 Veselovsky, V. and Orleanskaya, G. — Ugol, 1953, No 2, 33
Detection of Mine Fires

68 Schiemann, A. — Bergbautechnik, 1954, 4, 38
Origin and Combating Mine Fires

69 Terpogosova, E.A. — Izv. Akad, Nauk. USSR., 1954, 147
Inhibitors

70 Hall, D.A. — Steam Engineer, 1954-1955 (6 parts)
Surface Storage of Coals

71 McCrickard, J. — Journal Kings College Mining Society (Durham), 1952, 35

72 Burn, J.B. — Iron Coal Trades Rev., 1955, 170, 1391
Fires in India

73 Bullough, W. — Trans. Inst. Min. Eng., 1952, 112, 101
Spontaneous Heating in a Shaft

74 Ember, K. — Banyaszati Lapek, 1958, 13, 558
Controlling Spontaneous Fires in Hungary

75 Stott, J.B. — Min. and Quarrying Conf. Otago, 1956, 3, 64
Effect of Humidity

76 Zabavin, V. — Trudy. Inst. Goryuchikh, 1959, 8, 198
Oxidation 50^{o} to 150^{o}C - Chemistry

77 Wolowcyzk, P. — Bergakademic, 1960, 12, 4
Effects of Meteorological Factors

78 Sevenster, P.G. — Fuel, 1961, 40, 18
Oxidation 0^{o} to 90^{o} - S. African Coals

79 Olpinski, W. and others — Prace GIG Kom 204, 1958
Effect of Mining Conditions on Indigenous Fires

80 Mukherjee, P. and Lahiri, A. — Brennstoff Chem., 1957, 38, 55
Role of Moisture in Low Temperature Oxidation

81 Pekelko, J. — Uhli, 1957, 7, 161
Self-ignition in Czech Colliery

82 Both, W. — Gluckauf 1968, 104, 135
CO Recorders for Early Recognition of Fires

83 Churkia, V.K. and others — Ugol Ukaing, 1968, 12, 28 (No 2)
Extinction of Spontaneous Combustion in a Pillar

84 Veselinovic, V. — Sigernost u Rudnicima, 1967, 2, 27
Petrographic Composition and Spontaneous Combustion

85 Pregerman, S. — Paper D4, 14th International Conf. of Mine Safety Research, Establishments, Donestok, 1971
Tests for Tendency to Spontaneous Combustion

86 Cudmore, J.F. — Coll. Guardian, 1964, 209, 487
Spontaneous Combustion in Australia

87 Pursall, B.R. and Ghosh, S. — Mining Engineer, 1965, 124, 511
Early Detection using Gas Chromotrography

88 Hall, D.A. and Hook, W. — Mining Engineer, 1966, 125, 375
Spontaneous Combustion in Mines

89 Hall, D.A. — J. Inst. Fuel, 1967, 46, 474
Weatherproofing of Coal Stocks

90 Munzner, H. and Peters, W. — Erdol und Kohle, 1969, 22, 334
Isothermal Oxidation

91 Guney, M., Hodges, D.J. and Hinsley, F.B. — Mining Engineer, 1969, 129, 67
Effects of Humidity

92 Kurihara, K. and Tashiro, J. — Paper 41 Conf. of Safety in Mines Research, 1969, Tokyo
Oxidation Inhibitor - Diapon T

93 Chamberlain, E.A.C., Hall, D.A. and Thirlaway, J.T. — Mining Engineer, 1970, 121, 1
Ambient Temperature Oxidation of Coal and Early Detection

94 - — J. Mine Ventilation Soc. South Africa, 1970, 23, 158
Symposium on Underground Fires. Detection, Monitoring, Prevention

95 Chamberlain, E.A.C. — Inst. Min. Eng. Symposium on Prevention of Spontaneous Combustion, Harrogate, 1970
Continuous Monitoring for Detection of Spontaneous Combustion

96 Hall, D.A. and Lang, A.Z. — Symposium on Prevention of Spontaneous Combustion, 1970, Harrogate
Prevention of Spontaneous Combustion with Special Reference to N. Durham Area

97 Leclercq, J. — Publications Techniques Charbonnages de France, 1971, 2, 75
EEC Working Group "Rescue Mine Fires and Heatings". Precautions, etc

98 Chamberlain, E.A.C. and Hall, D.A. — 14th International Conf. of Mine Safety Res. Es., Paper D1. Donetsk, 1971
Ambient Temperature Oxidation of Coal (Spontaneous Combustion)

99 Chamberlain, E.A.C. and Caldwell, J.B. — Inter. Conf. Mine Safety Res. Es., Paper A9. Donetsk, 1971
Continuous Monitoring by Tube Bundles

100 Zupan, E. — Pub. Hungarian Mining Research Inst. 1971, No 14, 139
Forecasting Fires by Infra-red Radiation Measurements

101 Both, W. — Gluckauf, 1972, 108, 237
Preventing Spontaneous Combustion by Stopping Air-leakages

102 Nandry, D.K. and others — Journal of Mines, Metals and Fuels, 1972, 20, 41
"Crossing Point" Temperatures of 50 Indian Coals

103 Aksentsev, Z. — Bezopnost Truda v Promgschenost, 1972, 16, 16
Remote Sampling - polythene tube up to 1,000 metres

104 Hausman, A. — Coordinatiecentrum Reddingewezen Doc 70, March 72
Fire Detected by CO Recorder at Greisenan, Dortmund

105 Chamberlain, E.A.C. and Hall, D.A. — 15th International Conf. Mine Safety Research Establishments, Karlovy Vary, 1973
Inhibitors and Promoters

106 Chamberlain, E.A.C., Crook, M.D. and Gwatkin, G. — International Symposium on Automatic Control in Mining, etc. Sydney, 1973
Automatic Monitoring of CO in Coal Mines

107 Muller, R. — Charbonnages de France: Pub. Tech. No 7, 1972, 373
Application of Graham Fire Index

108 Chamberlain, E.A.C. and Hall, D.A. — Coll. Guardian, 1973, 221, 65
Liability of Coals to Spontaneous Combustion

109	Chamberlain, E.A.C. and Hall, D.A.	Coll. Guardian, 1973, <u>221</u>, 190 *Practical Early Detection of Spontaneous Combustion*
110	Chamberlain, E.A.C. and Hall, D.A,	Mining Engineer, 1973, <u>132</u>, 387 *Ambient Temperature Oxidation and Detection*
111	Chamberlain, E.A.C.	Energy Digest, 1973, <u>2</u>, 2 *Continuous Monitoring by Tube Bundles*
112	Gabzdyl, W.	Zeszty Naukowe Akad Gorniczo, 1972, <u>373</u>, 55 *Spontaneous Heating and Petrographic Analysis (Silesia)*
113	Il'yuschenco, R.G. and others	Khioniya Tverdogo Topliva, 1973, No 5, 51 *Low Temperature Oxidation in Mine Workings*
114	Miller, Y.A. and others	Bezopaspost Trada V. Prom., 1973, <u>17</u>, 19 *Controlling Spontaneous Fires in Coal Mines*
115	Feng, K.K., Chakravorty, R. and Cochrane, T.	Canadian Min. and Met. Bull., 1973, <u>66</u>, 75 *Spontaneous Combustion - a Coal Mining Hazard*
116	Kudryartseva, E.N.	Ugol, 1973, <u>28</u>, 50 *Prevention of Spontaneous Combustion in Waste*
117	Externbrink, W. and Lewer, H.	Gluckauf, 1974, <u>110</u>, 89 *Suppression by Montan Powder* ($CaCl_2$)
118	Chamberlain, E.A.C., Hall, D.A. and others	Mining Engineer, 1974, <u>133</u> 239 *Continuous Monitoring of Mine Gases, Tube Bundles*
119	Both, W. and Stark, A.	Gluckauf, 1974, <u>110</u>, 510 *Pressure Balancing in Fighting a Mine Fire*

120 Iki, S. and Higuchi, K. — J. Min. and Met. Inst, Japan, 1973, 89, 455
Mechanism of Spontaneous Oxidation Below 80°C

121 Thorp, P. — Canadian Mining and Met. Bulletin, 1974, 67, 96
Mine Fires - Prevention and Control

122 Igishev, V.G. and others — Ugol, 1974, 49, 56
Halogenated Halogens as Fire Preventative

123 Kaiser, I. — Gluckauf, 1975, 111, 713
Fire Prevention where Roof Coal Left

124 Street, P.J. and others — J. Inst Fuel, 1975, 48, 146
Hydrogen as Indicator of Spontaneous Combustion of Coal

125 Chamberlain, E.A.C., Barrass, G. and Thrulavey, J. — Fuel, 1976, 55, 217
Gases Evolved During Low Temperature Oxidation

126 Jeger, C. — Industrie Minerale Mine 3/76, 1976, 116
Origin of Spontaneous Combustion in French Collieries

127 Jeger, C. and Froger, C. — Charbonnages de France; Pub. Tech. 1976, No 2, 1997
Prevention and Monitoring

128 - — Queensland Government Mining J., 1976, 77, 307
Kianga Disaster Report

129 Litton, C.D. and Hertzburg, M. — USBM Report of Investigations, No 8242

130 Kutche, S., Hertzburg, M., Cato, Litton, C.D. and Van Dulah, W. — 15th Symposium on Combustion, Japan, 1974, 127

131 NCB — 1977
The Tube Bundle Technique for the Continuous Monitoring of Mine Airs

132 Highton, W., Richardson, G. and Wood, G.T. — 1978, Unpublished
The Prevention and Control of Spontaneous Combustion in the Western Area of the National Coal Board

ADDITIONAL REFERENCES

A1 Lukaszewski, G.M. — Ninth Commonwealth Mining and Metallurgical Congress, 1969

A2 - — Report of the South Wales Coal Owners' Association (1947)

A3 Griffin, O.G. and Atherton, E. — Ann. Occup. Hyg., 1972, 15, 361
The Physiological Requirements for Self Rescuers Related to the Performance of Existing Apparatus

A4 Lehmann, G. — Praktische Arbeitsphysiologie, (2nd Ed), 1962, 301

A5 King, J.G. and Wilkins — Conference on Ultra-fine Structure Porosity of Coal, 1943

A6 Yohe, G. and Harman, C.A. — J. Amer. Chem. Soc., 1941, 63, 555
Reaction with Titanous Chloride

A7 Jones, R.E. and Townend, D.T.A. — J. Soc. Chem. Ind., 1949, 68, 197
Trans. Faraday Soc., 1946, 42, 297
Role of Oxygen Complexes in Oxidation of Coal

A8 - — Cersham Report No 6205-07/3/031
Prevention et Lutte Contre les Feux de Mines

A9 Ponsford, A.P. — BCURA Bulletin, 1966, Vol XXX, No 1 and 2
Microbiological Activity in Coal

A10	NCB	1970 *Noxious Gases Underground*
A11	Coward, M.F. and Jones, G.W.	USBM Bull. 503, 1952 *Limits of Inflammability*
A12	Hughes, A.J. and Raybould, W.E.	Mining Engineer, 1960, 1, 37 *Rapid Determination of Explosibility of Mine Gases*
A13	Jagger, J., James, T. and Sproson, J.C.	Mining Engineer, 1963, 29, 393 *Simplified Graphical Method for Flammability*
A14	Pickering, A.J.	Mining Engineer, 1969, 129, 95 *Airflows and Methane Emissions on Fully Caved Mechanised Coal Faces in South Nottinghamshire*
A15	Summers, A. and Lord, S.B.	Mining Engineer, 1977, 136, 451 *Control of Spontaneous Combustion on Longwall Faces During the National Strikes of 1972-74*
A16	-	Trans. Inst. Min. Eng., 1962 *Sealing of Fires Underground*
A17	Glass, G.B.	Geological Survey of Wyoming. Report of Investigation No 11, 1975 *Analysis and Measured Sections of 54 Wyoming Coal Samples*
A18	Weimer, R.J.	Colorado Geological Survey. Symposium in the Geology of Rock Mountain Coal, 1976 *Stratigraphy and Tectonics of Western Coals*

APPENDIX "C"

BIBLIOGRAPHIC REFERENCES BY SUBJECT

1. This appendix lists the references given in Appendix "B" according to the main subject dealt with in the paper. Some papers deal with a number of aspects and are either listed under the main subject discussed or given in several sections. This will enable the reader quickly to locate papers associated with a particular aspect of spontaneous combustion in which he is interested and, where necessary, will point to further work available on this aspect.

History, Basic Principles and Researches:	2, 4, 5, 6, 8, 10, 12, 13, 17, 18, 28, 33, 42, 66, 72, 126, 128, 129, 132
Low Temperature Oxidation:	20, 22, 76, 78, 93, 98, 107, 110, 113, 120, 125
Factors Affecting Susceptibility:	
Rank	9, 16, 17, 56, 60, 108
Petrographic composition	26, 29, 49, 55, 84, 108, 112
Temperature	17, 19, 26, 30, 45, 56, 108
Available air	70, 108
Particle size	11, 14, 23, 54, 108
Moisture	25, 35, 62, 75, 80, 91
Sulphur	1, 21, 24, 36, 108
Other minerals	108
Bacteria	38
Laboratory Testing for Susceptibility:	
Isothermal	90, 108
Adiabatic	50, 85
Ignition temperatures	48, 51, 102
PANIC	93, 108
Geological and Mining Factors:	7, 15, 39, 46, 73, 77, 79, 81, 86, 88, 113, 115
Combating Fires:	47, 53, 57, 59, 63, 68, 119
Control of Fires:	64, 65, 74, 83, 114, 119, 121

APPENDIX "D"

SUCCESSFUL MINING IN AN AREA WITH A HIGH SPONTANEOUS COMBUSTION HAZARD

1. The South Midlands Area of the UK contains three separate coalfields, each having a different degree of risk from spontaneous combustion.

2. The most easterly coalfield is in Leicestershire and is worked by six mines extracting a total of eleven different seams. Of these, the Lower Main, New Main, High Main, Minge and Nether Lount are liable to spontaneous combustion.

3. In the north-west of the area is the South Derbyshire coalfield, worked by four mines, extracting a total of six seams. Of these the Main Coal and the Stockings seams are liable to spontaneous combustion.

4. To the south-west lies the Warwickshire coalfield, worked by five mines. Current workings are in the Seven Feet, Bench and various sections of the Warwickshire Thick Coal. The Bench and Thick Coal are liable to spontaneous combustion.

5. The routine preventive measures taken to reduce the likelihood of heatings are related to the risk factor involved and the seams have been grouped as below:-

(i) Lower Main, Main Coal, Thick Coal, Bench

(ii) New Main, Nether Lount, Stockings.

(iii) High Main and Minge.

The faces in category (i) seams require full preventive treatment as summarised below:-

(a) where possible, the face should be retreated,

(b) face travel should be as rapid as possible,

(c) if the face is advancing, the face start line must be adequately sealed in both gates, and peripheral sealing of the roadside adjacent to the gob must be adequate and routine,

(d) the district must be salvaged within one month after it ceases production,

(e) pressure over the final seals should be balanced if necessary by use of a balance chamber.

6. The faces in category (ii) seams are considered individually and the preventive measures taken depend on the risk factor in each case.

7. In category (iii), reliance is placed purely on early detection, either by use of continuous monitoring and/or routine examination by officials.

8. The seam most liable to spontaneous combustion is the Warwickshire Thick Coal and the section of this seam most dangerous to work is the Lower or Nine Feet section. This leaves the most spontaneous-combustion-prone coal, namely the Rider or Bare coal which comprise the centre third of the Thick Coal section, to lie within the gob area.

9. Minor incidents, indicated by increased carbon monoxide, odour or sweating, occur within this seam on an average two or three times every week and are dealt with on a routine basis at the mine. More serious incidents where a coal face is at risk and specialist advice is sought occur four or five times a year.

10. The major incidents that have occurred as a result of spontaneous combustion in the South Midlands Area since 1975 are listed below.

Mine	Date of Incident	Equipment Loss	Output Lost/Week	
		10^3 \$	Tons	10^3 \$
Cadley Hill	Feb 75	414	-	-
Baddesley	June 76	739	6,000	165
Newdigate	Jan 77	804	4,800	190
Newdigate	Aug 77	1,203	10,800	426
Coventry	Nov 77	1,288	4,000	152
Total		4,448	25,600	933

Exchange rate used \$1.90 = £1

11. However, the following tabulation illustrates that mining can be successfully conducted under hazardous conditions.

Year	Average Number of Faces			Average Monthly Saleable Tons		
	Advance	Retreat	Total	Advance	Retreat	Total
1975/6	40	14	54	456,197	198,173	654,370
1976/7	43	11	54	464,927	170,795	635,722
1977/8	39	13	52	444,004	166,545	610,549

APPENDIX "E"

HISTORY OF SPONTANEOUS COMBUSTION OCCURRENCES - CASE NO 1 - GERMANY

Extract from the paper "Control of a Concealed Mine Fire with Pressure Balancing at the Ewald-Fortsetzung Pit", Both and Stark, Gluckauf, Volume 110, 1974

SUMMARY

1. During mining operations in the Gretchen-Anna seam of the Ewald-Fortsetzung mine, spontaneous combustion led to a concealed mine fire in the gob. This fire was kept in check for around three weeks by ventilation pressure balancing, until longwall equipment was removed. Experience gained in the application of this method provides valuable background for combating similar occurrences.

LOCATION OF MINE

2. The Ewald-Fortsetzung mine is located in the Ruhr coalfield at Herne, West Germany.

SYSTEM OF WORKING

3. The mine is laid out on the horizon mining principle, that is having the main access roadways driven in rock. The Gretchen-Anna seam is 7 ft 6 in to 8 ft 2 in thick. The main southern panel, where the fire occurred (see Plate 39), is around 660 ft long on the eastern side of the 3,600-ft horizon, and dips northwards at 9^0 to 14^0. The longwall face was opened out from a heading driven to the rise and equipped with an armoured face conveyor and a coal plough; the roof was supported by new powered supports. The entries were equipped with scoop-trams, stage loaders, 40-in-wide belt conveyors and overhead monorail supplies haulage. The entries were supported by props and girders and contained electrical equipment including motors, transformers and switchgear. The face commenced production early in 1973 with "advanced headings", caving and gate side packs; the pack holes were supported by rows of wooden props.

VENTILATION

4. The face was descensionally ventilated, with an air flow of 65,000 ft^3/min; an air flow of 1,980 ft^3/min was short circuited via roadway No 1 by the old face heading. A methane drainage system was employed, but it was still necessary to apply for exemption from German mining regulations to permit men to work in a methane concentration of up to 1.5%, subject to all electrical gear being switched off when the concentration reached 1.2%.

INTERRUPTION OF FACE ADVANCE

5. Following the discovery of a geological fault which could not be worked according to schedule, the face had to be temporarily abandoned on 16th April, 1973, after an advance of 426 ft had been completed. Work re-commenced in the same panel around 130 ft to the east and the advance from the beginning of June, 1973, to 20th July, 1973, was approximately 390 ft. The old face was sealed off with stoppings No 416 and 417 (see Plate 39). The stoppings, which were completed

by 7th July, 1973, showed no signs of leakage at either face access point. Samples taken from the tube in stopping No 417 on 19th July, 1973, revealed only 3 ppm CO and 0.2% CH_4. The air losses in the rear part of the gob were within the range of the normal values obtaining for this kind of working.

DETECTION OF FIRE

6. At about 6.50 pm on Sunday, 22nd July, 1973, officials in the coal haulage road reported fumes and the smell of fire to the mine rescue leader. At the same time, the "UNOR" carbon monoxide monitoring instrument installed at the end of the ventilation district triggered the alarm in the control room on the surface. The officials reporting the fire and other miners were outside the carbon monoxide zone at the end of the ventilation road No 1 and east of the coal pillar in the coal haulage road, or at the face.

7. The mine rescue service was alerted at 6.53 pm and the workings affected were ordered to be closed immediately. At approximately 8.30 pm, the reconnaissance team reported thick smoke escaping from the gob to the west of face stopping No 417. Measurements with hand-held instruments indicated 1% CH_4 and 3,000 ppm CO in the free cross-section of the roadway; the dry-bulb temperature was 95°F and the wet bulb temperature 79°F. As visibility was greatly reduced by heavy smoke, rescue workers were only able to inspect the section of the roadway up to the ventilation dip road at the second attempt. This inspection revealed that the fumes were not caused by a fire at roof level or an open fire in the bottom road, but were coming from the caving area.

FIRE CONTROL AND FIRE MONITORING OPERATIONS

8. From the origin of the fumes and the facts which had led to the abandonment of the old face, it was assumed that spontaneous combustion had occurred in the gob of the stopped-off face. The source of the fire was suspected to lie in the fault area. Direct fire-fighting operations could thus not be effected, and the only possibility was to delay the intensity of propagation by reducing the differential pressure across the gob in order to install stoppings under the least hazardous conditions. The stopping-off points were determined in accordance with this concept. Of the stopping-off points No 1 to No 4, No 3 and No 4 were intended to confine the fire zone to the east to permit subsequent resumption of coal getting or the removal of face supports, machinery and material from the face and the forward gate roads with the aid of bypass roadways. The planning of stoppings No 1 and No 2 on the shaft side of the fire zone to cut off this zone in the direction of the underground workings, was determined by the projected layout of subsequent development work for deposits lying to the north.

9. As a precautionary measure to prevent the concealed fire spreading to the head gate, at about 11.00 pm rescue workers installed extinguisher jets at stopping No 417 and in the lower gate east of roadway No 1.

10. As the methane level of 0.7% in the return air seemed to entail no danger in reducing the volume of flow, the ventilation doors in roadway No 1 were opened at about 3.00 am to reduce the differential pressure (P_0 1.38-in water gauge) acting on the fire, and the volume of short-circuited air was increased from 17,650 ft^3/min (Q_0) to 44,000 ft^3/min (Q_1), the volume of air at the face was thus reduced from 65,000 ft^3/min (Q_0) to 44,000 ft^3/min (Q_1). This reduced carbon monoxide levels considerably.

11. This continual reduction of the cross-sectional area due to the erection of stoppings No 2 and No 4 (stopping No 2 was provided with two tubes of 28-in diameter, stopping No 4 with one tube of 28-in diameter) had a throttling effect which led to a gradual decrease in the air flow. There was thus an increase in the carbon monoxide level in the roadway cross-section and, more particularly, the methane level in the return air.

12. Closing the air lock in roadway No 1, which had been left open until this time, allowed the volume of air to be raised again and the methane level kept below 1%. At the same time, however, the differential pressure at the source of the fire increased again. Until stoppings No 2 and No 4 were completed, the air flow at the face was expected to be too low, thus causing a further increase in the methane level, and the differential pressure affecting the fire was expected to become so great that the fire would spread further, thus developing more carbon monoxide. To seal off the fire zone rapidly, which might become necessary in an emergency, stoppings No 2 and No 4 had to be completed apart from the closing of the tubes.

13. To reduce the differential pressure obtaining at the source of the fire and to provide sufficient air for the face at the same time, a fan was mounted on the tube of stopping No 4 to act as a pressure generator, and the quantity of air flowing through eastern face 1 immediately to the east of roadway No 1 was reduced.

14. After all the preparations had been completed, the fan was activated at 7.00 pm on 24th July, and the differential pressure obtaining at the fire was set to 0.24-in water gauge (P_2) by adjusting the regulator immediately to the east of the dip and the air-lock.

15. With the starting of the fan, the amount of air flowing past the face increased from 12,300 ft^3/min to 26,500 ft^3/min (Q_2), while the carbon monoxide level in eastern face 1 was reduced from more than 600 ppm to less than 100 ppm; the methane level sank to 0.7%. Tubing installed from stopping No 416 to stopping No 417, containing an inclined-tube manometer, allowed the differential pressure at the fire to be continuously monitored from this moment on. A rise or fall in the resistance values (caused by equipment removal and transport work) was compensated for by adjusting the regulators. At the same time, the distribution of air was monitored every two hours.

16. These measures resulted in the carbon monoxide levels recorded at the various measuring points remaining almost constant from the moment the fan was switched on until 11.00 am on 17th August, 1973, when the stoppings were completed. Ventilation conditions were recorded in respect of pressure and quantity, and the effects of any changes, or breakdown in the main or auxiliary ventilation were investigated by computerised simulation of the ventilation network. Contingency plans were drawn up on the basis of these results.

RECOVERY OPERATIONS

17. After starting the fan, which allowed carbon monoxide emission to be kept within reasonable limits, several mine rescue teams commenced recovery work on 24th July, 1973. This work was carried out without breathing apparatus, except in the lower face. Here the carbon monoxide level rose to more than 3,000 ppm following a brief fan breakdown. After about 90% of the machines and materials had been removed, final stopping-off operations were scheduled for 17th August, 1973, after agreement with the Mines Inspectorate and the Main Mine Rescue Centre.

SEALING OF THE FIRE ZONE

18. To keep the period in which carbon monoxide or methane levels could rise as short as possible, even in this final phase, it was agreed:-

(i) not to switch off the fan until immediately before closure of the tubes in stoppings No 1 and 2 and thus to leave it in the fire zone,

(ii) to disconnect the pipeline containing methane gas at stopping No 1 and switch off the gas drainage system only just before the switching off of the fan,

(iii) not to remove the methane and carbon monoxide monitoring devices at the bottom of the ventilation dip and the inclined tube manometer until shortly before switching off the fan.

19. The distribution of air pressure and volume in the various stopping off phases - the constriction effect of stoppings No 1 and No 2, switching off the fan, sealing of stopping tubes - were calculated by simulating the ventilation network by electrical analogue and checking with measured values. The successful conclusion of salvage work and the stopping off phase was due to the fan being started in good time and with the help of fan and regulator, the differential pressure being reduced from about 1.62-in water gauge to 0.24-in water gauge and stabilised at this value. Furthermore, the gas drainage system was kept in operation throughout.

RECOMMENDATIONS

20. Accurate ventilation parameters of hazard areas must be known in advance of, as well as during, the emergency operations. These must be based on both measurement and calculation.

21. Decreasing the differential pressure obtaining at the source of fire by ventilation measures only has a chance of success when the original differential pressure is greater than 0.4-in water gauge.

22. A check should first be made to see whether pressure can be relieved sufficiently by short-circuiting air and decreasing the general quantity of air, taking gas emission conditions into account (in the case described here, the short-circuited air in the dip road was increased).

23. The following points should be noted with respect to the use of fans:-

(i) When the fan is started care must be taken to adjust the air lock and fan regulators to balance the pressure across the old face line. Subsequently, this pressure may need to be finely adjusted to ensure the minimum emission of carbon monoxide from the heating area into the return.

(ii) When installing the fan air-lock and the regulator, care must be taken to ensure that the siting of the air-lock doors with their frames, and of the regulator, presents no additional spontaneous combustion hazard; if coal is present at these locations, sealing into the sides and grouting is necessary to prevent spontaneous combustion near the doors.

(iii) The differential pressure at the fire should generally be reduced to between 0.16-in water gauge and 0.2-in water gauge as the pressure fluctuations normally occurring entail danger of reversal of ventilation and thus appearance of carbon monoxide in the intake air. In the case under review, this value was kept to approximately 0.24-in water gauge, possibly due to the opposing effect of the warm combustion gases.

(iv) Continuous monitoring is required and, if necessary, adjustment of the differential pressure, which can be checked by measurements from the tubing.

24. Apart from decreasing the differential pressure, it is also necessary to cut down the leakage by sealing operations in order to effect a permanent reduction in carbon monoxide development. To this end, the packs on both sides of the roadway west of stopping 416 were sealed with insulating foam.

25. If, subsequently, gas emission occurs in the gob, it is possible that decreasing the differential pressure, and hence the short-circuited air current, will stop the formation of combustible gas-air mixtures over wide areas of the gob up to the return roadway. In this case, it should be ensured that the upper limit of flammability of the gas-air mixture in the gob is exceeded (ie methane levels exceed those under which an ignition is possible) by sealing off the packs on both sides of the roadway and deactivating any drainage system in operation. This increase of differential pressure increases the amount of short-circuited air and thus lessens the danger of combustible gas-air mixtures occurring, but it also feeds the fire with greater amounts of oxygen, rendering the spread of the fire and higher carbon monoxide production probable; this measure cannot therefore be fully recommended.

26. If the pressure balancing method is used over long periods it is advisable not only continuously to monitor the return air for carbon monoxide as it passes the fire, but also the intake air. This enables a reversal in direction of the short-circuited air (cf paragraph 23, (iv)) to be recognised in good time.

PD-NCB NOTE

The above extract contains the observations of the authors of the paper. PD-NCB are surprised that stopping No 4 should have been sited in a position where it clearly increased the pressure across the fire area, thereby creating much of the condition that the fan was subsequently installed to correct. It is also surprising that men were allowed to do recovery work on the coal face from 24th July to 17th August when apparently there was only one means of egress.

This case history is quoted to illustrate the occurrence of spontaneous combustion in a particular circumstance, but the method of combat is not endorsed.

APPENDIX "F"

HISTORY OF SPONTANEOUS COMBUSTION OCCURRENCES - CASE NO 2 - GERMANY

Extract from the paper "Control of a Mine Fire at Osterfeld Colliery by the Introduction of Nitrogen", Kugler and Schewe, Gluckauf, Volume 111, 1975.

SUMMARY

1. A gob fire in a sealed-off panel led to the adoption of a fire control technique in which nitrogen was used. This was the first occasion on which this technique was employed on such a scale in any country.

LOCATION OF MINE

2. Osterfeld mine is located in the Ruhr coalfield at Duisburg, West Germany.

SYSTEM OF WORKING

3. The mine is laid out on the horizon mining system, ie having the main access roadways driven in the rock. The Gustav seam at Osterfeld mine is approximately 8 ft 6 in thick and is fully mechanised using double-ended shearer loaders and shield supports on longwall faces. The panel is developed from south to north on both sides of a main roadway. Working of the first east panel was unexpectedly curtailed in the southern portion when a fault was encountered (see Plate 40). To protect the roadways and reduce leakage, roadside packs of anhydrite were built at each end of the 620-ft long face.

NATURE OF THE PROBLEM

4. Shortly before the planned limit of the panel was reached, carbon monoxide was detected in the gas produced by the methane drainage system, and the quantity increased slightly during working. The cause was traced to spontaneous combustion in the caved area. On 28th October, 1974, a decision was made to remove the shield supports and after the longwall was prepared for this operation, coal getting ceased on 6th November, 1974, and the face was cleared of shield supports by the 27th November. Equipment was also removed from the belt conveyor road and the top road (except pipes).

ERECTION OF STOPPINGS

5. Following the salvage operations, stoppings No 1 and No 2 (see Plate 40) were erected and the access tubes were closed simultaneously on 1st December, 1974. Auxiliary forced ventilation was used for the old conveyor road.

6. As a result of the high gas emission, it was anticipated that the sealed-off heating would be extinguished quickly as the methane level exceeded the upper explosion limit. However, before this condition was reached, two small explosions occurred which resulted in an increase in carbon monoxide and the auxiliary ventilation being made inoperative. A further, more serious, explosion occurred next morning and stoppings No 3 and No 4 were prepared in case the need arose.

Stopping No 5 could be put on by delivering anhydrite through a pipe in staple shaft 6-6-23.

7. As soon as conditions free from explosion hazard could be created, it was decided to install stopping No 2a by introducing large quantities of an inert gas (nitrogen) into the combustion zone from a point near No 2 stopping in the direction of the effective pressure gradient.

8. A mine rescue team was sent in immediately following a deflagration. This is the safest time since the products of combustion can temporarily produce an inert atmosphere in the fire zone. This team's task was to make the requisite connections for the lines which were to be used for nitrogen delivery in the old conveyor road. The nitrogen would reduce the rate of combustion sufficiently to allow counter measures to be pursued.

9. The more time-consuming work on stopping No 2a could then be carried out under the protection of the inert gas blown in. Analyses were to be made to determine whether the entire length of the old conveyor road right up to the face was free from explosible gas mixtures.

PREPARATION FOR NEUTRALISATION BY NITROGEN

10. To prepare the nitrogen supply, a suitable pipeline running from the surface via the shaft as far as the junction at staple pit 6-6-23 had to be cleared and connected with an anhydrite pipeline open at the face of the heading. This anhydrite slurry pipeline had been used in the installation of the roadside packs and stretched from the position for stowing stopping No 2 in the old conveyor road up to the original start line of the longwall.

CONDUCT OF THE OPERATION

11. All the preparations, including the stationing of three mine rescue teams at the operation centre on the fifth horizon at staple shaft 5-6-24, were completed by the morning of 6th December, 1974. Following a further very slight deflagration at 3.00 pm, a mine rescue team was ordered in. In two brief actions, the anhydrite line was connected up and a separate line for remote sampling was laid to the fifth horizon.

12. After it had been checked for leaks, the pipeline running from the surface to the base of staple pit 6-6-23 was cleared of air by pumping in nitrogen for ten minutes. In addition, a suction fan was used for 30 minutes to extract the air from the anhydrite pipeline. A hand-held meter was used to monitor the absence of oxygen. At 8.15 pm the valve was reversed, releasing the nitrogen into the anhydrite pipeline. Initially the flow was regulated from the surface to 1,060 ft^3/min and subsequently increased to 2,120 ft^3/min.

13. During the morning of 7th December, 1974, the supply of nitrogen was interrupted for almost three hours to permit the switching of pipes. Remote samples taken at point No 2a immediately showed a drop in the nitrogen level and a concomitant rise in the oxygen level. Analysis did not show the return to a non-explosible gas mixture until 3.00 pm. Plate 41 shows this development and traces the course of neutralisation in relation to the explosion triangle. By 5.00 pm the levels had dropped to such an extent that the order for the construction of stopping

No 2a could be given. By this time more than 1,400,000 ft^3 of nitrogen had been fed in.

14. One mine rescue team carried out the necessary work on the airlines and made other preparations, while a second team brought an inflatable stopping to serve as a barricade at the planned site of the stopping; this was inflated with compressed air and by 10.30 pm was in position operating efficiently as a seal.

15. At 12.05 am on 8th December, 1974, several rescue teams were able to install stopping No 2a after samples had indicated that the air behind the inflatable seal was totally inert. Subsequent analyses showed nitrogen levels as high as 95%.

16. On 9th December, 1974, after stopping No 2a had been constructed and had set, the nitrogen supply was cut back; it was then completely turned off on 11th December, 1974. A total of 5,400,000 ft^3 of nitrogen had been used. On 9th and 10th December, 1974, it was possible for normal operations to recommence in the adjacent workings that had been lying idle. Further analyses taken in December at stoppings No 1 and No 2 by remote sampling and at No 2a, which showed a high methane level, an oxygen level of almost zero and negligible carbon monoxide level, indicated that the fire had been extinguished throughout the entire combustion area.

CONCLUSIONS

17. This was the first time that nitrogen was pumped in to control a fire in the Federal Republic. This action proved most successful and prevented losses of materials and reserves of developed coal.

18. A total of 5,400,000 ft^3 of nitrogen were delivered. The results of analyses indicated that the gob fire was rapidly extinguished.

19. The successful control of the gob fire by means of inert gas and the knowledge gained in the process could provide a basis for controlling mine fires in similar circumstances.

20. In principle, inert gases of all types are suitable for fire control. The selection of the specific inert gas to be used will depend on the particular circumstances. Nitrogen neutralisation is the most simple procedure from a technical point of view and also the safest. In this process, use can generally be made of existing commercial equipment. In addition, producers of industrial gas are able to provide large quantities of nitrogen if required. Really large quantities of nitrogen could be used underground if it proved possible to deliver it in liquid form through pipelines to the source of the fire. However, research would first have to be conducted into the relevant technical systems required for this alternative method of delivery.

21. The method used at Osterfeld is suitable for control of mine fires and recovery of combustion areas. The procedure is of particular relevance in the presence of an explosion hazard.

PD-NCB NOTE

In a gassy seam it is unwise to seal off a fire in the gob by stopping at the face end (Ref A6). It was also dangerous to send men to No 2 stopping to make connections for nitrogen. It would have been better to have placed the stopping at 2a initially *and balanced the pressure. The sample taken in December 1974 suggests that the build up of methane had expelled the nitrogen by then. This build up might have prevented the explosion if the stopping had initially been erected at 2a without the use of nitrogen.*

APPENDIX "G"

HISTORY OF SPONTANEOUS COMBUSTION OCCURRENCES - CASE NO 3 - INDIA

Extract from the paper "Fires and Inundations in Indian Collieries", J.H. Burn, Iron and Coal Trades Review, June 1955.

SUMMARY

1. A seam previously free of fires became subject to spontaneous combustion as a result of robbing pillars and reducing them to a size inadequate to support the roof. Crushing of the pillars occurred and masses of broken coal accumulated in worked out areas. Fissures and cracks through to the surface allowed air leakage to supply oxygen to the crushed coal, resulting in spontaneous combustion.

MINING ENVIRONMENT

2. The mine had been operating for over 60 years, under profitable conditions in the early years of its existence but, due to competition from collieries mining higher-grade coals which had filled market demand, working had been reduced to two or three days' winding per week, and the mine was under threat of complete closure.

3. The 1939 to 1945 war affected the coal trade and demand was for a level of output that could not easily be met by an industry which was in a depressed state. It was obvious, therefore, that abnormal methods would be called for. Output from the mine was soon doubled, but this spurt could not be expected to continue for long unless more production capacity could be found.

SYSTEM OF WORKING

4. Four seams had been proved at the mine, of which two were workable economically. The upper of these was from 4 ft to 7 ft thick, including bands of stone up to 6 in thick. The seam outcropped within the lease area, which covered an area of about 5 miles^2. Initial working had been completed and 60-ft square main pillars had been split in both directions over a wide area, leaving quite small remnants. Pillar extraction had been carried out in two small areas to the dip of the winding shaft, without causing any appreciable subsidence, before working had been abandoned for economic reasons. Both this and the upcast shaft were centrally situated in the lease area and the seam was under 180 ft of cover at that point. Water had been allowed to fill the dip workings and overflow down a drift to the lower seam at a point about 800 ft to the dip of the shafts. During the war, a short drift was driven to this seam from below to enable further splitting of rise pillars to be carried out while faces were prepared elsewhere.

5. The lower seam was 11 ft thick, to the rise of the shafts, where it was under 260 ft of cover. It contained bands of "splint" coal which varied in thickness from 18 in to 3 ft but these gradually diminished towards the dip, where the coal thickness was reduced to 8 ft. To the rise of the shafts, both seams had been worked from inclines and no definite panel system had been practised. These rise pillars in the lower seam were 75 ft square, but considerable splitting had been done. Pillars had also been extracted in several areas and in the largest of these a

heating had occurred which had to be isolated. All these de-pillared areas had been isolated from the rest of the workings by over 100 stoppings.

6. The dip workings, which had been laid out in panels containing 100-ft square pillars, had been allowed to flood to within 750 ft of the shafts during difficult economic conditions. The workings consisted of two districts, the Main Dip and South-West crosscut, the latter having reached the lease boundary at a point 3,200 ft from the shafts.

7. There were no records of analyses of the dip side coal, and when these workings were later dewatered it was discovered that the 8-ft-thick clean seam was of excellent quality and, had the rise workings been left alone, the coal might have found a profitable market. It is possible that the cause of this abandonment of dip workings was not so much economics, but rather the lack of boiler power during the heavy monsoon rains. A long-term policy covering the dewatering of the dip workings was discarded, at any rate for some time, and a short-term policy of pillar extraction was adopted, starting from near the outcrop, which ultimately led to a most serious situation.

8. The mine was fairly well equipped and had a small power generating station, a screening plant, large workshops and $3\frac{1}{4}$ miles of private railway. The pumping plant was adequate for normal conditions and ventilation was produced by a fan at 2-in water gauge. Underground conditions were favourable with a gradient of 1 in 8, which flattened out to the north-east.

OCCURRENCE OF GOB FIRES

9. Before the war ended, and for some time afterwards, gob fires became frequent. This was unexpected, as the coal was not thought to be so liable to combustion. Eventually, however, it was noticed that the temperature under normal working conditions at the gob edges was cooler than elsewhere. Inspection of the surface revealed the existence of a large number of cavities, often hidden by jungle, which had formed over a period of years and which were rapidly increasing in number and size. Air was being drawn in by the fan, especially through newly-gobbed area. The practice had been temporarily to stop the fan when fires occurred, and build brick seals 11 ft high and about 2 ft 6 in thick over the width of the splits, under conditions of high temperature. When the extent of these cavities became known, the method adopted was to reverse the ventilation after a careful inspection of every stopping against old gob areas, surface sealing where necessary. In this way, the fires were put under positive pressure until the seals were complete. Inflammable gas was unknown and this method saved considerable time and trouble. It is clear that, had the cover been sufficient, the fires would not have occurred. Where cover was only 70 ft, collapses followed the working face line continuously.

LARGE PILLAR AREA

10. There was one section containing pillars which was large enough to provide output from splitting and so enable the practice of pillar extraction to be terminated without any serious reduction in output, but this area was sealed by a line of stoppings far below a fire which was known to be drawing oxygen through cracks in the vicinity of a fault. It was therefore proposed to put this area under positive pressure, by using the fan shaft as a downcast, and so drive heat back to the surface. The cause of this fire was reputed to be a connection to a gob area,

which had never been sealed at the time, made many years previously when a neighbouring gob had been isolated and subsequently fired.

11. The fan was reversed and one of the stoppings holed, but this attempt failed to put out the fire as the cracks proved too small to pass sufficient air. The stopping was again closed and the ventilation allowed to course normally.

REVERSAL OF VENTILATION

12. A further attempt was made by sinking a small-diameter shaft in the jungle near the outcrop, over workings which were well clear of the cracks and probable fire position. This operation was carefully carried out, using exploratory boreholes in the shaft, and when a connection was imminent a stopping near the return airway was holed to ensure that a join to the workings would be made in fresh air. An inspection proved that no active fire existed within 100 ft of the bottom of this shallow shaft. The next step was to withdraw all men, reverse the ventilation and expel the heat and smoke from the district through the new shaft to the surface. Unfortunately, too much pressure was applied and flame and smoke issued from the shaft. The attempt was postponed, the stopping closed and the shaft covered over.

13. After a period of 12 months, a second attempt was made, which was successful. On this occasion, after months of slow but steady progress, a row of 22 fire dams was built within 50 ft of six active fires and a duplicate row was subsequently built as a safety measure. The humidity was extremely high, the heat almost unbearable and it was necessary to keep the stoppings under positive pressure for some time until the fires died as a result of blanketing the cracks and covering the top of the shallow shaft. This recovered section enabled pillar extraction to be stopped.

CONCLUSIONS

14. This case is an example of a hitherto fire-free seam being rendered dangerous as a result of reducing support pillars to an inadequate size. Consequently, crushing of pillars took place and large amounts of broken coal accumulated in worked-out areas. Fissures and cracks permeated the coal mass and adjoining strata. A poorly supported area under such shallow cover caved to the surface and air leakage supplied excess oxygen to the already broken coal, resulting in spontaneous combustion.

APPENDIX "H"

HISTORY OF SPONTANEOUS COMBUSTION OCCURRENCES - CASE NO 4 - CANADA

Extracts from the papers "Spontaneous Combustion Problems in a Hydraulic Coal Mine", R.N. Chakravorty and K.K. Feng, ERP/MRL 75/113.

"Application of Infra-red Thermometry in the Early Detection of Spontaneous Combustion in Coal Mines", R.N. Chakravorty and R. Woolf, ERP/MRL 75/110.

SUMMARY

1. This example of fires caused by spontaneous combustion occurred in a Canadian mine where the method of working towards the outcrop in a mountainous district led to fissures communicating with the surface, producing air leakage in the pillars and consequential heating.

LOCATION OF MINE

2. The mine is situated at Sparwood, near Fernie in British Columbia, and is at present mining the coal of the Balmer 10 seam, which has an approximate thickness of 45 ft, pitching at an angle of 30^0 to 60^0. The coal is low to medium volatile bituminous. The overburden in this area is mainly sandstone and shale, and the depth of cover over the existing workings varies from 400 ft to 700 ft.

SYSTEM OF WORKING

3. Coal extraction is by a sub-level caving hydraulic mining technique. Full retreat is employed with continuous mining machines driving the development entries and sub-levels. A hydraulic monitor is used to extract the coal by a water jet discharging at a rate of 1,500 gal/min under a pressure varying from 550 lb/in^2 to 2,550 lb/in^2, depending on the hardness of the coal, and the monitor has a range of 80 ft. Coal dislodged by the water is washed through a feeder breaker and into a flume where it goes by gravity flow to the dewatering plant.

4. The main roadways were driven initially from a low point in the outcrop with a gradient to the rise so that they reached the outcrop on the other side of Sparwood ridge, leaving a strip of coal 500 ft to 1,000 ft in width between the main roadways and the outcrop. This strip of coal dips towards the main roadways, and is mined by driving sub-levels into it. The sub-levels are also driven at a gradient rising towards the outcrop. Hydraulic winning of the coal starts at the furthest limit of the sub-level. The headings, supported by steel arches, are retreated as the monitor retreats, between 40 ft and 60 ft at a time. Sub-levels are spaced about 60 ft apart.

5. Ventilation for all the panels worked so far was forcing with the main volume of return air passing through the gob into the outcrop. The typical ventilation system is shown on Plate 42. Different panels which were worked since inception are also shown on this plate.

6. Though the recovery percentage from the 45-ft-thick seam is remarkably high, a large amount of coal is still left in all the worked-out areas.

7. Development work on the deeper levels is completed by driving a rock tunnel and three additional roadways, also as shown on Plate 42. Production in panel 5A is almost completed, and panel 5B was expected to go into production by the spring of 1977.

LOCATION OF FIRES

8. The first fire was noticed in the panel 2 outcrop in late 1972, almost one year after completion of production in that panel. In this particular panel production continued almost up to the outcrop, and very little barrier pillar was left. The gob area close to the outcrop caved extensively and the fire was noticed initially in the caved area.

9. The second major fire broke out in early 1974 inside gob 4B, and smoke was found coming out through the fractured mass of coal close to the temporary wooden stoppings used for isolating the gob area after production in panel 4B was completed. The location of the fire area is shown on Plate 42. The fire area was immediately sealed off and later isolated from the rest of the working by erecting a number of concrete stoppings in all the sub-levels and crosscuts close to the affected area.

10. In April, 1975, a third fire became visible in the outcrop area of panel 2 close to an adit mouth at a distance of 200 ft to 300 ft from the area where the fire first started in 1972. The fire was blanketed by a thick layer of crushed rock.

11. Later, the return air from gob 5A started showing an increasingly high concentration of carbon monoxide, indicating the onset of spontaneous combustion inside the gob area. The gob was isolated by building stoppings, and the ventilation system re-organised.

CAUSE OF FIRES

12. Visual surveys of the underground roadways and the surface areas on top of the mine indicated that fissures and cracks caused by subsidence were prominent in certain areas, but not so visible in other places. It was obvious that gob 2 had become connected to the surface through numerous cracks and fissures after the area near the outcrop caved. Part of the outcrop area close to panel 4B had also caved after production in the panel was completed. When the fire was detected in gob 4B, some of the sub-levels close to the fire area showed extensive fissuration in the surrounding coal mass, in spite of arched supports in that area.

13. Subsidences resulting in major fractures were noticed on top of 4A and 4B gob areas, but it could not be ascertained whether these cracks directly assisted in air leakage to the gob at a depth of 500 ft to 700 ft.

14. It is known that a high concentration of loose coal in the worked out area and excessive fissuration due to strata movement producing air leakage, contribute significantly to the development of spontaneous combustion in coal mines. It is therefore obvious that elimination of spontaneous combustion is difficult with this system of working, where mining frequently promotes fissures through to the surface. This makes the early detection of heating an absolute necessity.

RECOMMENDATIONS

Detection of Spontaneous Combustion

15. The recurrence of incidents of spontaneous combustion made it imperative to develop systems suitable for the early detection of heating. Obviously heatings which remain undetected until it is too late to gain control may become expensive, but a heating which can be dealt with at an early stage will save the mine considerable damage and possible loss of production.

16. Two lines of approach were followed at the mine:-

(i) Infra-red technology,

(ii) Carbon monoxide monitoring system.

Infra-red Technology

17. Field and laboratory studies have indicated that infra-red technology would prove to be a powerful tool in the early detection of heating, provided the small variations of temperature could be correctly interpreted.

18. Though the development and manufacture of infra-red instruments are fairly intricate, the operation of the equipment is simple, and it appears to be robust enough for underground use. The mine ventilation engineers would have no problem in carrying out periodic surveys using this equipment.

19. Thermal surveys of all areas considered vulnerable to spontaneous heating, such as cracks, fissures, crushed pillars or any accumulation of coal, should be carried out once every two weeks. Should the area indicate any appreciable variation from the normal, more frequent surveys should be undertaken.

20. The infra-red detection system would be valuable for determining hidden oxidation or fire before it spreads extensively, and where it is difficult to notice carbon monoxide emission because of the blowing system of ventilation or otherwise. For detection of heating around the periphery of stoppings in the mine, or for locating heating in the cracks and fissures in the intake airway, infra-red technology would prove most useful.

21. From infra-red survey alone, it would be hard to draw any exact conclusions as to whether the heat build-up was deep below or near the surface. It would be advisable to determine the depth by inserting a thermo couple/thermistor whenever possible.

22. The infra-red instruments are not capable of detecting heating or fire deep inside a gob, nor where the equipment is not in line with the hot surface.

Carbon Monoxide Monitoring

23. Laboratory studies on the lower temperature oxidation of Balmer 10 seam coal showed that a significant amount of carbon monoxide is produced during the early stage of heating, and detection methods based on the analysis of other gases such as hydrogen, ethane, ethylene, etc, are not preferable for this coal.

24. For early detection of heating in the hydraulic mine it was therefore necessary to develop methods by precise monitoring of carbon monoxide. An analysis of spot samples indicated that the carbon monoxide in the return air varies between 1 ppm to 5 ppm, and with such a large volume of air passing through the gob, increases in carbon monoxide concentration will not be expected to exceed 10 ppm to 20 ppm during early stages. Under the circumstances, it would be essential to use an analyser which is capable of giving an accuracy of ± 1 ppm in the range of 0 to 50 ppm. In addition, it should be stable enough over a long period of unattended operation.

25. Consequently, only a four point monitoring system was built to keep the cost to the minimum. It was considered advisable to establish the suitability of the carbon monoxide monitoring under conditions prevalent in the hydraulic mine before any large-scale installation was undertaken. The system is capable of analysing air samples from four different locations in the mine sequentially. Pre-filtered air can be drawn into the system from four different locations up to a distance of 7,000 ft per point through $\frac{1}{2}$-in diameter polyethylene tubing, analysed for carbon monoxide content, and then exhausted to the atmosphere. The system essentially consists of the following functional components:-

(i) electro-chemical carbon monoxide analyser,

(ii) one thermal printer with accessories,

(iii) vacuum pumps, four in number,

(iv) polyethylene tubing,

(v) logic unit,

(vi) mini computer.

26. The electro-chemical carbon monoxide analyser is capable of giving an accuracy of ± 1 ppm over a sustained period. The indicator reads carbon monoxide directly to 0 to 10 ppm and 0 to 50 ppm. The thermal printer used with the analyser provides a record of the data at any given time. The information recorded in the printer is as follows:-

(i) day of the year (1 to 365),

(ii) time of day on 24-hour system,

(iii) sampling point number,

(iv) range selected (0 to 10 ppm or 0 to 50 ppm),

(v) carbon monoxide concentration in parts per million,

(vi) alarm condition due to system fault.

27. The logic unit controls the operation of the entire system. The major function of this unit is to control the sequence of opening and closing of the solenoid valve, activating the indicator lights and the thermal printer so that a print out can be obtained at the desired time interval.

28. The air sample from each line is analysed for a period of 15 minutes, and the results are printed out at the end of this period. Thus the results from each sample line are printed once every hour. It is possible to increase or decrease this time interval by modifying the logic unit.

29. The mini computer built in with the system is used for calculating the difference in carbon monoxide values at four-hour intervals for each sample line. Thus the difference in carbon monoxide concentration in parts per million is recorded for each line every four hours. The positive or negative sign in the print indicates whether the carbon monoxide concentration has increased or decreased during the past four-hour period.

30. The polyethylene tubing used for sampling air from different locations in the mine is colour coded, so that it can be easily identified. To avoid leakage, the number of joints in the polyethylene tubing are kept to a minimum.

31. Two sets of moisture and dust traps are used with each line to prevent clogging. However, the vacuum gauge on the front panel gives an advance warning as to whether the resistance of any sample line is increasing due to the accumulation of dust or moisture. End-of-line filters are used to remove coarse dusts. The finer dusts are eliminated by the 20-micron filter assembly just before the analyser.

32. The polyethylene tubing is laid out so that monitoring of panel 5B can be carried out during the life of this panel. The carbon monoxide analyser assembly is installed in a trailer located near the lower portal (intake airway). The polyethylene lines coming from the mine to the trailer are insulated and heated to guard against freezing during sub zero temperature.

33. The carbon monoxide analyser is periodically tested for accuracy and repeatability by using two pre-calibrated gases having a concentration of 5.8 ppm and 19.5 ppm respectively. Two standard gases instead of one are used so that both accuracy and repeatability can be ensured. The carbon monoxide monitoring system was commissioned towards the end of September, 1976. The problems associated with clogging of sampling lines because of dirt or moisture in the air were negligible and the sample lines withstood two cavings and roof falls without damage. Between September, 1976, and January, 1977, although four sampling points were drawing samples from four different sections in the mine they were all located in intake air. The return was exhausting into the outcrop area. In February, 1977, the ventilation was re-organised and two sample points started monitoring the return air.

34. During September and early October, 1976, the carbon monoxide content in air from all sampling points averaged about 2 ppm to 3 ppm. The air sample from the main flume roadway showed a value of 4 ppm to 10 ppm periodically, depending on the number of diesel vehicles operating underground and the proximity of the vehicles to the sampling points. However, carbon monoxide concentration returned to a value of 2 ppm to 3 ppm during the night shift, signifying that the rise was solely due to the movement of diesel vehicles.

35. When the air pre-heaters (installed to raise the temperature of the intake air) were started in October, 1976, the carbon monoxide values from all the sample points showed a moderate increase because of pollution from the combustion products produced by the pre-heating burners in the intake air. Depending on the performance of the burners, carbon monoxide values in the intake air showed a

variation between 3 ppm to 10 ppm, but no appreciable difference between this value and those in the other three lines could be noticed, signifying that no unusual oxidation is taking place inside the mine. Finally, because of diesel vehicles in the flume road, the carbon monoxide concentrations had occasionally shot up to a value of 20 ppm to 25 ppm for a very brief period.

36. In early February, 1977, the return air escaping into the outcrop, through gob 5A showed a carbon monoxide value of 1,000 ppm by spot analysis, using drager tubes. As mentioned earlier, the return air could not be monitored until February, 1977, because of the existing ventilation arrangements. However, the air samples monitored from different parts of the mine did not show any rise in carbon monoxide confirming that the heating is localised in gob 5A, and the product gases are not backing into the main ventilation system of the mine.

37. Since February, 1977, the return air for panel 5B has been monitored and studies on the carbon monoxide trends in both intake and return air will be continued during the life of panel.

38. For early detection of heating, the absolute level of carbon monoxide in mine air, whether high or low, is not of great significance but a steady increase in the carbon monoxide concentration is often indicative of unusual oxidation in the mine. In such situations, it would be advisable to keep a close watch on the problem area and, whenever possible, to carry out a thermal survey using infra-red equipment.

39. The present carbon monoxide monitoring system would also prove invaluable in ensuring mine safety by indicating the actual carbon monoxide concentration in different sections of the mine long before it reaches toxic level. Thus, the system would provide sufficient time for the orderly withdrawal of the work force if such a measure were warranted.

APPENDIX "I"

HISTORY OF SPONTANEOUS COMBUSTION OCCURRENCES - CASE NO 5 - UNITED KINGDOM

Extract from the report "Fire at Michael Colliery", H.S. Stephenson, Chief Inspector of Mines, London, HMSO, 1968, Cmd (3657).

SUMMARY

1. A mine fire caused by spontaneous combustion in the shaft pillar was masked by a lining of polyurethane foam, which is such a good sealant that all signs by which mine personnel might have detected a heating were absent. Recommendations included the banning of the use of polyurethane foam underground. At the time there were 311 men underground; it is remarkable that all but 9 escaped. This can be attributed to the efficient below-ground communication system.

LOCATION OF MINE

2. Michael mine is situated on the northern shore of the Firth of Forth, in Fife, Scotland.

SYSTEM OF WORKING

3. The working seams are all contained in the productive coal measures of the carboniferous series; the total thickness of the strata between the top seam and the bottom seam is 450 ft, within which there are 19 seams dipping seawards in a south-easterly direction at gradients varying from 1 in 3 to 1 in 2. At the time of the fire, five seams were being worked.

4. Access to the sections in the No 2 mine workings was by horizon tunnels and, in No 3 mine workings, by roads in the seams.

5. Ventilation was provided by a 1,000-hp radial flow fan situated at No 2 shaft, which was 20 ft in diameter and 860 ft deep, producing 310,000 ft^3 of air per minute at 3.5-in water gauge. No 3 shaft served as the downcast and was 24 ft in diameter and 600 ft deep.

PRE-FIRE EVENTS

6. The most significant events at the mine in the months prior to the fire in September, 1967, were a heating in the Loader roadway on 24th July and a fire in the Dysart Slope No 1 section on 6th August, 1967.

The Heating of 24th July, 1967

7. On 24th July, 1967, a heating was discovered in the shaft bottom area at the site of an old fall (see Plate 43). The burning material was dug out for quenching and ultimately a cavity 8 ft high and 10 ft long was excavated. After cooling to 70^{0}F, the cavity was filled with sandbags built up on steel girders with plaster puddled between the bags and the coal sides. Both the outbye and inbye sides of the cavity were treated in this way, leaving a narrow shaft up the middle, which was similarly treated using fireboards as supports for the sandbags. As soon as the immediate danger was past, it was decided that the lining of the roadway

with polyurethane foam should extend over a length of some 150 ft. Preparation of the site included the making of four recesses, each about 4 ft wide and 2 ft deep, cut into the sides of the roadway to provide adequate sealing for the foam lining. The work of applying the foam was completed on 6th August.

The Fire of 6th August, 1967

8. Later this same day a fire occurred in the Dysart Slope No 1 section of the mine. The management considered this incident to be a greater risk to the safety of the mine and it was decided to have the main roadway of this section treated with polyurethane foam. This work was completed on the night shift of 8th to 9th September.

9. Following this second incident, an increasing number of air samples were taken daily under special arrangements designed to give information about the effectiveness of the fire-fighting measures taken. On 8th September a carbon monoxide analysing and recording device installed in the section was tested satisfactorily and, as a result, the special arrangements for sampling were discontinued in favour of the normal sampling pattern.

THE EVENTS OF 9TH SEPTEMBER, 1967

10. During the night shift of 8th to 9th September at about midnight, a belt conveyor attendant working in the vicinity of the site of the first fire heard several rumbling noises and a loud bang which he thought were due to normal strata movements. At about 2.30 am he informed the overman who made an inspection of the area but noticed nothing unusual. An hour later the overman smelt smoke and, on investigation, he saw a blue haze. He went towards the site of the old fall and previous fire and saw what he took to be burning coal falling from the roof. There was no smoke. Amongst a small quantity of this material, he particularly noticed "one piece lying on the floor about 6 in square, and it was blazing; it was black but there were fumes coming from it". He rushed via other roadways to the opposite side of the fall area, where he met very heavy smoke. The distance was no more than 200 yd and the time taken probably no more than two minutes. Yet in this short time, an apparently clear atmosphere had changed to one laden with dense smoke.

11. The alarm was raised, telephone calls made and messages were sent to warn others. At the time there were 311 men underground; it is remarkable that all but nine escaped. There is no doubt that, in large measure, this was due to the comprehensive and rapid manner in which messages were transmitted round the mine. Six bodies were recovered from positions indicating that they were making their way to the shaft, whilst three other men whose last known positions were in the Dysart Dip and Four Foot district were unaccounted for.

FIRE FIGHTING

12. Since the hydrant nearest to the fire was in smoke, it could not be used; insufficient hose was available to reach the next hydrant in fresh air, so it was transferred nearer to the fire. This took time and it was not until some two hours after the outbreak of fire that water was first applied to it. This was successful in isolating the burning material on the floor but the fire was, by then, virtually out of control. The heat was intense and prevented any advance of the fire fighters and they had to withdraw. Smoke frustrated an attack from other directions and by 3.00 pm on 10th September, conditions had so deteriorated that it was decided that too many men were being put at risk and stoppings would have to be installed.

CAUSE OF THE FIRE

13. The investigation concluded that the fire was initiated by spontaneous heating of the coal in the roof somewhere in the section of roadway that had been lined with polyurethane foam. It is probable that the source of air leakage that caused the heating was in the direct connection between intake and return in the stopped-off heading overlying the seat of the fire, in which there was a difference in pressure of 1.5-in water gauge.

14. Attention was drawn to the virtual absence of warning of the initial heating. Experiments have shown that the foam is such a good sealant that it not only keeps out air, but effectively masks any temperature changes, noxious gas emissions and the smell associated with heatings. Thus all signs by which mine personnel might have detected a heating were absent. This would explain why the overman, who made an inspection less than an hour before the fire broke out, noticed nothing unusual.

RECOMMENDATIONS

15. Following the inquiry it was recommended that:-

(i) polyurethane foam should not be used underground,

(ii) any foam which had been placed underground should be removed,

(iii) the senior official on duty at the mine at any time should be authorised to call out the rescue services without reference to higher authority,

(iv) the personnel checking system should be examined for the possibility of improvement,

(v) signposting means of egress should be improved,

(vi) mine officials should regularly inspect all means of egress.

APPENDIX "J"

HISTORY OF SPONTANEOUS COMBUSTION OCCURRENCES - CASE NO 6 - AUSTRALIA

Extract from "Report on an Accident at Kianga No 1 Underground Mine on 20th September, 1975 - Warden's Inquiry".

SUMMARY

1. In this Australian mine, pillar and stall working leaving the top coal led to spontaneous combustion in the caved area. Lack of knowledge in dealing with the incident led to an explosion of methane which in turn propagated a coal dust explosion with consequential loss of life and sealing off of the mine. Recommendations are made for training at all levels and improvements in mining law.

LOCATION OF MINE

2. The Kianga No 1 mine is located about 11 miles from the township of Moura in Central Queensland, Australia.

SYSTEM OF WORKING

3. The basic mining method utilised continuous miners for development and pillar extraction. Barriers were left between adjacent panels so each panel could be sealed immediately working was completed. This procedure was adopted so that any subsequent spontaneous combustion could be controlled.

4. The method of mining involved the removal of the bottom 10 ft of the seam by the use of continuous miner-shuttle car combinations. The top 4 ft of coal was left against the roof.

5. The panel workings were developed with three headings: two intake airways (man-and-supply and belt road) and a return airway in each of four sections designated No 1, 2, 3 and 4 North (Plate 44).

6. No 4 North was the most remote panel from the surface. Its working face was located about 3,600 ft along the slope of the seam and then to the north at right angles, a distance of about 1,400 ft. As No 4 North panel developed, the management found difficulty in maintaining satisfactory roof conditions. A fall occurred in the development and it was decided to retreat from the section, recovering such coal as could be mined.

7. No 8 crosscut had fallen completely from the return road to the man-supply road. Roof coal and stone had broken to a horizon 8 ft above the seam at a smooth parting. Because of the time it would take either to clear or drive around the fall, it was decided not to develop the district any further north.

8. It was proposed that the coal in the section would be extracted from No 7 crosscut back to the main dips. It was estimated that the coal recoverable would be totally extracted within six months from 12th March, 1975. It was then planned to withdraw completely and erect permanent stoppings to seal off this section. This action was to be taken because it was known that coal in the Moura district tended to ignite spontaneously after an assumed incubation period of six months.

However, work progressed until 12th August, when the miners' annual holiday commenced, and restarted on 25th August, but then lapsed until 18th September because of an industrial dispute. Production took place on 19th September, the day before the explosion; the mine was not scheduled to work on Saturday, 20th September.

DISCOVERY OF FIRE

9. On a pre-shift inspection of the No 4 North section on this date a slight haze was observed in the main return near No 3 cut-through. Further investigation located smoke oozing from a wide area of fallen stone 3 ft to 4 ft thick, heaped upon 2 ft to 3 ft of coal. The area was defined as being in an extracted pillar outbye No 7 cut-through between the belt road and the supply road. There was slight ventilation and readings of 25 ppm carbon monoxide and 1.5% methane were taken. Where the gob had broken off in No 7 cut-through a reading of 4% methane was made. There was no smoke in this dead end and the air was stagnant where the 4% methane was detected. The decision was taken to build permanent brick stoppings inbye of No 4 cut-through.

10. Work was set in motion to erect brattice sheets prior to the construction of the brick seals. The brattice sheets were set on the supply road, the belt road and the return. When construction of the brick stopping began at about 11.30 am smoke behind the brattice had increased in density. The carbon monoxide content was 100 ppm and methane holding at 1.5%. Building of the stoppings was continued by the afternoon shift and meanwhile carbon monoxide and methane measurements continued to be made. A message at 4.50 pm indicated that the conditions underground regarding smoke remained the same. At about 5.10 pm an explosion was heard at the mine surface and a cloud of dust, together with roofing iron and timber, was blown out of the mouth of the mine. Analyses of samples taken during the next 24 hours indicated that the mine was on fire and a decision was made to seal off the mine the following day. The spontaneous-combustion-caused fire and subsequent explosion led to the loss of 13 lives and the closure of the mine.

NATURE OF OCCURRENCE

11. From the evidence it would appear that the explosion arose from the ignition of flammable gases by a spontaneous combustion source in the gob of No 4 North district.

12. The explosion propagated outbye involving coal dust, but evidence shows that it was extinguished before arriving at the mine portals.

13. The force of the underground explosion was sufficient to project material to the surface and cause damage to surface structures in a direct line from the mine portals.

14. Heat from the explosion was not experienced by witnesses on the surface, but some of the coal dust ejected shows evidence of having been affected by heat.

15. The explosion was followed by fires underground.

CAUSES OF OCCURRENCE

16. A heating developed in the gob area of No 4 North section of the mine. As the heating accelerated in its intensity, the coal would ignite at a temperature of around 750°F. This would draw air and gob gases, which by this time would include hydrogen, carbon monoxide and methane, to the fire; any of these gases could then have been ignited. Ignition temperatures are as follows:-

Hydrogen	1,080° to 1,090°F
Carbon monoxide	1,190° to 1,220°F
Methane	1,200° to 1,380°F

17. There appears to have been a large body of methane in the gob area of which the 4% methane found at the edge of the gob at No 7 cut-through was part.

18. Sufficient air was not passing over the hot material to dilute the gas or to cool the material below the ignition point of all the flammable gases. A drop in barometric pressure could increase the volume of flammable gases in the gob, so as to bring an explosive mixture of gas into contact with the fire.

19. Over the six-hour period prior to the explosion, a barometric pressure drop of not less than 5 millibars occurred.

20. Sufficient coal dust was present in the vicinity of the gas concentrations to propagate a coal dust explosion.

COMMENTS ON CAUSES

Planning

21. Due to disruptions to production, the panel was not completed within the six-month period. The continuation of extraction was justified by the management on the grounds of the presence of a Beckman analyser to alert them to an incipient heating. The exclusive reliance upon carbon monoxide determinations can be misleading unless the air quantity flowing remains constant. Sampling of the mine atmosphere for carbon monoxide without also measuring the air quantity produces unreliable data. In this regard, it must be emphasised that the distribution of the air within the district was never established, so that when emergency action had to be taken, the essential background information was not available.

METHOD OF WORK

22. The full thickness of the seam was not worked. This resulted in broken top coal being present in the gob area. Where seams are prone to spontaneous combustion it is preferable, if the seam cannot be worked completely in one lift, that bottom coal be left rather than top coal. In any event, the extraction of coal should be as complete as practicable.

23. No preparations had been made at the mine for speedy sealing of working sections.

Ventilation Systems

24. The No 4 North panel was designed to operate with a dip-side gob ventilated by a bleeder system. With respect to gassiness, the panels were designed to use bleeder returns in an attempt to keep gobs clear of methane accumulations.

25. Whether the attempted ventilation of the gob was justifiable, knowing the likelihood of spontaneous combustion, is strongly arguable. If the gob is to the dip of the returns, it is possible, without a bleeder system, that there will be some migration of air into the gob as a replacement for the lighter methane. However, this is not the case if the gob is to the rise of workings, where high percentages of methane will preclude oxidation of coal and hence spontaneous combustion.

Atmosphere Control

26. Whilst the Beckman gas analyser was in use at the mine, the system of sampling allowed for errors to occur and the lack of ventilation readings reduced the value of the gas analyses.

27. With regard to carbon dioxide, whilst some readings were taken, these were not used to establish carbon monoxide:oxygen ratios.

28. The normal signs of sweating, smell and haze were not detected in No 4 North return or gob area prior to the discovery of smoke.

Stone Dusting

29. This explosion involved the untreated coal dust in the gob area and formed a gas and coal dust explosion which was fed by insufficiently treated coal dust in the return. How far the coal dust explosion was propagated is unknown, but it is evident that it was brought under control by well stone-dusted areas outbye.

Emergency Action

30. The erection of the brattice "seals" in the man-and-supply road, the belt road and the return road, together with the destruction of the brick seal in No 4 cut-through, would have caused a drastic reduction in the current of air that was ventilating the eastern rise zone of the gob. Such a reduction in air flow would reduce the dissipation of heat at the site of the heating and thereby accelerate the spontaneous combustion process. In addition, any methane which was migrating through the gob would be less diluted. The increased rate of heating would draw air and any migrating gases to the source.

31. All authorities agree on the need to dilute gases surrounding a heating during sealing. Neither the Inspector nor management appeared to understand the effects of erecting brattices and no attempt was made to measure the air flow at any time on the day in question, and possibly the omission of this detail may have been in itself responsible for the explosion. However, it cannot be said with certainty that the explosion would have been averted if the brattices had not been erected.

32. Whilst on 20th September, 1975, two barometric pressure readings were taken and recorded by the respective Deputies, no weight was attached to the barometric changes by persons responsible for making decisions.

33. Notwithstanding the fact that the Manager and Superintendent were actively involved, the mine organisation underground on the day was wholly inadequate in that:-

(i) No senior officials were left in charge throughout the period.

(ii) No regular comprehensive sampling at specific sampling points was initiated.

(iii) No checks were made to see that men did not enter gob areas without the knowledge of the Deputy in charge.

(iv) No attempt was made to get as near as possible to the fire site, ie, the belt heading just outbye No 7 cut-through, after about 11.30 am.

Due to these inadequacies, the accelerated progress of the fire was not recognised.

34. During 20th September, 1975, persons were entering zones of smoke without instruments to determine the toxicity of the atmosphere, commencing with the initial inspection by the Manager and his Deputy.

35. No organisational structure with a definite line of command was established on the surface during the emergency period. Thus, there was no comprehensive system of briefing of officials or recording of the information obtained during the sealing operations.

RECOMMENDATIONS

36. It was recommended that:-

(i) the knowledge of all members of the coal mining industry be upgraded with regard to spontaneous combustion;

(ii) changes be made in the Mining Act to provide for:-

- additional protection against the propagation of a coal dust explosion,
- monitoring or sampling of ventilation,
- preparatory seals and the recognition and delineation of responsibilities of technical authority superior to a manager;

(iii) additional analytical facilities be provided.

Other general recommendations relating to safety were also made.

PD-NCB NOTE

The erection of brattices as temporary stoppings prior to the construction of permanent stoppings is dangerous and should not be done.

APPENDIX "K"

HISTORY OF SPONTANEOUS COMBUSTION OCCURRENCES - CASE NO 7 - USA

Extract from "Report of Coal Mine Fire, Somerset Mine", J.L. Bishop, J. Matekovic and R.L. Malenset, United States Department of the Interior, Bureau of Mines.

SUMMARY

1. A spontaneous-combustion-caused fire resulting from roof falls or floor heave which restricted the normal air flow led to the sealing off and temporary abandonment of this room and pillar mine which was extracting 8 ft of coal and leaving 4 ft of top coal and 10 ft to 12 ft of bottom coal. A fire at one of the primary seals resulted from chemical reaction and/or improper mixing of urethane foam.

LOCATION OF MINE

2. The Somerset mine is located at Somerset, Gunnison County, Colorado, along State Highway No 133.

SYSTEM OF WORKING

3. The mine is opened by four slopes, a drift and a shaft into the "B2" coal bed, which ranges from 20 ft to 25 ft in thickness. A total of 222 men, 188 underground, were employed on one maintenance and two coal-producing shifts a day, five days a week. Average daily production was 4,000 tons of coal.

4. The current operator started work at the Somerset mine in 1960. The area involved was developed by the room and pillar method prior to 1944 by the former operator. Entries were driven on 80-ft centres and crosscuts were turned on 90^0 angles at 80-ft intervals. The mining system consisted of extracting 8 ft of coal, leaving 4 ft of top coal and from 10 ft to 12 ft of bottom coal. Conventional timbering was employed as roof support - top coal left in place contributed towards roof control.

5. The No 3 entry and areas of No 1 and No 2 entries, Five West Mains, were rehabilitated after the present company started operations.

6. The mine is ventilated by 7-ft and 8-ft axial flow fans, operated exhausting. They are located at Bear Creek and Hubbard Creek respectively, circulating approximately 700,000 ft^3 of air per minute through ventilated areas of the mine. Approximately 800,000 ft^3 of methane were being liberated each 24-hour period. About 11,000 ft^3 of air per minute were passing through the No 1 and No 2 return entries in Five West Mains prior to the occurrence. The weekly examination for hazardous conditions was made of the immediate fire area at 2.30 am, 10th April, 1972, and no abnormal conditions were found.

DESCRIPTION OF OCCURRENCE

7. The third shift maintenance crew, consisting of 44 men, entered the mine at 12.01 am, 11th April, 1972, and regularly scheduled duties were performed without event until approximately 3.40 am, when a mechanic smelt a strange odour in the intake air. He called the third shift maintenance foreman, who was in another section. They met and travelled outbye until they lost the odour. The third shift mine foreman was notified by trolley telephone at 4.00 am. The returns from No 3 dip and No 3 south sections were checked and found clear. On proceeding through the airlock doors at No 2 raise, smoke was encountered in the east fan returns. The mine superintendent was notified of the occurrence by telephone at 4.35 am. He ordered all section powerlines to be de-energised and all men withdrawn from the mine. The mine foreman followed the men out of the mine and de-energised the dc trolley power by pulling the blade switches to haulage station No 25. All men reached the surface at 5.15 am.

8. About 5.30 am, the chief electrician was despatched to Bear Creek substation to de-energise and lock out all high-voltage mine power leading underground.

EMERGENCY ACTION

9. At about 6.00 am the mine superintendent, general mine foreman and fire bosses entered the mine. At haulage station No 46 they entered No 1 and No 2 entries, Five West Mains, through a man door, and proceeded inbye in No 1 entry until they encountered smoke; they had travelled about 400 ft to near No 1 raise. They discussed the situation and felt they were near the point of origin and decided to break the 6-in water line in the return and attempt to fight the fire directly with water. Water was applied in No 1 entry through a 2-in hose. Tests for methane and carbon monoxide were made and about 200 ft of progress was made without encountering an active fire. However, smoke recirculating along No 2 entry through the outbye crosscuts forced the men to retreat. After discussions and a review of the mine map, it was decided that this approach was impossible and that a few men should start erecting seals in No 1 and No 2 entries. After further discussion of sealing, it was decided that mine rescue personnel equipped with self-contained breathing apparatus would install the inbye seal at No 2 raise and that the No 1 seal would be erected to within a foot of the roof to ensure ventilation. This seal would be closed simultaneously with the inbye seal. The section foreman was sent to the Bear Creek fan to monitor continuously the return atmosphere, and communications were established to receive results underground.

DISCOVERY OF FIRE

10. The fire was discovered near haulage station No 58 along the rib of the crosscut and in No 2 entry. Four hundred feet of firehose were obtained, and at 10.20 am the fire was fought directly with water. The fire was extinguished along the rib of the crosscut to the intersection of No 2 entry, where an abandoned concrete overcast prevented water from being applied directly to the fire; however, water was applied in all other directions. Additional roof supports were installed. It was decided to obtain the portable foam-generating machine and to build a temporary air lock outbye the stopping to control the air. At approximately 1.20 pm the foam generating machine was set up and put into operation. At 2.40 pm No 1 and No 2 seals were completed, except for an area left open in No 1 seal for ventilation.

11. Tests were again made of the return atmosphere at No 2 raise about 3,000 ft from the fire and reported an increasing methane content. Two mine rescue teams equipped with apparatus and material to build the seal at No 2 raise entered the mine about 3.30 pm. Following a very thorough briefing of conditions, they proceeded to No 2 raise to erect the seal.

SEALING OFF THE AREA

12. The foam-generating machine was shut off after dispersing 300 gallons of detergent into the fire area. A schedule for final sealing was arranged and trolley telephone communications were established at the three locations to be sealed simultaneously. All men, except two at each location and two foremen, withdrew from the mine at 7.25 pm. No 1 seal was reported closed at 8.10 pm. The inbye seal at No 2 raise and No 4 seal at the bottom of No 1 raise were closed at 8.15 pm.

13. All persons were on the surface at 8.30 pm. The sealing of the return entries created a ventilation problem for the east-side seals, pump slopes and old manway seals. A 5-ft aerodyne fan, designated No 3, located adjacent to the main portal and previously used to ventilate part of the mine, was reactivated and circulated about 38,000 ft^3 of air per minute through the above-named area of the mine.

14. A small crew of men and two USBM inspectors entered the mine at 12.10 pm, 13th April, 1972, to build additional back-up seals at No 1 and No 4 seals and to erect three additional back-up seals at the bottom of No 2 raise to seal the area better. Air samples were collected and analysed on the surface by Orsat apparatus.

15. Air samples were collected from 14th to 17th April, 1972, at four-hour intervals. The sealed area was patrolled and the existing seals, three through eleven, were coated with urethane foam to prevent minor leaks. Based on analyses of air samples by the USBM, the Order of Withdrawal was modified at 7.30 pm, 17th April, 1972, allowing operations to resume. A 24-hour patrol of the sealed area by both certified company employees and USBM personnel was established.

FIRE AT NO 6 SEAL

16. The third shift maintenance crew entered the mine at 12.01 am, 18th April, 1972. They inspected No 1 seal and proceeded inbye to No 6 seal where they noted that urethane foam, applied during the previous shift, was discoloured (charcoal appearance) in the left-hand corner near the roof. After close examination of No 6 seal, it was noticed that a very small amount of smoke was coming from underneath the seal about 5 ft from the right rib. A few minutes later a noise was heard and a fire observed inbye.

17. At approximately 1.20 am, 15 minutes after water was applied, the flames were brought under control. Water was applied for about an hour to ensure that the fire was extinguished. Visual observation showed that the concrete seal had not been damaged. After further investigation, it was surmised that the fire at No 6 seal resulted from a chemical reaction in urethane foam which had been applied to No 6 seal at approximately 9.00 pm, 17th April, 1972. Seals seven through fourteen were checked to determine if newly foamed seals were heating. Results of this inspection revealed all other seals were intact and in good condition. At this time all men were out of the mine or accounted for.

18. A conference was held at the mine office on 18th April, 1972, and it was agreed to allow a small supervised crew to enter the mine to build back-up seals at No 6 and No 10 seals. The company requested the assistance of the USBM Technical Support Group, Pittsburgh, Pennsylvania, to investigate the cause of the fire created by the urethane foam applied to No 6 seal. Shortly after 8.00 am, several employees and a Federal coal mine inspector entered the mine. The two back-up seals, completed on the day shift, were coated with urethane foam and examined during the second shift. On the basis of this examination, the foam used on the seals was suitable, therefore the Order was modified and operations resumed on the 8.00 am shift, 19th April, 1972.

19. The Order was again modified on 23rd April, 1972, allowing mining operations to continue for a period of five days, based on the analytical results of the atmosphere in the sealed area. The sealed area was patrolled around the clock and sampling continued until 28th April, 1972, at which time the Order was again modified for fourteen days requiring certified company employees to patrol the sealed area at least every four hours, and sampling of the mine atmosphere within the sealed area was continued.

RECURRENCE OF FIRE

20. On Sunday, 7th May, 1972, the fire rekindled in Five West Mains, severing telephone communications.

21. It was verified that an active fire was burning in the main haulage entry inbye No 4 seal (see Plate 45).

22. Two certified company employees with proper equipment were immediately dispatched to the fans at Bear Creek and Hubbard Creek to monitor for gases. An employee was stationed at the portal checking all persons in and out of the mine.

EVENTS PRIOR TO THE RECURRENCE

23. The fire seals were patrolled at 4.00 pm by the fire boss, who also checked them at 5.00 pm, and all seemed normal. At about 8.15 pm, an employee when driving by Bear Creek Canyon on State Highway No 133, en route from Somerset to Paonia, Colorado, thought he detected an odour of burning coal and reported this information to the mine superintendent at his residence in Paonia. He immediately called additional company employees and started an investigation. A trip to Bear Creek fan verified the statement as smoke was observed exhausting from the mine. Several company employees entered the mine at 8.45 pm, through the main haulage entry, and discovered an active fire at No 5 seal. A total of 16 men were underground fighting the fire directly by applying water through three 2-in firehoses connected to the 6-in water line installed along the main haulage.

24. A report at this time from Bear Creek fan area revealed the methane and carbon monoxide gases at 2% and 3,000 ppm respectively. No 3 and No 4 seals appeared to be intact but could not be observed closely because of heat and steam. The bottom was heaved and the 90-lb track rails were twisted out of shape at No 5 seal. Water was being applied to the area inbye No 5 seal through another hose, and centre props were being installed to prevent the heated roof from falling. Water was being applied to the area around No 6 seal. At 1.30 am it was reported that the methane content was increasing at the Bear Creek fan. At No 6 seal it

was observed that the back-up seal had been destroyed by fire and air could be heard intaking through No 6 seal into the previously sealed area. The methane content was still increasing at Bear Creek fan return. All men were immediately withdrawn from the mine at approximately 2.20 am. All persons were on the surface and accounted for by 2.45 am, 8th May, 1972.

SEALING OF THE MINE

25. A conference was held on 8th May, 1972, to determine the best and safest approach to sealing the mine, and at 5.30 am the decision to seal all seven portals was made. Materials for sealing Bear Creek and Hubbard Creek fan openings were delivered by 4-wheel drive trucks, and materials for the main portal, manway, and No 3 fan were delivered by a front-end loader. Initial sealing began at 6.00 am and the manway seal was completed about 10.15 am. The seal at Bear Creek intake was completed at 1.30 pm. No 3 fan was stopped and the fan portal seal completed at 2.25 pm. The Hubbard Creek intake seal was completed at 5.44 pm, which reversed the air at Bear Creek fan return. Bear Creek fan was stopped, and sealing there was completed at 6.08 pm. The Hubbard Creek fan was stopped, a door in the return and a door in the main portal were dropped in place simultaneously, using ropes from a remote location, to complete sealing of the mine at 6.25 pm, 8th May, 1972.

26. There were no injuries to employees during the occurrences and property damage was confined to the sealed area.

CONCLUSIONS

27. The main points to be borne in mind when considering the cause of the fire are that:-

(i) A fire, apparently of spontaneous origin, occurred in No 1 and No 2 entries, Five West Mains, at the bottom of No 1 raise.

(ii) The required weekly inspection of the area, made on 10th April, 1972, did not indicate any unusual conditions.

(iii) Inherent temperature in the area, as monitored at the bottom of No 2 raise, indicated a temperature of 94°F. This excessive heat is a natural condition in this and other areas of the mine and contributed to an increase in the rate of oxidation.

(iv) Return air coursed through No 1 and No 2 entries was used primarily to ventilate seals along Five West Mains and this may have created leakage of air resulting in the spontaneous combustion incident.

28. The probable cause of the fire was spontaneous combustion resulting from roof falls, bottom heaving or other physical conditions which restricted the normal flow of air through No 1 and No 2 return entries, Five West Mains. Combined inherent heat in the area and reduced ventilation flow allowed the coal to overheat and ignite.

29. The fire at No 6 seal, 18th April, 1972, resulted from a chemical reaction and/or improper mixing or application of urethane foam. The use of this material is now no longer legal in US coal mines.

APPENDIX "L"

COMBAT INCIDENT - COVENTRY MINE, UK

1. A serious heating occurred on 57 district, Coventry mine, and was combated by the use of a pressure control technique. Although the heating was associated with a longwall advancing face, it provides valuable background that is relevant to dealing with heating in, for example, other inaccessible locations between two airways.

2. Longwall 57 was advancing in the top section of a 25-ft thick seam. The longwall was 360 ft in length with a gradient of 1 in 14 dipping from return to intake. It had advanced 180 ft from the face start line at the time the heating occurred. The quantity ventilating the face was 5,600 ft^3/min. Regular samples were taken at a sample point at the outbye end of the return road and normal carbon monoxide concentration had been established by daily sampling as 12 ppm with a carbon monoxide: oxygen ratio of 0.22.

3. The heating was indicated by an increase in carbon monoxide from the norm of 12 ppm to 125 ppm over three days. Concurrently, the carbon monoxide: oxygen ratio rose to 1.5.

4. Examination of the section with a Draegar carbon monoxide detector showed that the main issue of carbon monoxide was occurring at the return end of the face start line. It was apparent that this was not consolidated and that sufficient air was leaking from intake to return to initiate and develop a heating.

5. The rate of rise was too rapid to allow effective conventional sealing to be completed in time. Under these circumstances, the ends of the face start line would normally be pumped solid with a sealant.

6. It was therefore decided to erect a pressure chamber across the junction with the face start line in the return gate. The site before construction of a pressure chamber for this type of heating is shown on Plate 48. The object of the chamber was to balance the pressure difference existing across the leakage path and exclude the oxygen and also to ascertain exactly where the leakage was taking place in the intake gate so that permanent roadside sealing could be carried out effectively.

7. The pressure drop across the face setting off line was 0.25 lb/ft^2. This pressure was measured and subsequently monitored on a gauge connected to a small-bore plastic tube which was laid around the coal pillar between both ends of the face setting off line.

8. Due to the relatively close proximity of the face line, the chamber erected was only 150 ft in length, the inbye door and fan duct being 100 ft from the return roadhead. A regulator, 75 ft outbye of the face setting off line, determined the outer limit of the pressure chamber. The fan was started up and the regulator and fan damper adjusted (see Plate 49) in order to produce 0.25 lb/ft^2 of pressure over the chamber length, whilst at the same time maintaining the original district air quantity. Under these conditions a check in the intake gate revealed no emission of carbon monoxide and the level at the control point in the return was stable at 115 ppm. It was apparent that the buoyancy pressure of gases within the face setting off line was effectively maintaining the original flow rate.

9. After $1\frac{1}{2}$ hours, the pressure in the chamber was increased to 0.50 lb/ft^2 and the effect on the carbon monoxide at the control point was immediate. This fell to 30 ppm. No carbon monoxide could be found in the intake gate, so a further increase of 1.0 lb/ft^2 was made. At this level carbon monoxide began to appear in breaks above the lagging in the vicinity of the face start line in the intake gate. The points of emission of carbon monoxide were marked and the chamber pressure reduced to 0.25 lb/ft^2. At this level the carbon monoxide concentration at the return control point stabilised at 28 ppm (see Plate 50).

10. After two weeks of sealing work, the carbon monoxide level at the control point had reduced to 12 ppm and the chamber was removed.

11. During the two weeks the chamber was kept in operation no trouble was experienced due to it becoming seriously out of balance. Underground officials were required to read the gauge at intervals during their shift and trained to make any correction found to be necessary.

APPENDIX "M"

COMBAT INCIDENT - NEWDIGATE MINE, UK

1. An incident at Newdigate mine, associated with a retreating longwall working the lower part of a 25-ft thick seam, illustrates a combat situation involving retreating as part of a multi-lift method, similar to that under consideration for some western US thick seams.

2. A serious heating developed on 4B section at Newdigate mine. The longwall was 600 ft in length and was working directly beneath the gob of 4A longwall, which had recently been advanced in the upper section of the seam and had stopped 240 ft ahead of 4B's start line (see Plate 51).

3. After production had ceased at 4A longwall, stoppings had been installed in the upper roads inbye of 4B's start line. They were constructed of 15 ft of mine stone injected with a sealant. In addition, a pressure chamber wall, 3 ft thick, had been built 24 ft outbye of the stoppings in the right-hand gate. The active longwall, 4B, was serviced from the upper roads and coal was conveyed along a pre-driven road in the lower part of the seam to a short slope connecting into 4A's old belt road. As 4B longwall retreated, additional slopes were driven into 4A's belt road and the upper roads were stopped off inbye each slope as it connected. The roads in the lower part of the seam were stopped off over 150 ft as the face retreated.

4. At the left-hand return gate similar slopes were driven at intervals without pre-heading. Connections to the foot of these were by means of. a lower section roadway in the gob formed as the face retreated. A continuous, 7-ft-wide pack supported the waste side of this airway. As the face retreated, both the old upper section and the newly-formed lower section roads were stopped off inbye of each drift as on the intake side.

5. The routine control sample position for this face was situated at the outbye end of the old upper section roadway and the normal carbon monoxide content was established at 8 ppm with a face air quantity of 11,000 ft^3/min.

6. 4B's face had retreated 150 ft and ten months had elapsed since old 4A's was stopped off, when a rapid rise in the carbon monoxide content at the outbye control point occurred (see Plate 52). Within 2 hours the carbon monoxide concentration rose from 10 ppm to 30 ppm and in the next 6 hours it rose to 40 ppm. An extremely rapid rise then occurred and during the following 6 hours it had risen to 200 ppm.

7. At this time it was apparent that a heating had started either on 4A's old face line which was sealed off, or on the start line of 4B itself. A third possibility was that the heating lay within the short lengths of airway which served as connections between the upper and lower section workings.

8. It was also very apparent with this rapid rate of rise something had to be effective quickly if the district were to be saved.

9. It was decided to attempt to block the paths through which the products of combustion were flowing with fresh air, thereby closing the return path from the heating and denying it oxygen. To do this, a bagged stopping was constructed at position "Y" inbye of the first connection slit in the left-hand lower section airway and a board stopping was constructed in the upper section airway at position "X". Stopping "Y" was constructed round a 12-in ventilation duct which was turned into the second slit. A 15-in diameter low-capacity fan was coupled to the duct in order to pressurise the area behind stoppings "X" and "Y".

10. The pressure difference across 4B's face was measured as 0.8 lb/ft^2 and there was a difference in level between the face ends of 50 ft and between the upper and lower section airways of 14 ft. Whatever buoyancy effect existed would tend to encourage flow to the left-hand return stopping in the old upper section airway.

11. The construction of both stoppings was completed in 7 hours and at that time the carbon monoxide content at the return control point had reached 250 ppm. The district return was cleared of all personnel, the fan was started and a pressure of 0.8 lb/ft^2 was established behind the stoppings.

12. There was an immediate drop in the carbon monoxide content in the return from 250 ppm to 30 ppm, within minutes. At this point, as a safeguard, it was decided to establish a sample point, 4B2, in order to detect any issue of carbon monoxide from the gob or from the right-hand end upper or lower section roads.

13. The fan pressure was raised after 3 hours to 1.0 lb/ft^2 in an attempt to reduce the samples still further. This resulted in 4B2 sample point rising from 10 ppm to 20 ppm and at this level it was apparent that some slight recirculation of carbon monoxide was occurring.

14. The pressure was maintained at this value with adequate supervision and within the next 3 days the control point sample was down to 10 ppm.

15. As the face retreated, the ducting was extended through each subsequent stopping, and when the face had retreated a total of 200 ft, an attempt was made to dispense with the fan altogether. Within $3\frac{1}{2}$ hours the outbye control point had risen to 100 ppm and the fan was restarted. After 2 hours the control point was sampled at 6 ppm.

16. Initially, the 12-in diameter duct line was extended as the face retreated and was kept continuous through each successive stopping erected in the face entry. Eventually, the duct line was broken and for the remainder of the life of the face it merely projected through the last erected stopping. The pressure was reduced progressively as the face retreated and after a year it was down to 0.15 lb/ft^2.

17. It is significant that in every instance when the fan stopped through power failure or breakdown, there was a rapid rise in carbon monoxide percentage at the outbye control point.

APPENDIX "N"

RAPID APPRAISAL OF SPONTANEOUS COMBUSTION ASSESSED LIABILITY (RASCAL)

1. Subjected to certain mining practices, all coals have some risk of developing spontaneous combustion. However, experience indicates that some coals are more at risk than others. For example, spontaneous combustion is almost unknown with hard anthracite coals whereas, at the other end of the scale, it is a frequent problem with many low rank sub-bituminous coals.

2. While the liability of a coal to spontaneous combustion can to some extent be predicted by laboratory tests, the full significance of the spontaneous combustion situation can only be judged by operating experience. However, a preliminary indication of the degree of risk can be obtained by considering the following factors:-

(i) Rank of coal, as a factor of oxygen content.

(ii) Presence of pyritic sulphur minerals.

(iii) Hardness.

(iv) Humidity of the ventilating air.

(v) Strata temperature.

(vi) Unworked roof coal thickness.

3. It must be stressed that coal characteristics can vary within a seam and that in many cases a part of a seam is particularly susceptible, probably due to the spatial arrangement of petrographic types. The rapid appraisal (RASCAL) gives only a very generalised indication of susceptibility and should never be used as the sole measure of risk.

4. As a guide to the emphasis that should be given to each of the factors, values have been given as follows:-

(i)

Rank of coal	Oxygen content, %	Points
Sub-bituminous	+15	18
	15 - 12	16
Bituminous	12 - 10	14
Weakly coaking	10 - 8	12
Coking	8 - 6	8
Semi-anthracites	6 - 4	3
Anthracites	4 - 2	1
	less than 2	0

(ii)	Pyritic sulphur minerals	%	
		less than 0.25	0
		0.25 - 0.5	1
		0.5 - 1.0	2
		1.0 - 2.0	3
		2.0 - 3.0	5
		+3.0	7
(iii)	Hardness	Hard	- 2
		Medium hard	0
		Friable	+ 2
		Very friable	4
(iv)	Humidity of ventilation air	Saturation %	
		0 - 20	- 5
		20 - 40	- 2
		40 - 60	0
		+60	+ 2
(v)	Virgin strata temperature	°F	Factor
		32 - 50	x 1.0
		50 - 70	1.0
		70 - 85	1.25
		85 - 105	2.0
		+105	5.0

(vi)	Unmined roof coal thickness	Up to and including	
		ft	
		2	x 1.5
		4	2.0
		6	2.5
		8	3.0
		10	3.5
		+10	4.0

Method of Calculation

5. Add the points values under items (i) to (iv) and multiply by the factors given in (v) and (vi).

Examples:-

Coal A		Points
(i)	Bituminous, oxygen content 12%	14
(ii)	Pyritic sulphur minerals 1.1%	3
(iii)	Friable	2
(iv)	Humidity of ventilation air 65%	2
		21
	Roof coal 2 ft, factor x 1.5	
	Strata temperature 60°F, factor x 1.0	
	Risk factor = 21 x 1.5 x 1.0 =	31.5

Coal B		
(i)	Semi anthracite, oxygen content 5.0%	3
(ii)	Pyritic sulphur minerals 0.5%	1
(iii)	Medium hard	0
(iv)	Humidity of ventilation air 40%	0
	Roof coal 4 ft 6 in, factor x 2.0	

Strata temperature 60^0F, factor x 1.0

Risk factor = 4 x 2.0 x 1.0 8

6. The overall risk factor can be assessed as follows:-

Less than 10	-	Low risk
10 - 20	-	At risk
Greater than 20	-	High risk

APPENDIX "O"

THE ESSENTIAL CHARACTERISTICS OF THE CO ANALYSER FOR CONTINUOUS MONITORING IN CONJUNCTION WITH THE TUBE BUNDLE SYSTEM

1.	Resolution:-	0 to 20 ppm	0.5 ppm
		20 to 1,000 ppm	1.0 ppm
		100 to 1,000 ppm	1% of full scale deflection
		0.1% to 1.0%	1% of full scale deflection
		1.0% to 5.0%	1% of full scale deflection
2.	Ranges:-	Shaft monitor system	0 to 20 ppm
			0 to 100 ppm
		General purpose tube bundle system	0 to 100 ppm
			0 to 1,000 ppm
			0.1% to 5%

3. Linearised outputs on all ranges.

4. Freedom from sensitivity to other gases, CO_2, CH_4, C_2H_6, C_3H_8.

5. Heated optical bench with thermostatic control.

6. Stable zero and span.

7. Circuit for the automatic correction of the output for zero drift initiated by the control unit.

8. Automatic indication when zero drift exceeds pre-set limits.

9. Modular electronics to allow easy servicing should a component fail.

APPENDIX "P"

SEALANTS AND SEALANT COATINGS

INTRODUCTION

1. Sealants and sealant coatings for use underground or at the surface near any shaft or drift should be non-combustible. In addition, the sealants and sealant coatings should not present a health or safety hazard at normal or elevated temperatures during storage, transport and handling, and during and after application.

2. Sealant coatings are defined as follows:-

(i) Sealants are those materials that can be placed by pumping to fill cavities, packs and strata breaks to minimise leakage of air or gas.

(ii) Sealant coatings are those materials that are applied to rock, coal or any other exposed surface primarily to minimise leakage of air or gas.

3. An explanatory note on non-combustibility and other general requirements for sealants and sealant coatings is given later.

LIST OF SEALANTS AND SEALANT COATINGS IN GENERAL USE

4. Gypsum with additives - basically gypsum (calcium sulphate) with chemicals added to control the set.

Mandoseal P - a mixture of de-laminated exfoliated vermiculite, Portland cement, whiting and suitable additives.

Bentonite - a naturally occurring mineral clay.

NON-COMBUSTIBILITY

5. A non-combustible material may be classified as one which will not burn and will not contribute materially to an underground fire.

6. Inorganic materials can generally be classified as non-combustible and organic materials as combustible. It follows, therefore, that if a material is formed by a mixture of inorganic (eg vermiculite, cement, gypsum) and organic (eg neoprene, rubber) constituents it will, to some extent, be combustible. When the amount of organic materials in a mix exceeds about 3%, the product is likely to be classified as combustible.

7. In the mining industry, it is necessary to use materials such as treated timber, PVC conveyor belting, brattice sheet, ventilation ducting, trailing cables, etc, for which complete non-combustibility would be neither feasible nor practicable. However, such materials are subject to stringent requirements with respect to their fire resistance.

SAFETY AND HEALTH REQUIREMENTS

8. Non-combustible sealants and sealant coatings should produce no significant amounts of smoke or toxic gases at normal or elevated temperatures.

9. Sealant coatings must be mixed and packaged before delivery if any of their constituent materials present a danger to safety or health at normal or elevated temperatures during storage, transport, mixing, handling or application.

OTHER GENERAL REQUIREMENTS

10. Apart from being non-combustible and presenting no health or safety hazard, sealant coatings need to satisfy the following requirements:-

(i) The materials should be capable of being pumped and sprayed and easily applied with little or no preparatory work to coal, rock, pack, timber and other exposed surfaces underground.

(ii) The materials should have the physical properties, eg adhesion, flexibility, compressibility and structural strength, to suit applications underground. These properties, and particularly that of adhesion, should be maintained at elevated temperatures.

11. In addition, sealant coatings require to have a low permeability to air and gas.

12. The cost of the material is also a major consideration but this can only be judged after taking into account the effectiveness of the material, cost of application (including preparatory work) and cost of transport of the material underground.

USE OF SEALANT COATINGS

Introduction

13. The information below is for sealant coatings in general use, although this list is not exhaustive and other materials may be available which fulfil the requirements listed above (paragraphs 10 to 12).

Adhesion

14. The importance of good adhesion of sealant coatings to underlying surfaces cannot be over-emphasised. Coatings may fail as sealant surface coatings if good adhesion is not achieved.

(i) Dusty Surfaces

None of the presently available sealant coatings will satisfactorily adhere to dusty surfaces. De-dusting is therefore an essential prerequisite for successful application. If a material is applied by spray (see Plate 46), the force of the spray will de-dust the surface to some extent.

(ii) Damp Surfaces

None of the currently available sealant coatings will satisfactorily adhere to any surface that is visibly damp without the aid of a support such as wire mesh. Coatings cannot be applied successfully to any surface on which there is free or running water.

(iii) Consistency

All types of coating should be mixed, pumped and sprayed at the recommended consistency (details of the recommended mixing procedure for each individual material are given below). Materials mixed too wet result in an inferior product with respect to strength, permeability and, particularly, adhesion.

(iv) Spraying

The adhesion of any type of coating to a surface will generally be better if the material has been sprayed rather than applied by hand. Improved adhesion and less wastage results from spraying downwards, ie from roof to floor, rather than floor to roof.

The adhesion of any type of coating to a surface decreases with increase in the thickness of the first application. It is essential, therefore, that a thin priming coat is applied first to the surface being treated in order to establish a good bond, particularly when the surface is comparatively smooth.

Thickness

15. The required thickness depends on the type of material being used and the local conditions. The recommended thickness to be applied for each material is given below.

Permeability

16. The ability of a coating to restrict the passage of air/gas depends not only on the inherent permeability of the material but, more important, on the resistance to cracking. Cracks can increase permeability many hundred times. It is important, particularly in unsettled ground, to examine sealant coatings periodically and to repair any cracks that may have formed.

17. It must be emphasised that whenever a sealant coating is used on the sides of a roadway, it should be applied to the coal and/or rock surfaces. Preparation of the surface should include the removal of any loose stones and lagging. The chance of a sealant coating cracking is considerably reduced by the use of a wire mesh reinforcement (eg 1-in wire mesh).

General Health Precautions

18. Although it is not the general practice to apply a surface coating to timber that has been impregnated with fire-retardant salts, there may be cases where it is necessary to coat a roadway in which both treated and untreated timber has been used. The application of a surface coating to treated timber may give rise

to a release of ammonia, due to a chemical reaction between the chemicals used for impregnation of the timber and those present in the fire retardant coating. Sufficient ammonia may be given off to be noticeable and care is, therefore, necessary to ensure that the air velocity in the vicinity of the spraying is adequate.

19. Mandoseal P, used for sealant coatings, is alkaline. This can cause skin irritation, particularly if the skin is broken by abrasions or scratches. Men handling these materials, either dry or wet, should wear gloves and wash off any material that may get on their skin. The wearing of goggles is also desirable, particularly when the material is being sprayed.

NOTES OF GUIDANCE

Gypsum-based Compounds

Application

20. Gypsum-based compounds have an application as a sealant coating except in locations where they could be subjected to heating at temperatures above 260°F for a prolonged period. They can also be used as sealants for the construction of explosion-proof seals, strata consolidation and cavity filling.

General

21. The sealant consists basically of gypsum (calcium sulphate) with chemical additives to control the set.

22. These materials will set and subsequently harden in all atmospheric conditions except frost. However, satisfactory adhesion to most surfaces can only be obtained if applied as a very thin coating of the order of 0.1 in; thicker coatings tend to flake off easily. Although these materials can withstand high temperatures for short periods of one to two hours, prolonged exposure to temperatures as low as 260°F to 276°F can result in the gypsum component dehydrating. Consequently, they have limitations as sealant coatings in locations where they could be subjected to the sustained heat from a spontaneous combustion.

23. The materials do not present any health hazard and no special precautions need to be taken by workmen during application.

24. Under normal storage conditions the shelf life is at least three months.

Mixing, Application and Thickness

25. These materials are generally available ready mixed in 28-lb bags. Mixing underground consists of adding clean water in the proportion of four gallons of water to three bags (84 lb) of material to give a creamy consistency. For practical reasons, it is usually necessary in underground work to use a somewhat weaker mix in order to minimise blockages in the machinery and hose. However, care should be taken to ensure that workmen do not attempt to overcome blockage problems by using excessively thin mixes which will result in an inferior product.

26. Three grades are generally available which have nominal setting times of 15, 30 and 90 min respectively. An important point to appreciate, however, is that very much faster setting can occur if the wet material comes into contact with already set or partially-set material. The danger of early setting seriously limits the distance over which the material can be pumped and can present blockage problems, particularly in the event of an involuntary stoppage. It is very important that the equipment is thoroughly flushed out with water both immediately before and after use.

27. The materials can be hand mixed and applied at a more concentrated consistency than they can be pumped. In view of the difficulty in obtaining satisfactory adhesion, the long-setting sealant should preferably be applied behind shuttering, eg for sealing gateside packs. The resultant thickness will, therefore, be governed by site conditions and practical problems associated with fixing and shuttering, rather than the minimum thickness required to provide an adequate seal. Even so, thickness should not normally be less than 4 in to 6 in.

28. Mixing and pumping units are available and seals can be "pumped on" remotely from several hundred feet away.

29. Strata injection is accomplished by pumping the gypsum mixture into boreholes by means of a pump (see Plate 47). When the hole goes tight it is essential to either clear the pipes and pump with water, or to re-circulate the mix back to the mixing tank and thin it down with extra water. If the sealant goes hard in the pump, then the pump has to be stripped and cleaned.

30. Seals are constructed by building a back wall of bagged hardstem or shuttering and spars. This wall is hard faced with a thick mix of gypsum to prevent leakage of the liquid sealant. The front wall is similarly built, typically 9 ft in front and 3 ft high. The void between is then filled with pumped gypsum mix and the front wall built up another 3 ft and the process repeated to the roof of the roadway. Second and third sections are then built until the seal is long enough for the size of airway, a guide to this is minimum length of seal in feet =

$$\frac{\text{width of entry + height of entry}}{2}$$

31. If the seal is to be leakproof as well as explosion-proof, the surrounding strata should be injected until the whole structure is bonded tight.

32. Seals pumped on in this manner tend to shrink, and it is necessary to top up the structure by further pumping.

33. A seal 10 ft thick by 8 ft high by 10 ft wide requires 26 tons of gypsum mix and contains when completed 40 tons of slurry. A seal of this size can be pumped on in a shift.

Mandoseal P

Application

34. Mandoseal P is suitable as a sealant coating.

General

35. It comprises a mixture of de-laminated exfoliated vermiculite, Portland cement, whiting and a number of suitable additives.

36. The material will set and subsequently harden in all atmospheric conditions except frost. When set, the material has a degree of compressibility and will indent rather than fracture when hit. It has good adhesion properties to most surfaces and is resistant to attack by any impurities likely to occur in mine waters.

37. Mandoseal P, in the wet mix, is sufficiently alkaline to require precautions to be taken during application (see General Health Precautions, paragraphs 18 and 19).

38. Under normal storage conditions, the shelf life of Mandoseal P is at least three months.

Mixing, Application and Thickness

39. The constituents of Mandoseal P are well mixed at the manufacturer's before being bagged and delivered. Mixing underground consists of adding water in the proportion of $3\frac{1}{2}$ gallons to 4 gallons to 1 bag (50 lb) of Mandoseal P.

40. Although the proportion of water is not critical, it is better not to make the mixture too wet or the properties of the material will suffer. To obtain the best results it is essential to wet the material properly and allow a short period (about two to three minutes) between wetting and applying. The wet mix can be left in the mixing and pumping equipment for a period of at least two hours without risk of setting and blockage.

41. It is necessary to provide a thickness of about 1 in for a sealant coating. In conditions liable to be subjected to appreciable strata movement, or where the surfaces are damp, it is advisable to provide an internal reinforcement by means of 1-in wire mesh.

Bentonite

Application

42. Bentonite is suitable for use in injection of fractured strata, coal and packs. It is not suitable for use as a sealant coating.

General

43. Bentonite is a naturally occurring mineral clay which swells to many times its own volume when mixed with water. This gelling process is reversible so that when the gel is agitated or pumped it returns to the fluid state. The main constituent of the gel is water and, consequently, a large volume of filler is obtained from a relatively small volume of materials conveyed by the mine transport system. The gel appears to be stable; examination of old airways pumped solid some months earlier still contained gel in its original form.

Mixing and Application

44. The best method of application is to mix the material alternately in two 50-gallon tanks containing agitator paddles. Thorough stirring and mixing is essential.

45. A typical mix would consist of 40 gallons of water, 18 oz of tetron, 4 lb of lime, 56 lb of bentonite and 2 gallons of sodium silicate. The tetron is added to the water before the bentonite and the sodium silicate is added last.

46. The addition of an equal weight of cement to the bentonite would result in the formation of an irreversible gel, which may have application where large voids are to be filled.

47. Both the gelation time and the set strength are controllable and, by suitable formulation, a set time as short as one hour and a strength of up to 200 lb/ft^2 can be obtained.

APPENDIX "Q"

COAL GEOLOGY

COLORADO

1. Coal deposits underlie 30,000 square miles or approximately 28% of the State. Coal resources with an overburden of less than 6,000 ft are estimated at 434,000 million tons, of which some 80% can only be mined by underground methods. The US Bureau of Mines has identified some 14,000 million tons of in-situ coal within the State that are available for extraction using present underground mining technology, of which 34% are sub-bituminous and 66% are bituminous in rank.

2. Colorado coals vary in age from early Late Cretaceous to Eocene with their best development in Upper Cretaceous sediments.

3. Eight coal-bearing areas have been identified (see Plate 22), of which the Green River and Uinta regions are the most important in terms of available reserves and current production.

4. The coalfields of the Denver basin, Green River, Raton Mesa and Uinta regions occur in broad, structurally-simple basins with local structural complexities near the basin margins. Canon City, North and South Park fields are in smaller, more structurally-complicated basins.

Rank

5. Older coals generally have higher rank. The Cretaceous coals of the San Juan River region are high volatile B bituminous, while the youngest Cretaceous and Tertiary coals of the Denver and Green River regions are lignite to sub-bituminous C in rank.

6. Locally, tectonism and igneous intrusions have caused an increase in rank of some coals to anthracite. However, anthracite reserves are estimated at 28 million tons, and are therefore of minor importance in comparison to the bituminous and sub-bituminous reserves.

Moisture, Ash, Sulphur and Heating Values

7. The moisture content of Colorado coals on an as-received basis averages 12% and commonly varies between 1% and 20%. In a few localities it may be as high as 35%. The ash content on an as-received basis averages 6% and varies between 2% and 15%. In a few cases it is as high as 29%.

8. Colorado coals are low in sulphur and commonly vary between 0.2% and 1.0%. More than 99% of the coal has sulphur values of less than 1%, and more than half contain less than 0.7%. Normal sulphate and organic sulphur contents are low. Abnormal sulphur contents of up to 4.8% are occasionally found and principally occur as pyrites. Nearly all Colorado coals can be washed to less than 0.5% sulphur.

9. The average heating value of Colorado coal is 13,950 Btu/lb (dry, ash-free basis), or 11,370 Btu/lb on an as-received basis. Heating values commonly vary between 13,300 Btu/lb and 14,500 Btu/lb, and for some sub-bituminous coals may be as low as 11,440 Btu/lb.

Thickness

10. Data on seam thickness, given in the Keystone Coal Industry Manual, 1977, have been analysed, and the following thickness parameters have been estimated:-

	ft
Median Thickness	10
Lower Quartile	5
Upper Quartile	12
Lower Decile	4
Upper Decile	18

11. The information indicates that 50% of the known seams in Colorado have thicknesses between 5 ft and 12 ft and 80% have thicknesses between 4 ft and 18 ft. Eight seams with thicknesses in excess of 20 ft have been recorded.

12. US Bureau of Mines data (1974) show that some 85% (7,800 million tons) of the in-situ underground bituminous reserves occur in seams thicker than 3 ft 6 in and 50% (2,400 million tons) of the in-situ underground sub-bituminous reserves occur in seams thicker than 10 ft.

WYOMING

13. Coal deposits underlie 40,000 square miles or approximately 41% of the State. Coal resources with an overburden of less than 6,000 ft are estimated to be 937,000 million tons and the State has the largest in-situ coal resources of the nation. The US Bureau of Mines has identified some 29,490 million tons of in-situ coal within the State that are available for extraction using present underground mining technology, of which 85% are sub-bituminous and 15% are bituminous in rank.

14. Wyoming coals vary in age from Lower Cretaceous to Eocene with their best development in the Upper Cretaceous and younger sediments.

15. Ten coal-bearing areas have been identified (see Plate 23) of which the Powder River and Bighorn Basin regions contain the largest quantities of known reserves.

16. Most of the State's coal seams are relatively flat-lying and occur in broad asymmetrical basins. Steeper dips and folding are common at some basin margins, especially on the flanks of the mountain ranges separating the individual basins. The Powder River region is least affected by structural complexities, while Hams Fork region and Hanna coalfield are the most disturbed. Faulting is most common in the southern and western coal regions but is not restricted to those areas.

Rank

17. Older coal seams in any given field are generally higher rank than the younger beds. Coal within the State varies from lignite to high volatile bituminous rank. However, lignite reserves are unimportant and are restricted to the north-eastern part of the Powder River region. While, with few exceptions, the bituminous coals are all of Cretaceous age, not all Cretaceous coals are of bituminous rank. Sub-bituminous coals are found in all the major coalfields except the Black Hills region.

18. Cretaceous bituminous coals are found in the Black Hills region, in portions of the Hanna field, and in the Green River, Hams Fork and Bighorn Basin regions. High volatile B and A bituminous coal is only known in the Hams Fork region.

Moisture, Ash, Sulphur and Heating Values

19. The moisture content of Wyoming coals, on an as-received basis, commonly lies between 10% and 13%. In a few localities, such as in the western and north-western parts of the State, the moisture content can be as high as 20% to 30%.

20. The ash content, on an as-received basis, averages 6.5% and varies between 4% and 13%.

21. Wyoming coals are low in sulphur and average 0.5%. More than 99% of the coal resources have sulphur values of less than 1%, and about one half contain less than 0.7%. Some coals in the Green River region have sulphur contents as high as 7% but such values are unusual. Most of the sulphur (70% to 72%) in Wyoming coals occurs in the organic form; therefore conventional washing can reduce the sulphur content only by some 30%.

22. Heating values are commensurate with their rank. Bituminous coals have values between 11,000 Btu/lb daf and 14,400 Btu/lb daf, while sub-bituminous coals vary between 8,400 Btu/lb daf and 13,000 Btu/lb daf. The lowest heating values are found in the young coals of the south-western part of the State where values as low as 9,350 Btu/lb daf are reported.

Thickness

23. Coal in Wyoming is mined largely from strip mines and, as a consequence, the data on seam thicknesses reported in Keystone Coal Industry Manual, 1977, are dominated by records for the thick seams amenable to this type of mining. Analysis of the seam thickness data suggests that known seams lie within two groups - one 5 ft to 14 ft thick (average 10 ft) and the other 14 ft to 22 ft thick (average 20 ft). Over twenty seams have recorded thicknesses in excess of 30 ft; the largest thickness recorded is for Healy Seam in the Powder River region which locally exceeds 220 ft. Many of the larger thicknesses are the result of two or more seams coalescing. Shale partings, commonly 1 ft to 2 ft thick, but on occasions up to 15 ft thick, are also found in the thicker seams.

24. US Bureau of Mines data (1974) show that some 82% (3,700 million tons) of the in-situ underground bituminous coal reserves occur in seams thicker than 3 ft 6 in, while 58% (14,500 million tons) of the in-situ underground sub-bituminous reserves lie in seams thicker than 10 ft.

UTAH

25. Coal deposits underlie 15,000 square miles or approximately 18% of the State. Coal resources are estimated to be 39,300 million tons. The US Bureau of Mines has identified some 3,780 million tons of in-situ bituminous coal within the State that are available for extraction using present underground mining technology.

26. Utah coals are predominantly of Cretaceous age.

27. Twenty coalfields have been identified of which Book Cliffs, Castlegate, Emery and Kaiparowits Plateau fields are the most important, both in terms of reserves and current production (see Plate 24).

28. Coal beds are lenticular and the nature of floor and roof conditions and seam thicknesses quite variable. Splits and washout structures within the coal seams are common.

Rank

29. Utah coals are high volatile B and C bituminous in rank. The largest reserves of high volatile B coal are found in the Book Cliffs field, while the largest concentrations of high volatile C coal are found in the south-western part of the State in the Kaiparowits Plateau field.

Moisture, Ash, Sulphur and Heating Values

30. The moisture content of the Utah coals, on an as-received basis, averages 10% and varies between 4% and 20%. The moisture content for the more important producing fields varies between 4% and 10%.

31. The ash content, on an as-received basis, averages some 8% to 9.5% and commonly varies between 5% and 12%. The ash content for the major fields is commonly between 6.5% and 7.5%.

32. The sulphur content averages between 0.8% and 0.9% on an as-received basis. The range is commonly between 0.5% and 2.0%.

33. Some high moisture coals that are insignificant in the State's reserves have sulphur values as high as 4.5% (La Sal-San Juan and Wales fields). The heating values have a range of 9,500 Btu/lb daf to 13,400 Btu/lb daf but commonly average between 11,500 Btu/lb daf and 13,000 Btu/lb daf.

Thickness

34. Utah coals, which are largely exploited by underground methods, are lenticular and have variable seam geometry because of seam splits and wash outs.

35. Data on seam average thickness, given in Keystone Coal Industry Manual, 1977, have been analysed and the following thickness parameters have been estimated:-

	ft	in
Median thickness	6	6
Lower quartile	5	0
Upper quartile	9	0
Lower decile	3	6
Upper decile	12	0

36. The information indicates that 50% of the seams which are known in Utah have an average thickness of between 5 ft and 9 ft, and 80% have an average thickness between 3 ft 6 in and 12 ft. Nine seams have been recorded with thicknesses in excess of 20 ft.

37. US Bureau of Mines data (1974) show that all the identified in-situ coal reserves (3,800 million tons) that can be exploited by present underground methods occur in seams thicker than 3 ft 6 in.

NEW MEXICO

38. Coal deposits underlie 25,000 square miles or approximately 20% of the State. Coal resources are estimated to be 180,000 million tons. The US Bureau of Mines has identified some 2,136 million tons of in-situ coal within the State that are available for extraction using present underground mining technology, of which 72% are bituminous and 28% are sub-bituminous in rank. A very small proportion of anthracite is also present.

39. New Mexico coals vary in age from Pennsylvanian to Paleocene. However, the major coal development is found in Upper Cretaceous and Paleocene rocks.

40. Ten coal-bearing areas have been identified (see Plate 25) of which the San Juan River and Raton Mesa regions are the most important in terms of reserves.

41. The seams in the two major coal-bearing regions occur in simple basins that are affected by only a few minor faults. However, most of the remaining coalfields are affected by numerous faults, local areas of steep dip and igneous intrusions.

Rank

42. New Mexico coals vary in rank from sub-bituminous B to anthracite, but the majority of the reserves have ranks from sub-bituminous A to high volatile C bituminous coal.

43. The coking coals of the Raton Mesa region are high volatile A to B bituminous rank. The coals of the San Juan River region vary from sub-bituminous A or B to high volatile C or B bituminous in rank.

44. Anthracite and semi-anthracite (eg the Cerrillos field) are relatively unimportant as they comprise less than 0.1% of the total in-situ underground reserves.

Moisture, Ash, Sulphur and Heating Values

45. The moisture content of the early Upper Cretaceous coals, on an as-received basis, averages about 15% and commonly varies between 2% and 21%. Coals from the late Upper Cretaceous section average 14% moisture (4.5% to 16%). Coals from the Raton field average 6% moisture (2% to 11%).

46. The ash content, on an as-received basis, varies between fields and ranges between 3% and 22%. Coals from the Raton Mesa region have an ash content of about 14%. Coals from the San Juan River region vary from 3% to 23% for the early Upper Cretaceous coals and 10% to 22% for late Upper Cretaceous coals.

47. Sulphur content varies from 0.4% to 1.0% for most coals. The major exception is the Monero field in the north-eastern part of the San Juan River region where values up to 3.5% can be found. Pyritic sulphur averages less than 0.3% in the coals, and conventional washing cannot materially reduce the total sulphur content.

48. The heating values of sub-bituminous and bituminous coals vary from 9,100 Btu/lb daf to 15,200 Btu/lb daf and are dependent on rank. Coals from the Raton Mesa region vary from 12,700 Btu/lb to 14,300 Btu/lb. The late Upper Cretaceous coals of the San Juan River region vary from 9,100 Btu/lb to 14,100 Btu/lb, while those of early Upper Cretaceous age vary from 9,800 Btu/lb to 15,200 Btu/lb.

Thickness

49. Most coal beds are highly lenticular. The long axes of the lenses are parallel to the ancient Mesozoic shorelines, and extend for distances of 1 mile to 30 miles. The short axes extend for relatively short distances, $\frac{1}{2}$ mile to 5 miles, and are perpendicular to the shorelines.

50. Data on seam thickness, as given in the Keystone Coal Industry Manual, 1977, have been analysed and the following thickness parameters have been estimated:-

	ft	in
Median thickness	6	0
Lower quartile	4	6
Upper quartile	8	0
Lower decile	3	6
Upper decile	11	0

51. The information indicates that 50% of the seams which are known in New Mexico have a thickness between 4 ft 6 in and 8 ft, and 80% have a thickness between 3 ft 6 in and 11 ft. Three seams have been recorded with thicknesses in excess of 20 ft.

52. US Bureau of Mines data (1974) show that 68% (1,040 million tons) of the in-situ bituminous reserves occur in seams thicker than 3 ft 6 in. Some 95% (577 million tons) of the sub-bituminous reserves occur in seams 5 ft to 10 ft thick and the remaining 5% occur in seams with thicknesses greater than 10 ft.

APPENDIX "R"

FIELD VISIT - MINE NO 1

INTRODUCTION

1. The mine is located in the Yampa field, Colorado, and supplies coal to a utility plant about 250 miles away. Present production is about 2,800 tpd or 700,000 tpa.

GEOLOGY

2. The seam varies between 5 ft and 22 ft in thickness. There is little faulting and the coal is hard (7,000 lb/in^2) and bright. The roof is a shaley soapstone and is very weak. This necessitates leaving a minimum of 18 in of top coal. The floor, by contrast, is medium to strong. The dip is variable between 4% and 9%. The coal is referred to as the "lower" seam to distinguish it from the "upper" one which is being exploited by strip mining. Cover varies from zero at the outcrop to 500 ft; working to a maximum depth of 700 ft is envisaged.

METHOD OF WORKING

3. There are two mine areas, each about 1,500 yards square. Working is by conventional multiple entry from the outcrop, usually with five entries, each 20 ft wide. Pillar centres are either 55 ft or 90 ft. Extraction is said to be between 30% and 35%. Machines are Lee Norse and Joy continuous miners supported by shuttle cars delivering to Long Airdox feeder breakers. Long Airdox continuous belt haulage equipment is available but is not used as the continuous miners are unable to haul it up the 7% gradient. A face advance of 100 ft is obtainable on a good shift but 80 ft is more typical. Roof support is one row of wooden props on 5-ft centres along one rib. Crosscuts are always driven from the intake to the return.

TRANSPORT

4. Access is by adits driven directly from the hillside. Coal is removed by 36-in belt conveyors on to a surface gantry from which it is discharged on to a floor stockpile. It is then loaded by shovels into road trucks for a 15-mile journey to the rail loading point.

LABOUR

5. The operation is controlled by a mine superintendent assisted by three mine managers who work in shifts. Under them are foremen for each working section. Support staff include three technical specialists responsible for safety, planning, surveying, etc. The total underground labour force is about 100 and, in addition, there are about 14 men employed on the surface.

VENTILATION

6. Air samples for laboratory analysis are taken every six months. There is an automatic methane detector that gives an alarm at 1% concentration and shuts off all power at 2% concentration. This is reinforced by manual checks each shift. Methane is not normally detectable in the workings. The two main fans are each

rated at 82,000 ft^3/min at a very low water gauge. Seals are constructed of two thicknesses of lightweight concrete blocks. Ventilation doors are of ¾-in blockboard covered with 16-gauge galvanised steel.

WATER

7. There is some water in one mine area which is beneath a creek.

PRODUCTIVITY

8. Overall productivity is estimated at about 21.5 tons per man-day.

MARKETING

9. All sales are made to a single utility. The contract specification is 10,500 Btu/lb at 9.45% moisture. No preparation, apart from crushing, is carried out.

10. The proximate coal analysis is understood to be as follows:-

Volatile matter	38.36%
Moisture	9.41%
Carbon	49.17%
Ash	2.63%
Sulphur	0.43%

SPONTANEOUS COMBUSTION EXPERIENCE

11. There is no knowledge of any previous spontaneous combustion problems. Underground mining conditions are extremely good; there is little weight on the pillars and ventilation pressure is low. The mine appears to have a very low spontaneous combustion risk.

GENERAL

12. The mine is adjacent to a series of earlier workings and current operations have been going on for about two years. There are no plans to adopt any significantly different mining techniques in the future. There are two strip mines in the area but the nearest operating underground mine is 30 miles away. Labour recruitment is difficult. Surface facilities are simple and utilitarian.

APPENDIX "S"

FIELD VISIT - MINE NO 2

INTRODUCTION

1. The mine is located in the Hanna field, Wyoming, and supplies coal to a captive utility in Iowa. Present production is 1,750 tpd or 440,000 tpa but it is planned to increase this to 1.1 million tpa.

GEOLOGY

2. The mine is in a complex basin with many coal seams and significant faulting. Problems are encountered with water from aquifers released along the faults. The seam worked is the No 50; the roof is sandstone and shale, and the floor is soft. The coal is moderately hard and its thickness is fairly constant at 14 ft to 16 ft. Depth of cover varies from zero to 500 ft but planned developments will increase this to 1,500 ft. The maximum dip is 25%.

METHOD OF WORKING

3. Present operation is with conventional and continuous miners but a mining area about 1 mile square is being developed by Jeffrey continuous miners for longwall extraction. Present working height is 8 ft to 10 ft. The working height of the proposed longwall will be about 10 ft to 12 ft.

TRANSPORT

4. Access is by three slopes at an inclination of about 20%. Coal is handled on 42-in belt conveyors, while Eimco front-end loaders are used for materials. Man transport is by Ensign jeeps and Eimco personnel vehicles.

LABOUR

5. The mine is controlled by a Vice President (Operations) assisted by a mine superintendent, underground supervisors and section foremen. Other staff include a chief engineer, and specialist mining, mechanical, electrical, reclamation and safety engineers. There are also three surveyors, a geologist and an analyst. These staff supervise an 850,000-tpa strip mine operation.

6. In addition, there is an underground labour force of about 160 and a surface labour force of about 28. The average age is only 23 years and there is a high labour turnover (78% per annum).

VENTILATION

7. There is a single main fan that produces 178,000 ft^3/min at 2.5-in water gauge; there are plans to add a ventilation shaft later. The mine atmosphere is cool and damp but there are extreme seasonal temperature changes. In winter, the intake air is heated to avoid icing underground. The methane concentration is not normally detectable but spontaneous combustion problems have occurred in the locality and one part of an earlier mine was sealed off for this reason.

WATER

8. The mine is wet with a lot of water coming from freshly exposed faults which dry up when development extends further down dip. The present pumping rate is 2.6 million gallons per week.

PRODUCTIVITY

9. The mine is in the development stage and present productivity is about 6 tons per man-day. It is planned to double production without increasing the labour force when longwall mining is put into operation.

MARKETING

10. All the coal is shipped to a utility in Iowa in 100-ton rail cars. The journey time is about 38 hours. At present, the only preparation consists of crushing to minus $1\frac{1}{2}$ in but a washing and blending plant is under construction. This will use magnetite dense medium separation for the $1\frac{1}{2}$ in x $\frac{1}{4}$ in fraction and cyclones for the $\frac{1}{4}$ in x 28 mesh fraction. The minus 28 mesh material will be rejected.

11. Typical coal analyses, supplied by the company, are:-

Proximate Analysis

Volatile matter	39.06%
Moisture	9.61%
Fixed carbon	46.93%
Ash	4.30%

Ultimate Analysis

Carbon	58.20%
Hydrogen	4.02%
Nitrogen	1.01%
Oxygen	12.76%
Chlorine	0.01%
Sulphur organic	0.66%
Sulphur inorganic	0.34%
Calorific value	10,300 Btu/lb
Non agglutinating	
Ash fusion temperature (reducing atmosphere)	2,260°F

SPONTANEOUS COMBUSTION EXPERIENCE

12. The high oxygen content of this coal suggests that it would have a high susceptibility to spontaneous combustion. The fact that stockpiling is avoided because surface stocks tend to self-ignite within a few days and that fires frequently occur on the exposed windward side of the cone bunker, serve to confirm this inference. The loss of the earlier No 1 Mine as a result of extensive spontaneous combustion is also significant.

13. Ameliorating factors are undoubtedly the low ventilating pressure and the low relative humidity of the ventilation air, which is said not to exceed 15% at any time during the year. Coal underground will therefore tend to lose water by evaporation and the chemi-sorption of water with resultant heating is very unlikely. The low inorganic sulphur content, less than 0.4%, is another factor in reducing the liability to spontaneous combustion underground. Greater precautions are indicated, nevertheless, when the longwall system of mining is introduced in seams of this thickness, particularly if less than the full seam is mined and coal is left in the roof. No plans exist for any significant change in mining methods, other than longwalling at the maximum practicable thickness.

GENERAL

14. Mining conditions are difficult due to the gradient, the water and the faulting. There are very high winds on the surface that also cause problems. It is proposed to concentrate production on longwall extraction with a working height of about 10 ft to 12 ft. This mine appears to have a high spontaneous combustion risk.

APPENDIX "T"

FIELD VISIT - MINE NO 3

INTRODUCTION

1. The mine is located in the Rock Springs field, Wyoming, and supplies coal to a number of industrial consumers. Present output is about 200,000 tpa but it is planned to expand this to 1.2 million tpa.

GEOLOGY

2. Seven seams of the Rock Springs formation occur within the property but only one, the No 3 seam, averaging 7 ft to 9 ft thick, is being worked at present, although development of a second seam (No 1) is imminent. The roof of the worked seam is of sandy shale and the floor is soft. Depth of cover is 700 ft to 800 ft. All the seams dip at an average of 12% to 15% and in areas where rolls have occurred the pitch may be as much as 25%.

METHOD OF WORKING

3. Extraction is carried out using continuous miners with load-haul-dump units transporting to Stamler feeder/breakers and thence on to conveyors. Main headings and crosscuts are driven 15 ft wide on 75-ft centres, as are panels driven at right angles to the main entries. Panel crosscuts are at 80-ft centres. Extensive roof bolting is carried out.

TRANSPORT

4. Main access is by two parallel 2,100-ft slopes descending at 10%. These are 14 ft wide by 12 ft high and are supported by steel arches. One slope is used for coal transport, using a 42-in belt conveyor, and the other is used for the transport of men and materials. There are two 300-ton surge bunkers and a 12,000-ton surface silo.

LABOUR

5. The operation is controlled by a general manager supported by a chief engineer, a mine superintendent and about eight other senior staff members. The company employs 130 payroll staff; in addition there are about 30 contractor's personnel on site. It is planned to increase the labour force to 250 as output increases.

VENTILATION

6. The mine is ventilated with an 8-ft fan which is rated at 250,000 ft^3/min at 5-in water gauge. The humidity is very low (annual rainfall is $3\frac{1}{2}$ in). Arrangements are being made to heat the intake air in the winter.

WATER

7. The mine is being re-developed after being inactive for a number of years. Most of the old workings were flooded and these must be de-watered. Once this has been completed, it is estimated that the pumping rate will stabilise at about 200 gal/min.

PRODUCTIVITY

8. Present productivity is about 5 tons per man-day, but this figure includes labour on pre-production development. When the mine reaches full production output, this should increase to about 20 tons per man-day.

MARKETING

9. The coal is crushed to minus 2 in and is then loaded into unit trains for shipment to the consumers, consisting of some cement plants and several smaller customers.

10. Typical coal analyses, supplied by the company, are:-

Proximate Analysis

Volatile matter	37.66%
Moisture	7.84%
Fixed carbon	48.60%
Ash	5.80%
Sulphur	1.05 to 1.20%

Ultimate Analysis

Carbon	59.76% to 62.06%
Hydrogen	4.11% to 4.99%
Nitrogen	1.16% to 1.30%
Oxygen	12.02% to 14.60%
Chlorine	0.01% to 0.02%
Sulphur inorganic	0.15% to 0.20%
Sulphur organic	0.90% to 1.00%
Calorific value	10,280 to 10,350 Btu/lb
Non agglutinating	
Ash fusion temperature (reducing atmosphere)	$2,910^0$ to $3,100^0$F

SPONTANEOUS COMBUSTION EXPERIENCE

11. The high oxygen content of this coal indicates that it is susceptible to spontaneous combustion and, indeed, stockpiling is rigorously avoided for this reason. Should there be a delay in the arrival of the unit train, production is cut

back to avoid putting coal on the ground. The cone bunker is totally enclosed and sealed, partly to avoid spontaneous combustion and partly to control atmospheric dust pollution. Advantageous factors underground are the very low humidity of the ventilation air throughout the year and the low pyritic sulphur content, less than 0.2%.

12. There are signs of spontaneous combustion at the outcrop and one neighbouring mine experienced an underground fire in 1950.

13. It is of interest that there is no recorded case of this coal self-igniting in railroad cars during transit. The current mining plans envisage all production from conventional room and pillar operations.

GENERAL

14. The mine is beginning to build up capacity after a major re-opening operation involving de-watering and the driving of two new slopes.

APPENDIX "U"

FIELD VISIT - MINE NO 4

INTRODUCTION

1. The mine is located in the Carbondale field, Colorado, and produces metallurgical grade coal. Present production is about 350,000 tpa.

GEOLOGY

2. The workings are located in the upper part of the Coal Basin A/B seam. The mined section is about 9 ft with a roof of shale and a floor of sandstone. The coal is of medium hardness and dips fairly uniformly at about 18%. Bumps and outbursts occur from time to time. The terrain is mountainous and the cover varies from zero to 3,000 ft.

METHOD OF WORKING

3. Working is by means of strike panels off a dip entry system. There is one 500-ft advancing longwall face and one continuous-miner dip development. Entries are typically 16 ft wide by 9 ft high.

TRANSPORT

4. Access is by slope entries in the seam. One is used for coal transport, using a 36-in belt conveyor, another for trackless material transport and a third for rope-hauled man-riding. The two flank drifts are used as ventilation returns.

LABOUR

5. The operation is controlled by a Vice President (Coal), supported by a manager of mines, a district superintendent and a mine superintendent. Specialist engineering and other services are provided by the parent company. In addition, there are about 80 mine workers.

VENTILATION

6. Ventilation is by means of two exhaust fans rated at 150,000 ft^3/min and 500,000 ft^3/min respectively. There is also up-hole methane drainage on the longwall face. In general, methane emission levels are high.

WATER

7. Water is a nuisance problem only.

PRODUCTIVITY

8. Present productivity is about 12 tons per man-day.

MARKETING

9. The raw coal is not crushed but beneficiation is carried out using heavy medium separators, Deister tables and froth flotation, followed by thermal drying.

10. All the output is metallurgical grade and typical analyses are:-

Proximate Analysis

Volatile matter	25.70% to 27.10%
Moisture	4.20% to 5.80%
Fixed carbon	69.10% to 70.70%
Ash	3.60% to 6.70%
Sulphur	0.42% to 0.62%

Ultimate Analysis

Carbon	85.33% to 86.23%
Hydrogen	5.18% to 5.30%
Nitrogen	1.54% to 2.03%
Oxygen	2.59% to 3.01%
Sulphur organic	0.30% to 0.40%
Sulphur inorganic	0.12% to 0.22%
Calorific value	12,475 to 12,750 Btu/lb
Strongly agglutinating	
Ash fusion temperature (reducing atmosphere)	2,300°F

SPONTANEOUS COMBUSTION EXPERIENCE

11. There are no reports of any occurrences of spontaneous combustion. The low oxygen content of the coal (about 3%) is significant in this respect.

GENERAL

12. It is proposed, ultimately, to work the lower portion of the A/B seam. It is also planned to use a shield longwall technique in the upper portion and increase the extraction thickness to about 15 ft in one lift.

APPENDIX "V"

FIELD VISIT - MINE NO 5

INTRODUCTION

1. The mine is located in the Uinta region, Utah, and produces high volatile metallurgical coal. Present production is 800,000 tpa.

GEOLOGY

2. There are two principal seams - the upper, 4 ft to 6 ft thick, and the lower, 5½ ft to 7 ft thick. These are separated by a shale parting, which varies from zero to 40 ft thick. These seams contain reserves sufficient for at least 20 years at current production rates. There are also other seams but they are too thin to mine. The cover varies between zero and 2,000 ft, depending on the topography. The dip of the seams varies from 10% to 20%

METHOD OF WORKING

3. The seams have been developed by drifts from the outcrops. Production is from retreating longwall faces using shearers. Face lengths are about 550 ft, and panel lengths vary between 4,000 ft and 6,000 ft. The two entry developments are driven by Joy continuous miners.

TRANSPORT

4. There are nine shafts and twenty-one drifts but the main haulage routes are two drifts about 7,000 ft long. These employ rope haulage and have a capacity of 2,000 tons per shift and 1,800 tons per shift respectively, using 5-ton mine cars. Coal is brought from the face to the foot of the inclines by 42-in belt conveyors.

LABOUR

5. The operation is controlled by a mine manager with a mine superintendent responsible for each of the two main mining areas. Other senior staff include a chief mining engineer, a master mechanic and a safety manager. In all, there are 400 employees.

VENTILATION

6. Two forcing ventilation fans have capacities of 320,000 ft^3/min at 2.3-in water gauge and 420,000 ft^3/min at 2.6-in water gauge respectively. Three exhaust fans handle a total of approximately 600,000 ft^3 of air per minute at water gauges varying from 2.0 in to 5.5 in.

7. Dust concentrations are generally within the 2 mg/m^3 standard.

8. 250,000 ft^3/day of 98% methane is being drained from one new longwall face area by means of two 3-in diameter holes bored 450 ft into the coal.

WATER

9. The deeper sections of the mine are wet and 2 million gallons per day have

to be pumped out. The water is used for coal preparation, for dust suppression and for irrigating alfalfa. The upper sections of the mine are dry.

PRODUCTIVITY

10. Overall productivity is $9\frac{1}{2}$ tons per man-day.

MARKETING

11. All coal is crushed to minus 2 in. The 2-in to 60-mesh fraction is passed to a Baum washer, and the fines go to froth flotation. It is then loaded into 8,400-ton unit trains at about 4,000 tph for transport to the captive steelworks, where it is blended with other coking coals.

12. A typical proximate analysis, supplied by the operator, is:-

Volatile matter	36%
Moisture	6% to 9%
Fixed carbon	47% to 50%
Ash	6.4%
Sulphur	1.0%
Calorific value (daf basis)	14,000 Btu/lb

SPONTANEOUS COMBUSTION EXPERIENCE

13. Spontaneous combustion incidents have occurred underground between 1940 and 1973. In 27 years there have been about seven such incidents, which have resulted in a loss of production but no casualties. The normal method of attacking such a fire is with water and rock dust or by digging it out. If these methods fail, then it is necessary to resort to sealing off the affected area.

14. One underground fire continues to be active at the present time. Air samples are periodically taken from the sealed area; these presently contain 900 ppm of carbon monoxide.

15. All waste piles are now compacted as problems have been experienced with fires; indeed, some old ones are still burning.

16. Coal stocks get hot if kept for more than three months, so every effort is made to keep the coal moving steadily.

APPENDIX "W"

FIELD VISIT - MINE NO 6

INTRODUCTION

1. The mine is located in the Emery field, Utah, and supplies 70% of its output to the power station market and the balance to various industrial and domestic consumers. Present production is about 135,000 tpa.

GEOLOGY

2. There are a number of coal seams present but only one is being worked. The overburden includes shale with sandstone aquifers and massive sandstone, and varies from zero to 300 ft. The floor consists of hard clay that becomes soft when wet. The dip varies between 6% and 10%. Reserves on the property are stated to be 300 million tons.

METHOD OF WORKING

3. There are two basic methods of working, either conventional with a working height of 7 ft to 8 ft, or using Joy continuous miners with a working height of 12 ft. The total seam thickness is about 24 ft and normally 2 ft of coal is left in the floor and the remainder in the roof. The percentage extraction is very low, 17% by conventional means and 27% by continuous miner based on the total seam thickness. Based on the height being extracted, the percentage extraction is considerably better, being 42% by conventional means and 57% by continuous miners.

TRANSPORT

4. Access is by three drifts and the coal is transported on 36-in wide belts. There is no track haulage and transport of men and materials is by electric battery vehicles and diesel tractors respectively.

LABOUR

5. The labour force comprises six management personnel, 21 other staff and 94 mine workers.

VENTILATION

6. Ventilation is by means of a 54-in diameter exhausting fan handling 125,000 ft^3/min of air at 6.5-in water gauge. The humidity is low but there is a large seasonal temperature variation (0 to 105°F). There is very little problem with methane except immediately after shot firing. Routine tests are carried out using MSA methanometers.

WATER

7. The mine is wet. About 700,000 gallons of water per day have to be pumped out.

PRODUCTIVITY

8. Overall productivity is estimated at 11 tons per man-day.

MARKETING

9. The principal market is local power stations, although sales are made to other industrial and domestic consumers. Preparation is limited to crushing and screening. Industrial coal is sold as minus $1\frac{1}{4}$ in to plus $^3/_{16}$ in, while steam coal is $1\frac{1}{4}$ in to zero. There is also a small domestic market for plus 4-in sizes. All transport is by road, although a rail contract is being negotiated.

10. A typical proximate analysis, supplied by the owners, is:-

Volatile matter	38%
Moisture	7%
Fixed carbon	47.25%
Ash	7%
Sulphur	0.75%
Calorific value (daf basis)	14,300 Btu/lb
Hardgrove grindability index	45
Petrographic analysis	clarain with durain bands

SPONTANEOUS COMBUSTION EXPERIENCE

11. There has been a fire in the surrounding coal outcrops. Heating occurs in the stockpiles of steam coal if they are retained for a few months and there have been fringe fires which have required digging out. If coal is to be kept in stock, it is now standard policy to compact the heap. The heaps also need to be drained to avoid collection of rainfall.

12. One underground fire, which occurred 20 years ago, was believed to be due to spontaneous combustion. However, the present operators have no further knowledge of this and have had no problems themselves.

13. Longwall mining is being considered but difficulties are envisaged with top coal caving, spontaneous combustion and water.

APPENDIX "X"

FIELD VISIT - MINE NO 7

INTRODUCTION

1. The mine is located in the Raton Mesa region of southern Colorado and northern New Mexico. It supplies metallurgical coal to a captive steel plant. Present production is about 1 million tpa.

GEOLOGY

2. All coal is mined from a single seam which varies from 4 ft to 10 ft thick, being thickest at the outcrop. The roof conditions are variable but are mainly poor. Cover varies up to a maximum of 750 ft. It is estimated that there are sufficient reserves for 15 years. A second seam is present at a depth of 1,400 ft but this seam is not worked, although it has been exploited elsewhere.

METHOD OF WORKING

3. There are two basic methods of working; room and pillar using continuous miners and retreat longwall faces. There are, at present, two working longwall faces. These are 500 ft long and panel lengths are up to 6,200 ft. Typically, each face progresses 50 ft per week, and production output averages 1,150 tons per shift.

TRANSPORT

4. Access is by means of two sets of drifts and coal is handled by 42-in and 48-in belt conveyors. Men are transported by battery-operated vehicles as far as the restricted area.

LABOUR

5. The operation is controlled by a manager and four superintendents. There are also two mine foremen, a number of section foremen, and 343 mineworkers.

VENTILATION

6. There are three forced draft fans on the surface. Two are rated at 375,000 ft^3/min at $3\frac{1}{2}$-in water gauge; the third is rated at 170,000 ft^3/min at 1-in water gauge. These fans produce 30,000 ft^3/min on the individual longwall faces and a minimum of 9,000 ft^3/min at the last open crosscut in the room-and-pillar workings. Use is made of 5-ft diameter raises to provide return ventilation facilities to the surface. The velocity in the entries is about 45 ft/min. The humidity in the mine is low and the temperature is about 58°F.

7. The methane emission rate is moderate. The mine produces 700,000 ft^3 to 1 million ft^3 of methane per day.

8. Dust levels are normally within the 2 mg/m^3 maximum.

WATER

9. There are no problems with water.

PRODUCTIVITY

10. Overall productivity is about 10 tons per man-day.

MARKETING

11. Most sales are to a captive steelworks. All coal is crushed to minus 4 in and is cleaned as follows:-

4 in to $^5/_{16}$ in	-	heavy medium (magnetite)
$^5/_{16}$ in to 60 mesh	-	heavy medium cyclones
minus 60 mesh	-	froth flotation

12. The rejects amount to 26% of the raw coal feed. The cleaned coal is then loaded into trains of eighty-four 100-ton cars, with an average loading time of 2 hours.

13. A typical proximate analysis is understood to be:-

Volatile matter	38%
Moisture	8%
Fixed carbon	46%
Ash	7.5%
Sulphur	0.5%
Calorific value	12,700 Btu/lb

SPONTANEOUS COMBUSTION EXPERIENCE

14. No spontaneous combustion problems were reported at this mine.

GENERAL

15. The change from room-and-pillar to longwall working was principally due to the roof conditions. However, the resultant improvement to 85% recovery has increased production.

APPENDIX "Y"

FIELD VISIT - MINE NO 8

INTRODUCTION

1. The mine is located in the Weld field, Colorado, and supplies sub-bituminous coal for steam generation and to other industrial and domestic consumers. The mine was re-opened about a year ago and production is being built up to about 150,000 tpa.

GEOLOGY

2. Although there are five seams, only one is mined; this seam averages 9 ft to 10 ft thick. The extraction height is 7 ft to 8 ft, and 2 ft of top coal is left. The strata are not generally inclined but rolling grades of 5% to 10% exist in the vicinity of faults that traverse the property. The average depth of cover is 420 ft. Reserves are estimated at 30 years.

METHOD OF WORKING

3. The seam has been developed from the main slope, which has been driven 1,800 ft at an average grade of 20% to intersect the coal. All development is carried out in-seam using a multiple entry system with depillaring where strata conditions allow. Extraction is carried out using continuous miners and shuttle cars.

TRANSPORT

4. The coal is transported up the main slope using 36-in belt conveyors. Electric-trolley-wire vehicles are used for man-riding and for materials transport.

LABOUR

5. The operation is controlled by a general supervisor supported by a mine foreman and section foremen. In addition, there are five other staff and 70 mineworkers.

VENTILATION

6. The main ventilation is through a 480-ft shaft using a forcing fan handling 84,000 ft^3/min at 4-in water gauge. Ventilation of the entries is through auxiliary 18-in diameter duct systems. No methane problems have been experienced. Periodic sampling indicates 20 ppm to 30 ppm of carbon monoxide in the last open crosscut. It was suggested that the numerous old workings that have been intersected were a possible source of carbon monoxide.

WATER

7. Water presents a nuisance problem, particularly in association with accumulations in old workings. This is pumped to the surface but details of the quantities involved were not available.

PRODUCTIVITY

8. Overall productivity is estimated at 10 tons per man-day.

MARKETING

9. The minus 2-in coal is screened out at the pit head and sold for industrial fuel. The plus 2-in fraction is trucked two miles to a preparation plant which uses heavy medium and cyclone separation with the objective of producing a washed product for the domestic market.

10. A typical partial proximate analysis is understood to be:-

Moisture	25% to 26%
Ash	6.8%
Sulphur	0.6%
Calorific value	9,000 to 9,400 Btu/lb

SPONTANEOUS COMBUSTION EXPERIENCE

11. This coal has been known to self-ignite at the outcrop. There have also been cases where smoke has been detected after coal has stood for three to four weeks in stockpiles or in rail cars.

GENERAL

12. The mine is about 30 years old and has passed through periods of production and closure dependent on market conditions. The present owners acquired it in mid-1976 and are planning to increase production after access to new reserves has been gained through old workings.

APPENDIX "Z"

STATUTORY REQUIREMENTS

FEDERAL COAL MINE HEALTH AND SAFETY ACT OF 1969

1. The Act details many requirements in relation to activities pertaining to spontaneous combustion, viz:-

Section 103 - Inspections and Investigations

Section 104 - Findings, Notices and Orders

Section 303 - Ventilation

Section 304 - Combustible Materials and Rock Dusting

Section 311 - Fire Protection

Section 317 - Miscellaneous

However, no specific reference to spontaneous combustion is made.

CODE OF FEDERAL REGULATIONS

2. The Code of Federal Regulations, Title 30, Mineral Resources, contains the following references to matters related to spontaneous combustion:-

Sections 75.300 - 75.330	- Ventilation
Sections 75.400 - 75.404	- Combustible Materials and Rock Dusting
Sections 75.1100 - 75.1106	- Fire Protection
Section 75.1704	- Escapeways
Section 75.1714	- Self-Rescue Devices
Sections 80.1 - 80.33	- Notification, Investigations, Reports and Records of Accidents

There is no specific reference to spontaneous combustion in the Code of Federal Regulations.

3. Although there is no direct reference to the detection, prevention and methods of dealing with incipient and/or active heatings, the following general requirements are relevant:-

(i) In the event of any accident occurring in a coal mine, the operator shall notify the Secretary of the Interior (Act, Section 103 (e)). An accident is defined as including a mine fire not extinguished within 30 minutes (Regulations, 80.11 (d)).

(ii) An authorised representative of the Secretary of the Interior may issue an order requiring the operator to withdraw all persons from any area of a mine in which an imminent danger exists (Act, Section 104 (a)).

(iii) Any notice issued pursuant to Section 104 may be modified or terminated by an authorised representative of the Secretary (Act, Section 104 (g)).

(iv) All active workings shall be adequately ventilated and the minimum quantity of air reaching the last open crosscut in any pair of developing entries or rooms shall be 9,000 ft^3/min. The minimum quantity of air reaching the intake end of a pillar line shall be 9,000 ft^3/min. The minimum quantity of air reaching each working face shall be 3,000 ft^3/min (Act, Section 303 (b)). Although not stipulated, these minimum air quantities imply minimum ventilation pressure differences.

(v) Except in working places using a blowing system as the primary means of face ventilation, the minimum mean entry air velocity shall be 60 ft/min (Regulations, 75.301-4 (a)).

(vi) Pre-shift and during-shift inspections shall be carried out by certified persons to ascertain if hazardous conditions exist (Act, Section 303 (d)(1)).

(vii) Idle and abandoned areas shall be inspected (Act, Section 303 (m)).

(viii) An approved ventilation system and methane and dust control plan shall be adopted by the operator (Act, Section 303 (o)).

(ix) Entries used as intake and return air courses shall be separated from belt haulage entries and the air velocity coursed through belt haulage entries shall be limited to that necessary to provide an adequate supply of oxygen and to ensure that air therein shall contain less than 1% of methane. Such air shall not be used to ventilate active working places (Act, Section 303 (y)(1)).

(x) All areas from which pillars have been wholly or partially extracted, and abandoned areas, shall be ventilated by bleeder entries (Act, Section 303 (z)(2)).

(xi) Seals or bulkheads are to be constructed of solid, substantial and incombustible materials to prevent an explosion (Regulations, 75.329-2).

(xii) The mining system shall be designed so that as each working section of the mine is abandoned, it can be isolated from the active workings with explosion-proof seals or bulkheads (Act, Section 303 (z)(3)).

(xiii) Deposited coal dust, loose coal and other combustible materials shall be cleared up and not be permitted to accumulate in active workings (Act, Section 304 (a)).

(xiv) Except where dust is wet, or too high in incombustible content, rock dusting shall take place to within 40 ft of all working faces (Act, Section 304 (c)). The minimum incombustible content in return air courses shall be not less than 80% and in all other places not less than 65%.

(xv) Each coal mine shall be provided with suitable fire-fighting equipment adapted for the size and conditions of the mine (Act, Section 311 (a)).

(xvi) At least two separate and distinct travellable passageways which are maintained to ensure passage at all times of any person, and which are to be designated as escapeways, at least one of which is ventilated by intake air, shall be provided from each working section continuous to the surface (Act, Section 317 (f)(1)).

(xvii) An approved self-rescue device shall be made available to each miner (Act, Section 317 (n)).

STATE LEGISLATIVE REQUIREMENTS

Colorado

4. With the following exceptions, the requirements of the State law are covered in the Federal legislation.

5. Article 92-10-17 of the Coal Mining Laws of the state of Colorado outlines in paragraphs (4) and (5) the necessary action to be taken in the event of a fire occurring in a mine. Paragraph (6) requires that if the fire gets out of control, men shall be withdrawn and the part of the mine in which the fire is located or the entire mine, as the conditions may require, shall be sealed or flooded.

6. Article 92-10-25 refers to heated gobs. If any increase of temperature be localised in any part of the gobs or other places, prompt action shall be taken to remove the heated gob or debris, or to extinguish the fire by water or other means, but if the fire has already reached such proportions that it is impossible to extinguish it in such way, then it shall be the duty of the owner to effectively seal the area immediately in a prescribed manner. All permanent seals used to block off heated gobs must have a pipe not less than 1 in in diameter and be equipped with a valve for the purpose of testing gases which are confined behind the seal and a pipe not less than 2 in in diameter equipped with a valve not more than 1 ft from the bottom of the seam for the purpose of draining off water or forcing water in behind the seal.

New Mexico

7. No requirements beyond those included in Federal law are included in the State mine safety laws and regulations. Minimum ventilation quantities are referred to as at least 100 ft^3/min for each person and 300 ft^3/min for each animal.

Utah

8. Under the Miscellaneous Sections of the State law pertaining to Mining Activity, Coal Mines, Title 40-2, there is one reference additional to the relevant Federal requirements. Miscellaneous Offenses, Title 40-5, under 40-5-1, Surface Hazards from Mining - Slack Coal Afire-Liability, requires that if any owner, lessee, or agent of a mine has heaped or piled slack coal on the surface, and such slack coal shall take fire and endanger the life or safety of any person or animal, he shall cause the fire to be extinguished or the burning coal to be enclosed with a sufficient fence.

Wyoming

9. The Mineral and Mining Laws of Wyoming, Title 30, include many of the provisions of the Federal law. Section 30-183 (d) and (e) stipulates the procedure to be adopted when a fire is discovered underground. Paragraph (f) requires isolation of the affected area by sealing or flooding in the event that the fire gets out of control.

TABLE I

PERCENTAGE LOSS OF CALORIFIC VALUE OF LOW RANK COAL IN FIRST YEAR OF STORAGE

Size	Stock at 70^{0}F	Stock at 160^{0}F
1 in - ¾ in	0.1	1.25
½ in - ¼ in	-	2.25
$\frac{1}{8}$ in - $\frac{1}{16}$ in	0.7	6.00
100 mesh	1.2	10.50
200 mesh	2.0	11.50
325 mesh	2.0	10.00

Source: PD-NCB Data

TABLE II

CHANGES IN COKING PROPERTIES DURING STORAGE

(Free Swelling Index)

	Size	Initial	After 6 Months	After 12 Months	After 24 Months
Stored without rise in temperature	2 in - ½ in	5	4	4	3
	½ in - $\frac{1}{8}$ in	3	2½	2½	2½
	$\frac{1}{8}$ in - $\frac{1}{16}$ in	2½	2	2	2
Stored in dump at 160^0F	¼ in - $\frac{1}{8}$ in	3	2	-	1½
	$\frac{1}{8}$ in - $\frac{1}{16}$ in	2½	2	-	1
	1 in Slack	8	3	-	-
	1 in Slack	1½	-	1	1

Source: PD-NCB Data

TABLE III

PRINCIPAL BITUMINOUS COAL FIELDS OF THE WESTERN STATES

State	Region or Field	County	Formation	Age	Rank
Colorado	Denver Region	Weld, Morgan, Boulder, Adams, Arapahoe, Elbert, Douglas, El Paso	Laramie, Dawson Arkose	Cretaceous Paleocene	Sub-bituminous B & C
	Raton Mesa Region	Huerfano, Las Animas	Vermejo, Raton	Cretaceous Paleocene	Bituminous High Volatile A-B
	North Park and Middle Park Fields	Jackson, Grand	Coalmont	Paleocene	Sub-bituminous
	San Juan River Region	Dolores, Montezuma, La Plata, Archuleta	Mesaverde (Menefee, Fruitland) Dakota	Cretaceous	Bituminous
	Green River Region	Moffat, Routt	Mesaverde (Ilse, Williams Fork) Lance, Fort Union	Cretaceous Paleocene	High Volatile C to Sub-bituminous
	Uinta Region	Rio Blanco, Garfield, Mesa, Delta, Pitkin, Gunnison	Mesaverde (Ilse, Williams Fork)	Cretaceous	Anthracite to Sub-bituminous
New Mexico	San Juan River Region	San Juan McKinley	Mesaverde (Fruitland, Menefee, Dilco)	Cretaceous	Sub-bituminous
Utah	Kaiparowits Plateau Field	Kane, Garfield	Straight Cliffs	Cretaceous	High Volatile C
	Kalob Plateau Field	Kane, Garfield Iron, Washington	Tropic, Straight Cliffs	Cretaceous	Bituminous to Sub-bituminous
	Castlegate and Emery Fields	Sanpete, Sevier, Emery, Carbon	Mesaverde (Blackhawk)	Cretaceous	High Volatile A-C
	Book Cliffs and Castlegate Fields	Carbon, Emery	Mesaverde (Blackhawk)	Cretaceous	High Volatile A-C
Wyoming	Kemmerer Field	Lincoln, Uinta	Adaville, Frontier	Cretaceous	High Volatile A
	Rock Springs Field	Sweetwater	Mesaverde (Rock Springs, Almond) Lance, Fort Union, Wasatch	Cretaceous Paleocene	Sub-bituminous to High Volatile C
	Hanna Field	Carbon	Mesaverde Medicine Bow, Ferris, Hanna	Cretaceous Paleocene	High Volatile C to Sub-bituminous
	Wind River Region	Fremont, Natrona	Mesaverde, Fort Union, Meeteese	Cretaceous Paleocene	
	Bighorn Basin Region	Park, Hot Springs, Bighorn, Washakie	Mesaverde Meeteetse, Lance, Fort Union	Cretaceous Paleocene	High Volatile C to Bituminous
	Powder River Region	Sheridan, Johnson, Natrona, Converse, Niobrara, Weston, Crook, Campbell	Lance, Fort Union, Wasatch	Cretaceous Paleocene Eocene	Sub-bituminous

Source: Keystone Coal Industry Manual, 1977

TABLE IV

DETAILS OF UNDERGROUND MINES IN THE WESTERN UNITED STATES

Mine Name	Company	1976 Production (Ton)	Manpower	Seams Mined	Method of Extraction	Seam Thickness (Inch)	Proximate Coal Analysis				
							Moist. %	Vol. %	Ash %	S %	Btu/lb
Colorado											
Allen	C.F.& I. Steel Corporation	619,000	437	Allen	Continuous and Longwall	48-72					
Bear	Bear Coal Company	109,000	52	Juanita C	Room and Pillar, Continuous	84					
Bear Creek	Mid-Continent Coal and Coke Company	115,000	76	B	Room and Pillar, Continuous	84					
CMC	Cambridge Mining Corporation	50,000	38	Cameo							
Coal Basin	Mid-Continent Coal and Coke Company	109,000	90	B	Room and Pillar, Continuous	85					
Dutch Creek No 1	Mid-Continent Coal and Coke Company	134,000	105	B	Continuous and Longwall	84	5	26	5	0.5	12,600
Dutch Creek No 2	Mid-Continent Coal and Coke Company	267,000	84	Middle	Room and Pillar, Continuous	93					
Eagle	Imperial Coal Company	32,000	5	Laramie No 3	Room and Pillar, Continuous	108					
Hawks Nest East	Western Slope Carbon Inc.	27,000	130	E or Hawks Nest	Room and Pillar, Continuous	84	6	39	4.5	0.4	13,000
Hawks Nest West	Western Slope Carbon Inc.	153,000		E or Hawks Nest	Room and Pillar, Continuous	84	6	39	4.5	0.4	13,000
King	Adolph Coors Company	Temporarily inactive	2	Lower B	Room and Pillar, Continuous	192	4.5	39	5.4	0.6	12,900
Lincoln	Imperial Coal Company	35,000	75	Laramie No 3	Room and Pillar, Continuous	110	13	38	6.8	0.6	11,000
Orchard Valley	Colorado Westmoreland Inc.	11,000	-	D	Room and Pillar, Continuous	48-312	9.5	-	10.5	-	11,000
Somerset	US Steel Corporation	950,000	305	B and C	Room and Pillar, Continuous	96-144	7	34	15	0.55	11,700
Twin Pines	Twin Pines Coal Company	37,000	9	Brookside	-	72	8.6	36.9	8.9	0.8	11,100
Sub Total	c/f	2,648,000									

TABLE IV

(Continued)

Mine Name	Company	1976 Production (Ton)	Manpower	Seams Mined	Method of Extraction	Seam Thickness (Inch)	Proximate Coal Analysis				
							Moist. %	Vol. %	Ash %	S %	Btu/lb
Colorado (Contd)	b/f	2,648,000									
Wise Hill No 5	Empire Energy Corporation	382,000	114	F	Room and Pillar, Continuous	95	9.4	38	2.6	0.4	-
L.S. Wood	Mid-Continent Coal and Coke Company	262,000	121	B	Room and Pillar, Continuous	84					
Sub Total		3,292,000									
New Mexico											
York Canyon	Kaiser Steel Corporation	830,000	400	York Canyon	Continuous and Longwall	60-130	8	38	7.5	0.5	12,700
Sub Total		830,000									
Utah											
Beehive	American Coal Company	536,000	70	Blind Canyon	Room and Pillar, Continuous	132					
Belina No 1	Valley Camp of Utah	1,000	24	Upper O'Conner	Room and Pillar, Continuous	96-324					
Braztah No 3	Braztah Corporation	550,000	500	Castlegate Sub 3	Room and Pillar, Continuous and Longwall	72-144					
Braztah No 5	Braztah Corporation	328,000		Castlegate No 8	Room and Pillar, Continuous	72-144					
Convulsion Canyon	Southern Utah Fuel Company	1,043,000	190	Upper Hiawatha	Room and Pillar, Continuous	96-180	9	38	9	0.6	11,200
Co-op	Co-op Mining Company	110,000	16-18	Upper Hiawatha	Room and Pillar, Continuous	228					
Deer Creek	Peabody Coal Company	855,000		Blind Canyon	Room and Pillar, Continuous	-					
Sub Total	c/f	3,423,000									

TABLE IV
(Continued)

Mine Name	Company	1976 Production (Ton)	Manpower	Seams Mined	Method of Extraction	Seam Thickness (Inch)	Proximate Coal Analysis				
							Moist. %	Vol. %	Ash %	S %	Btu/lb
Utah (Contd)		b/f 3,423,000									
Deseret	American Coal Company	530,000	65	Hiawatha	Room and Pillar, Continuous	132					
Dog Valley	Western States Coal Corporation	48,000	-	-	-	-					
Emery	Consolidation Coal Company	159,000	121	Ferron I	Room and Pillar, Continuous	148	7	38	7	0.75	12,350
Geneva	US Steel Corporation	603,000	279	Lower Sunnyside	Room and Pillar, Continuous	168	7	36	12	0.86	12,200
King	United States Fuel Company	615,000	200	Hiawatha	Room and Pillar, Continuous	156					
Soldier Canyon	Soldier Creek Coal Company	184,000	131	Rock Canyon	Room and Pillar, Continuous	92-132					
Star Point No 1	Plateau Mining Company	393,000	83	Hiawatha Wattis	Room and Pillar, Continuous	90-96	9	36	8.5	0.65	11,500
Star Point No 2	Plateau Mining Company	157,000	83	Hiawatha Wattis	Room and Pillar, Continuous	90-96	9	36	8.5	0.65	11,500
Sunnyside No 1	Kaiser Steel Corporation	655,000	320	Lower Sunnyside	Continuous and Retreating Longwall	76-150	7	36	6	1.0	12,200
Sunnyside No 2	Kaiser Steel Corporation	Temporarily inactive	-	Upper Sunnyside	Longwall	60-84					
Sunnyside No 3	Kaiser Steel Corporation	155,000	100	Upper Sunnyside	Longwall and Continuous Miners	52					
Swisher No 2	Swisher Coal Company	197,000	38	Castlegate No 8	Room and Pillar, Continuous	72-144	9	42	10	0.5	12,000
Swisher No 3	Swisher Coal Company	183,000	38	Hiawatha	Room and Pillar, Continuous	72-144	9	42	10	0.5	12,000
Utah No 2	Valley Camp of Utah	345,000	65	Upper O'Conner	Room and Pillar, Continuous	96					
Wilberg	Peabody Coal Company	224,000	-	-	-	-					
Sub Total		7,871,000									

TABLE IV

(Continued)

Mine Name	Company	1976 Production (Ton)	Manpower	Seams Mined	Method of Extraction	Seam Thickness (Inch)	Proximate Coal Analysis				
							Moist. %	Vol. %	Ash %	S %	Btu/lb
Wyoming											
Rainbow No 8	Colombine	119,000	Mine closed May 1977								
Stansbury	Stansbury Coal Company	94,000	130	No 1	Room and Pillar, Conventional and Continuous	60-156	8	38	5.3	1.01	10,950
Vanguard No 2	Energy Development Company	249,000	270	No 50	Room and Pillar, Conventional and Continuous	90	13	33	12.5	0.36	10,200
Vanguard No 3	Energy Development Company	52,000		No 50	Room and Pillar, Continuous	90	13	33	12.5	0.36	10,200
Sub Total		514,000									
Total		12,507,000									

Sources: USBM, Keystone Coal Industry Manual, 1977 and Dames & Moore Data Files

TABLE V

UNDERGROUND MINES PLANNED IN THE WESTERN UNITED STATES, 1976-1985

Mine Name	Parent Company	Capacity at Full Operation
		(10^6 tons)
Colorado		
Rienau No 2	American Fuels, Inc.	1.40
Thompson Creek No 1	Anschutz Coal	0.50
Thompson Creek No 3	Anschutz Coal	0.50
Mt. Gunnison	Atlantic Richfield Co.	2.00
Maxwell	CF&I Steel Corp.	0.50
CMC No 1	Cambridge Mining Corp.	1.40
CMC	Cambridge Mining Corp.	0.50
Dawson Unit	Coal Fuels Corp.	2.00
Anchor-Tresner Unit	Coal Fuels Corp.	4.00
Converse	Colorado Westmoreland, Inc.	1.00
Craig	Colowyo Coal Co.	3.00
King	Coors Co.	0.50
McGinley	Eagle Head Coal Co.	0.50
Wise Hill No 6	Empire Energy Corp.	0.60
Wise Hill No 7	Empire Energy Corp.	0.60
Wise Hill No 8	Empire Energy Corp.	0.60
McKinley No 1	Energy & Export Co. Ltd.	0.30
Lorencito	Freeport Coal Co.	1.00
Grand Junction	General Exploration Co.	0.50
-	Moon Lake Electric Co.	1.15
Sun	Ruby Construction Co.	0.50
Old Blue Ribbon	Sunflower Energy Corp.	0.30
-	Tipperary Oil & Gas Corp.	0.50
Sub Total	-	23.85
Utah		
-	Centennial Coal Assn.	0.50
-	Clinton Oil Co.	1.00
Browning	Consolidation Coal Co.	1.40
John Henry	5M Corporation	0.40
Gordon Creek 3	General Exploration Co.	0.20
ICPA	Intermountain Power Project	10.00
-	Inspiration Development Co.	1.00
Star Point No 3	Plateau Mining Co.	1.00
No 1	Southern Utah Fuel Co.	1.50
Huntington Canyon 4	Swisher Coal Co.	0.20
No 5	Swisher Coal Co.	0.20
-	United States Fuel Co.	1.50
Straight Canyon	Utah Power & Light Co.	2.50
		c/f 21.40

TABLE V

(Continued)

Mine Name	Parent Company	Capacity at Full Operation
		(10^6 tons)
Utah (Contd.)		b/f 21.40
Escalante	Utah Power & Light Co.	6.00
O'Connor No 1	Valley Camp of Utah	0.20
Belina No 2	Valley Camp of Utah	0.80
Thompson	Western American Energy Corp.	0.20
Rilda Canyon	Western American Energy Corp.	0.20
Sub Total	-	28.80
Wyoming		
Hanna	Rocky Mountain Energy Corp.	2.50
Carbon Basin	Rocky Mountain Energy Corp.	Not available
Long Canyon	Sunoco Energy Development Co.	1.00
Winton	Rocky Mountain Energy Corp.	Not available
Sub Total	-	+3.50
New Mexico		
No Projections available	-	-
Total	-	+56.15

Source: Keystone Coal Industry Manual, 1977

TABLE VI

SAMPLES COLLECTED DURING FIELD VISITS

Mine	Coalfield/ Region	Seam Code	Seam Thickness	*Sample Location	Coal Lithotype	Sample No	Notes
			in	in			
A	Weld Field	1	104	7	Durain		Some cannel coal in upper and lower parts of seam
		1	104	38	Durain		
		1	104	64	Durain	1	
		1	104	102	Durain		
B	Carbondale Field	1	93	4	Clarain		Not worked at present
		1	93	29	Bone	15	
		1	93	63	Durain		
		1	93	85	Clarain/Durain	9	
		1	88	8	Clarain	14	Seam up to 25 ft thick but only top 8 ft to 9 ft extracted
		1	88	50	Clarain/Durain		
		1	88	75	Durain		
C	Yampa Field	1	95	6	Clarain/Durain		Seam up to 13 ft
		1	95	32	Durain		
		1	95	66	Clarain/Durain	2	
		1	95	89	Durain		
D	Emery Field	1	148	7	Durain		
		1	148	29	Durain		
		1	148	78	Clarain	12	
		1	148	95	Clarain/Durain		
		1	148	119	Clarain/Cannel		
		1	148	139	Clarain	13	
E	Uinta Region	1	67	4	Clarain		
		1	67	32	Clarain/Durain	8	
		1	67	65	Durain		
		2	58	2	Durain		
		2	58	28	Clarain/Durain		
		2	58	54	Clarain/Durain	7	

/continued

TABLE VI

(Continued)

Mine	Coalfield/ Region	Seam Code	Seam Thickness	*Sample Location	Coal Lithotype	Sample No	Notes
			in	in			
F	Rock Springs Field	1	139	2	Clarain		
		1	139	31	Clarain/Durain		
		1	139	62	Clarain/Durain	4	Some fusain in upper and middle parts of seam. 19-in shale partings start 63 in from top of seam
		1	139	83	Clarain	3	
		1	139	108	Clarain		
		1	139	137	Clarain		
		2	95	2	Durain		
		2	95	34	Clarain		Some fusain in upper part of seam
		2	95	65	Durain	5	
G	Hanna Field	1	90	2	Durain		Sulphur streaks, $< \frac{1}{4}$ in thick
		1	90	33	Clarain/Durain		
		1	90	72	Clarain/Durain	6	Sulphur spots on joints
		1	90	89	Durain		
H	Raton Mesa Field	1	124	2	Clarain		
		1	124	45	Clarain		
		1	124	69	Clarain/Durain	11	18-in parting (70% shale and 30% durain) starts 25 in from top of seam
		1	124	91	Clarain		
		1	124	122	Clarain	10	

*Mid-point of sample, measured from top of seam.
Sample interval is 2 in to 3 in on either side of mid-point.

TABLE VII

ANALYTICAL DATA

Sample No	As-received Moisture %	Air-dried Basis %			Dry, mineral-matter-free Volatile Matter %	Total Sulphur %	Coke Type	Free Swelling Index	Calorific Value, Btu/lb			CO in Oxidation Test		ASTM Rank
		Moisture	Ash	Volatile Matter					Air-dried	Dry, mineral-matter-free	Moist, mineral-matter-free	At 100°C (212°F)	At 120°C (248°F)	
1	22.0	10.8	4.9	35.7	41.9	0.31	A	0	10,970	13,090	11,580	800	1,400	hvCb
2	8.0	6.7	3.1	41.0	45.2	0.42	A	0	11,980	13,340	12,400	600	1,000	hvCb
3	15.9	9.7	2.0	37.3	42.2	0.60	A	0	11,340	12,880	11,600	440	870	hvCb
4	15.0	8.1	1.5	39.1	43.3	0.55	A	0	11,630	12,880	11,830	375	840	hvCb
5	12.0	8.1	6.5	37.7	43.7	4.34	A	0	10,610	12,740	11,470	450	800	sub A
6	9.0	7.1	8.5	39.0	45.0	0.58	A	0	11,290	13,640	12,440	350	670	hvCb
7	3.1	2.9	5.3	36.7	39.6	3.06	B	1	13,000	14,380	13,880	140	660	hvBb
8	3.4	2.4	8.7	35.8	39.4	0.59	B	1	12,820	14,790	14,160	105	545	hvBb
9	0.8	0.7	3.5	27.0	27.7	0.51	G10	9	15,160	15,930	15,780	152	470	mv
10	1.7	1.2	6.8	34.9	37.0	0.41	G5	7½	14,010	15,420	15,130	135	430	hvAb
11	1.7	2.0	12.1	34.8	40.5	0.43	G6	8	13,100	15,400	15,100	116	395	hvAb
*12	2.8	2.5	4.7	44.8	48.0	1.17	D	1½	13,570	14,750	14,330	120	440	hvAb
13	3.3	2.7	3.7	42.3	44.8	1.21	D	1½	13,640	14,710	14,240	125	410	hvAb
14	0.2	1.2	8.2	23.4	24.7	0.47	G8	8	14,380	16,010	15,800	108	314	hvBb
**15	0.7	0.6	44.4	17.0	22.1	0.50	G5	7½	8,540	16,960	16,440	-	-	hvAb

Notes:

1. Analyses of the part of the seam (usually representing about 6 in) used for oxidation test.
2. In several cases 2 sections from a seam were analysed and the results do not show any important divergences.
3. The samples are listed in order depending on production of carbon monoxide in oxidation test.
4. * This sample gave very large quantities of methane and ethane in the oxidation test.
5. ** Analysis only as appearance very different from other parts

TABLE VIII

CONTINUATION OF ANALYTICAL DATA

(%)

Sample No	Air-Dried Basis							Dry, Ash-Free Basis					
	Carbon	Oxygen	Hydrogen	Carbon-dioxide	Nitrogen	Organic Sulphur	Chlorine	Carbon	Oxygen	Hydrogen	Carbon-dioxide	Nitrogen	Sulphur
1	63.9	14.8	3.9	0.23	1.4	0.3	0.02	75.8	17.6	4.6	0.27	1.6	0.4
2	69.5	14.3	4.7	0.25	1.3	0.4	0.02	77.0	15.9	5.2	0.27	1.4	0.5
3	65.9	14.9	5.4	0.11	1.5	0.6	0.02	74.6	16.9	6.1	0.12	1.7	0.7
4	67.7	16.3	4.3	0.07	1.5	0.6	0.02	75.0	18.0	4.7	0.17	1.7	0.6
5	64.0	15.3	4.0	0.23	1.4	0.7	0.03	75.0	17.9	4.7	0.27	1.6	0.8
6	63.9	13.9	4.3	1.11	1.7	0.6	0.02	75.7	16.5	5.1	1.32	2.0	0.7
7	74.3	10.7	4.6	0.04	1.5	0.7	0.04	80.9	11.7	5.0	0.04	1.6	0.8
8	72.0	9.6	5.0	0.25	1.7	0.6	0.05	81.0	10.8	5.6	0.28	1.9	0.7
9	84.6	4.0	4.7	-	2.0	0.5	0.03	88.3	4.2	4.9	-	2.1	0.5
10	77.5	7.2	5.2	0.82	1.7	0.4	0.02	84.2	7.8	5.7	0.89	1.8	0.5
11	72.2	6.8	5.0	0.84	1.5	0.4	0.03	84.1	7.8	5.8	0.89	1.8	0.5
12	74.0	11.2	5.6	0.24	1.3	0.7	0.03	79.7	12.1	6.0	0.26	1.4	0.8
13	74.7	12.1	4.8	0.47	1.3	0.7	0.03	79.8	12.9	5.1	0.50	1.4	0.8
14	81.2	2.5	4.6	0.59	1.8	0.5	0.03	89.6	2.7	5.1	0.65	2.0	0.6
15	47.4	2.8	3.1	-	1.2	0.5	0.03	86.2	5.1	5.6	-	2.2	0.9

TABLE IX

CARBON MONOXIDE EMISSION RESULTS OBTAINED FROM PANIC TESTS

(parts per million)

Temperature		Sample Number and Rank																	
°C	°F	1 hvCb	2 hvCb	3 hvCb	4 hvCb	5 Sub A	6 hvCb	7 hvBb	8 hvBb	9 mv	10 hvAb	11 hvAb	12 hvAb	13 hvAb	14 mv	A hvBb	B hvAb
30	86	5	16	1	1	1	23	1	0	0	2	2	2	1	0	2	1
35	95	13	34	4	3	3	36	1	0	0	2	3	3	2	1	3	-
40	104	23	51	9	5	5	49	1	0	0	3	4	4	4	1	4	-
45	113	37	64	13	12	7	67	1	0	1	4	6	6	5	2	8	-
50	122	57	76	21	16	12	82	2	1	2	6	7	8	8	3	13	2
55	131	78	91	46	20	19	106	2	1	3	8	9	12	11	5	20	-
60	140	110	108	54	30	43	125	3	1	7	12	11	16	15	8	28	5
65	149	192	144	61	65	56	128	5	3	12	16	14	21	20	12	45	-
70	158	-	166	84	80	83	136	7	5	18	23	19	27	26	19	64	13
75	167	302	200	109	100	135	161	12	8	28	33	27	36	34	28	85	-
80	176	394	258	180	126	173	187	20	18	45	44	36	47	45	37	114	30
85	185	490	364	217	162	230	216	37	30	63	61	49	60	57	50	150	-
90	194	565	421	275	240	297	254	62	50	85	81	66	80	76	69	189	-
95	203	672	508	364	308	388	307	100	75	113	101	87	94	95	82	247	-
100	212	797	591	480	410	460	348	143	103	152	135	116	127	116	108	310	80
105	221	920	773	570	484	539	417	221	161	201	172	158	173	161	140	374	140
110	230	+1,000	800	657	590	606	503	345	252	260	233	218	226	221	182	458	-
115	239	+1,000	878	772	696	700	599	486	384	346	316	300	308	323	239	561	-
120	248	+1,000	989	874	837	790	670	659	545	470	431	395	411	440	314	723	265

Note: Samples A and B are UK coals for comparison

TABLE X

METHANE EMISSION RESULTS OBTAINED FROM PANIC TESTS

(parts per million)

Temperature		Sample Number and Rank															
°C	°F	1 hvCb	2 hvCb	3 hvCb	4 hvCb	5 Sub A	6 hvCb	7 hvBb	8 hvBb	9 mv	10 hvAb	11 hvAb	12 hvAb	13 hvAb	14 mv	A hvBb	B hvAb
30	86	0.4	-	-	-	8	8	10	8	516	278	43	2,464	1,578	56	9	1,500
40	104	-	125	7	-	9	9	8	7	207	221	52	2,790	2,627	41	7	-
50	122	-	157	8	8	8	10	8	9	223	300	41	3,490	3,558	89	8	4,050
60	140	1.4	145	13	9	9	8	7	8	226	335	53	4,040	4,375	49	9	-
70	158	-	127	8	-	8	9	-	8	207	390	63	4,074	4,372	51	9	-
80	176	3	91	12	-	8	8	7	8	175	418	69	3,634	4,047	-	9	2,916
90	194	-	48	-	9	8	10	8	9	162	396	69	2,826	3,358	36	10	-
100	212	5	22	14	-	8	10	8	9	119	352	66	2,032	2,522	-	13	-
110	230	5	16	14	10	12	9	18	10	93	320	67	1,345	1,636	-	11	1,000
120	248	-	13	14	10	12	10	14	25	69	-	60	832	996	42	14	700
125	257	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	220

Note: Samples A and B are UK coals for comparison

TABLE XI

TEMPERATURES AT WHICH CHANGES IN MECHANISM OF OXIDATION REACTION OCCUR

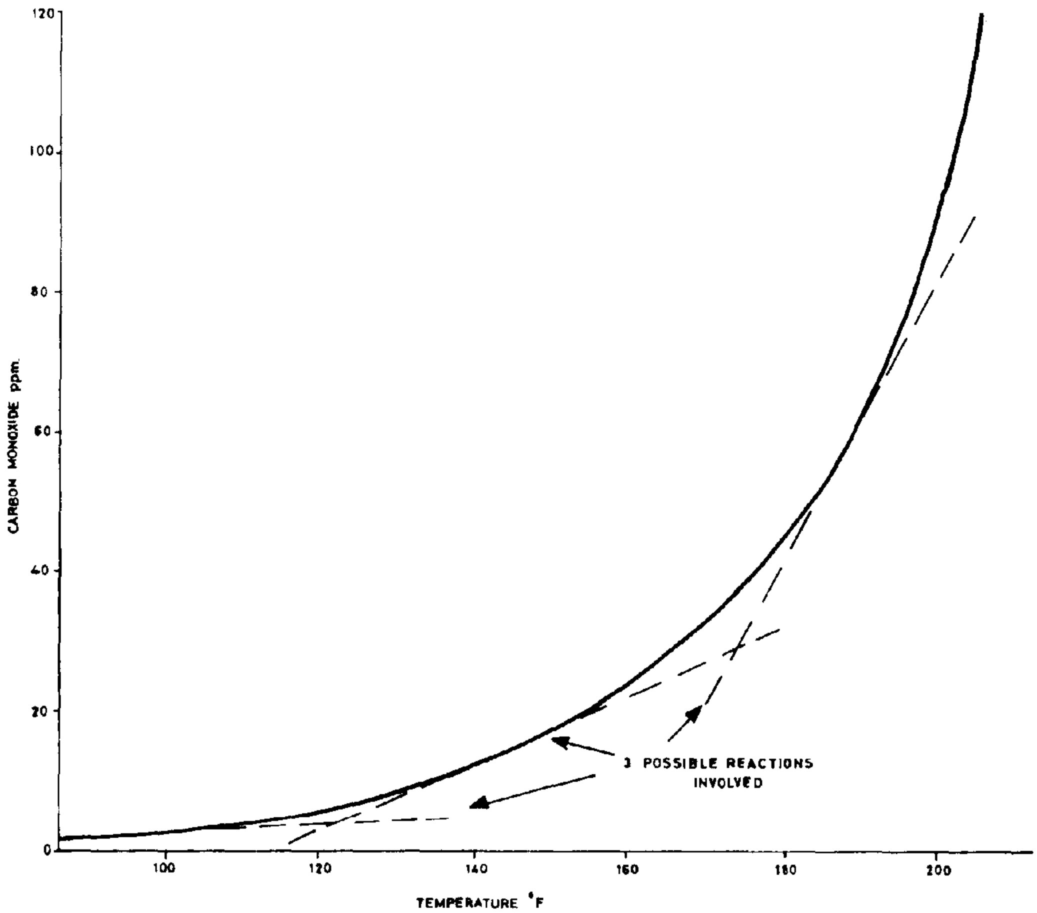
As indicated by plotting log CO against $\frac{1}{T^{o}R} \times 10^{-3}$

Sample No	First Change ^{o}F	Second Change ^{o}F
1	95	160
2	95	160
3	105	150
4	-	160
5	-	170
6	-	140
7	-	140
8	-	150
9	108	167
10	-	145
11	-	153
12	105	167
13	-	195
14	95	160
A	-	160

Note: Sample A is from Ellington Colliery, UK.

PLATE 1

PRODUCTION OF CARBON MONOXIDE FROM HEATED COAL.



Note: The degree of carbon monoxide production varies with coal rank. However the general shape of the curve is common to all coals. This particular example is for a U.K. high volatile, non-caking coal

Source: PD-NCB Data

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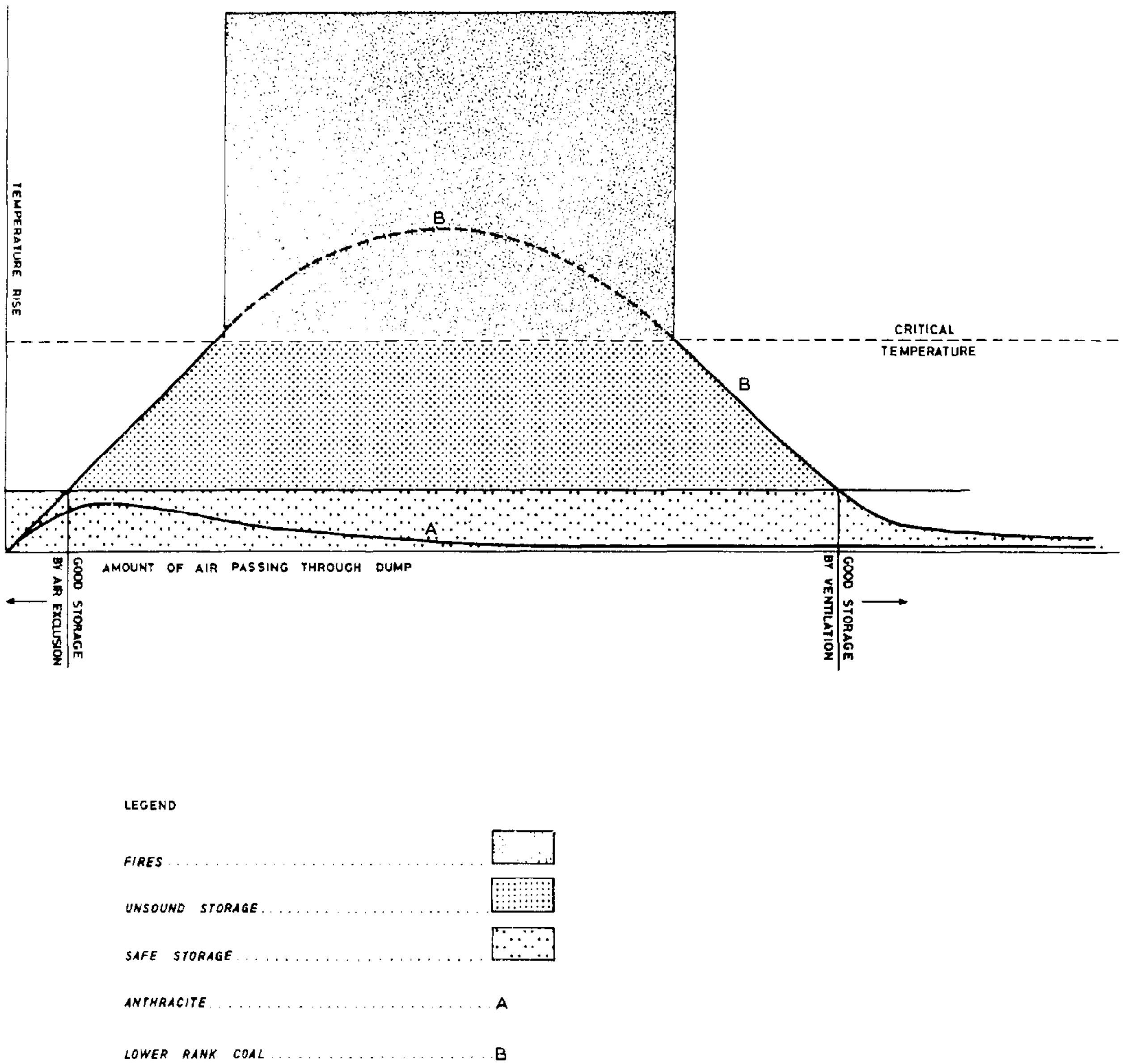
DIAGRAM TO ILLUSTRATE THE SPONTANEOUS IGNITION OF A STOCK OF COAL.



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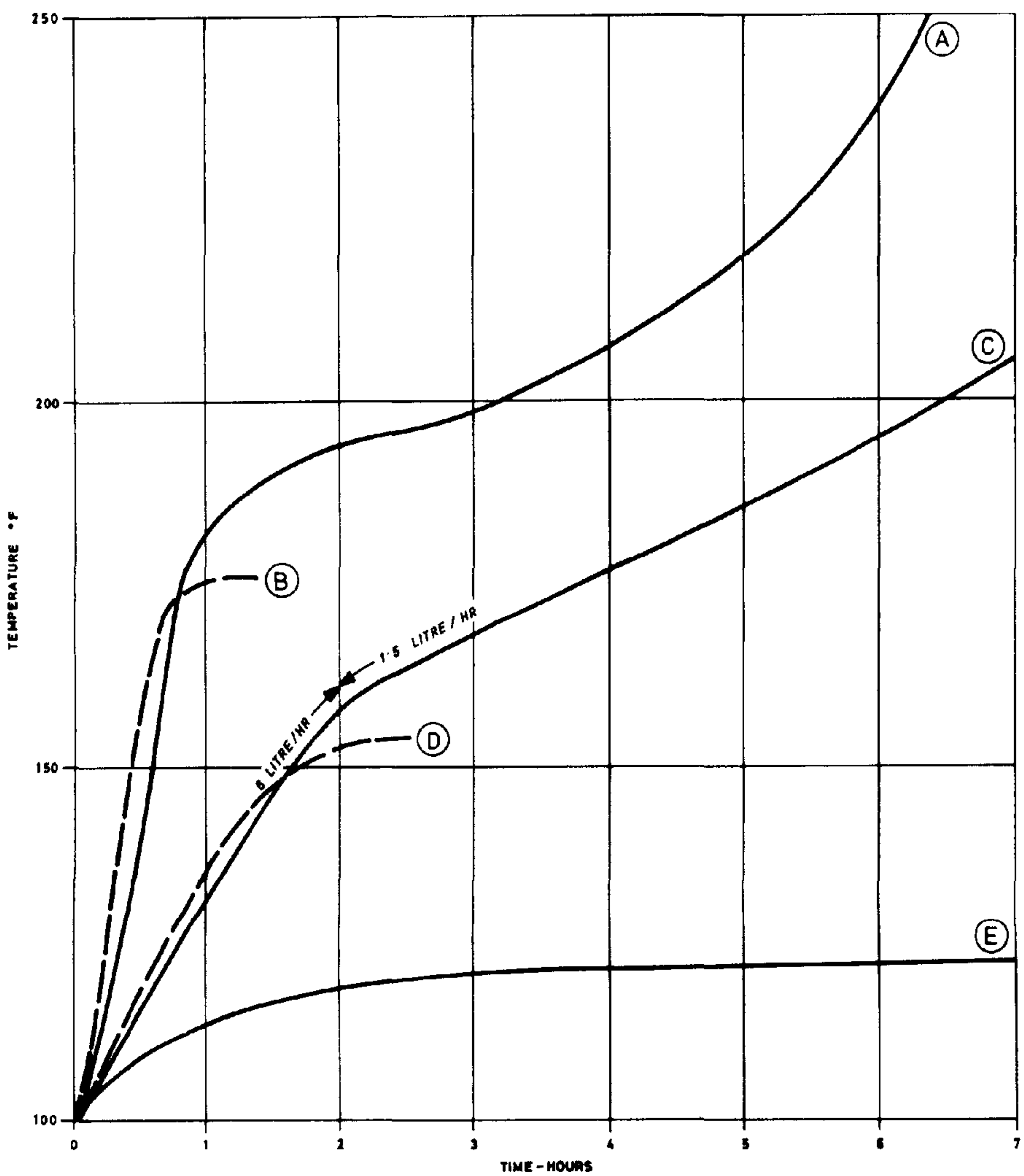
D.A.H.	Feb. 78	647/ 2

HEATING CURVES FOR COALS WITH FIXED HUMIDITIES



(A) DRY COAL, AIR SATURATED AT 104 °F. 6 LITRES/HR.

(B) DRY COAL, NITROGEN SATURATED AT 104 °F. 6 LITRE/HR.

(C) DRY COAL, AIR SATURATED AT 72 °F. 6 LITRE / HR FOR FIRST TWO HOURS THEN 1·5 LITRE / HR.

(D) DRY COAL, NITROGEN SATURATED AT 72 °F. 6 LITRE / HR.

(E) COAL IN EQUILIBRIUM AT 10 %. RELATIVE HUMIDITY (MOISTURE CONTENT 2·15 %), AIR SATURATED AT 72 °F. 6 LITRE / HR.

Source : ref A8

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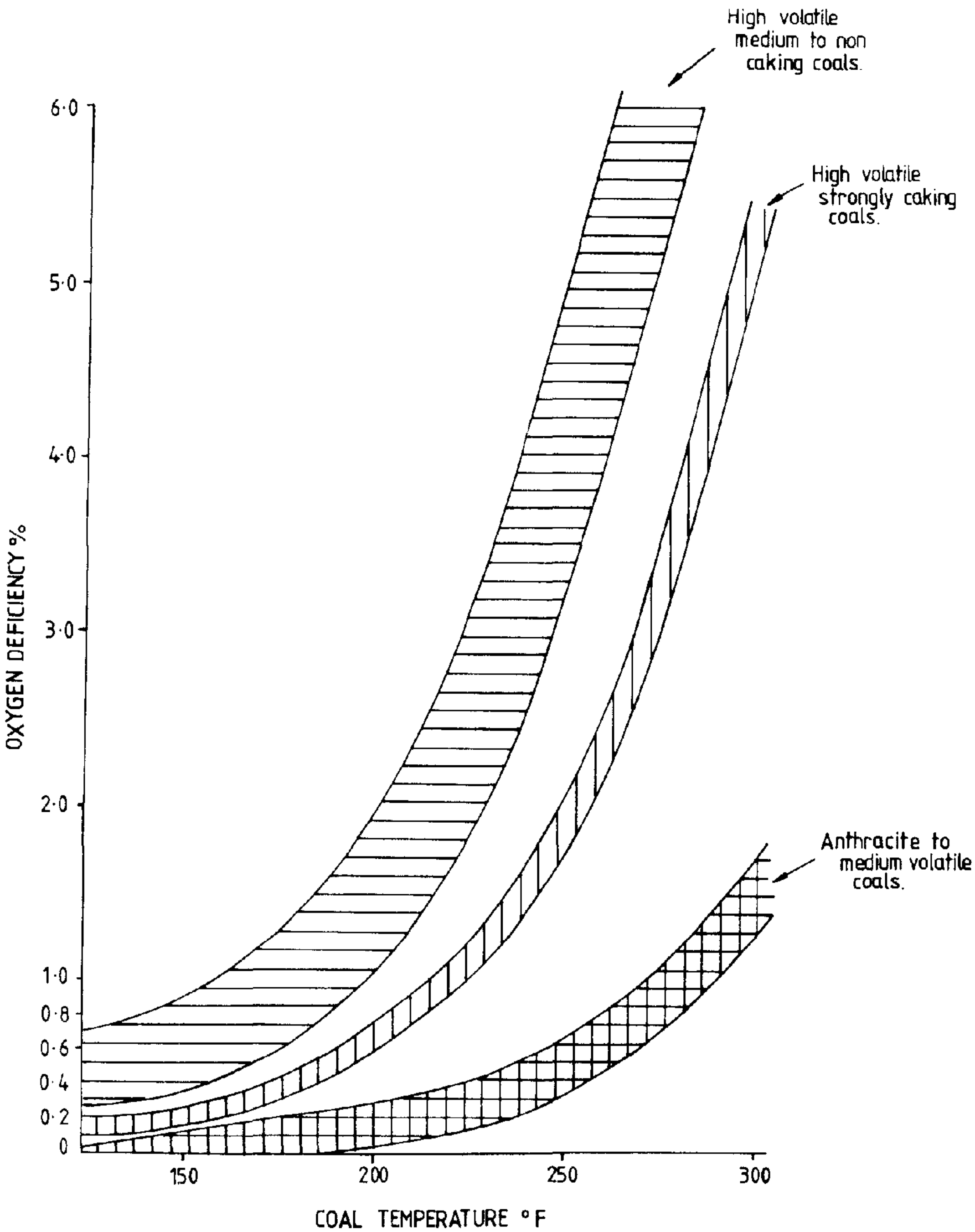
OXIDATION IN DRY AIR OF COALS OF DIFFERENT RANKS.
OXYGEN DEFICIENCY v TEMPERATURE.



Source: ref. 93

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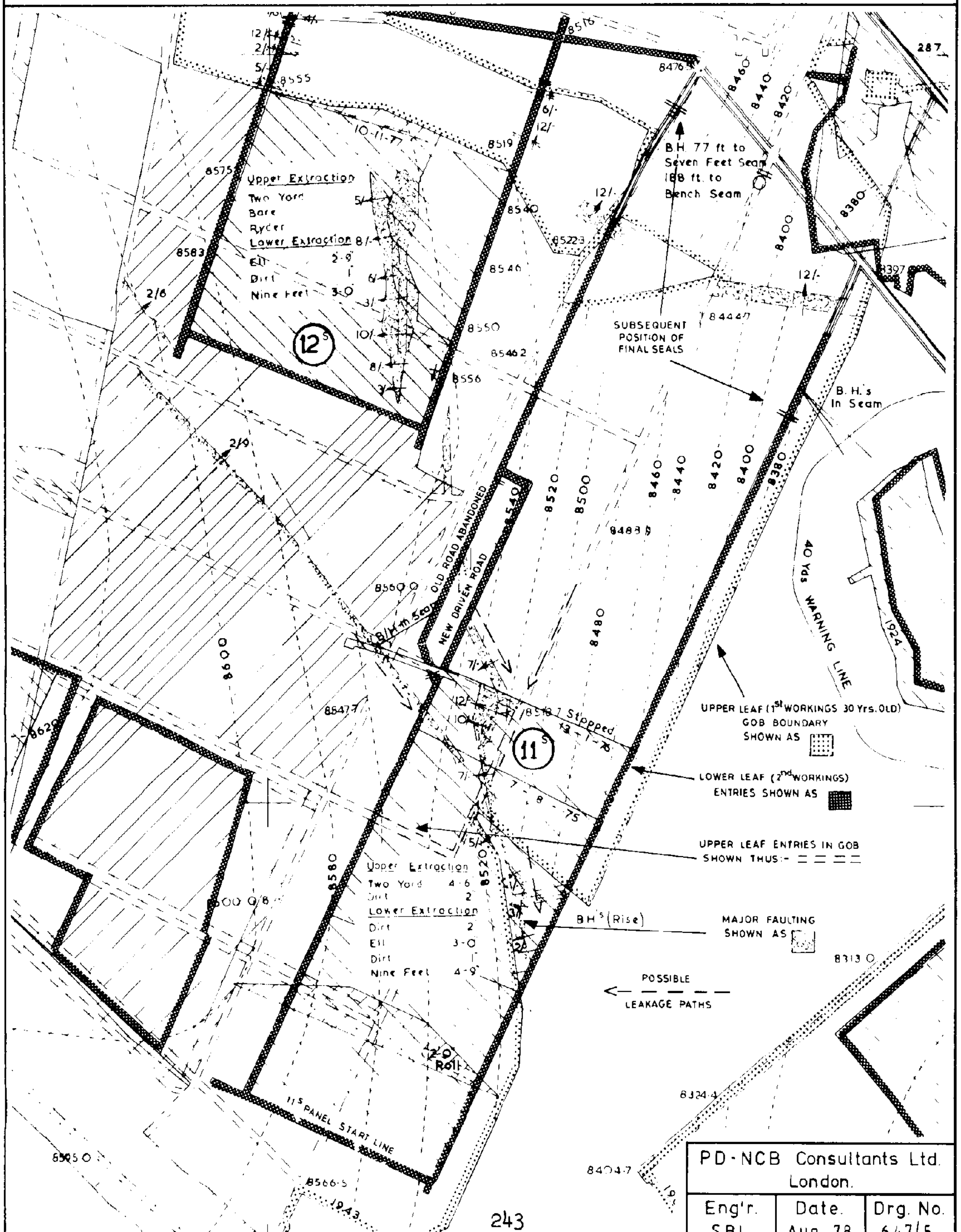
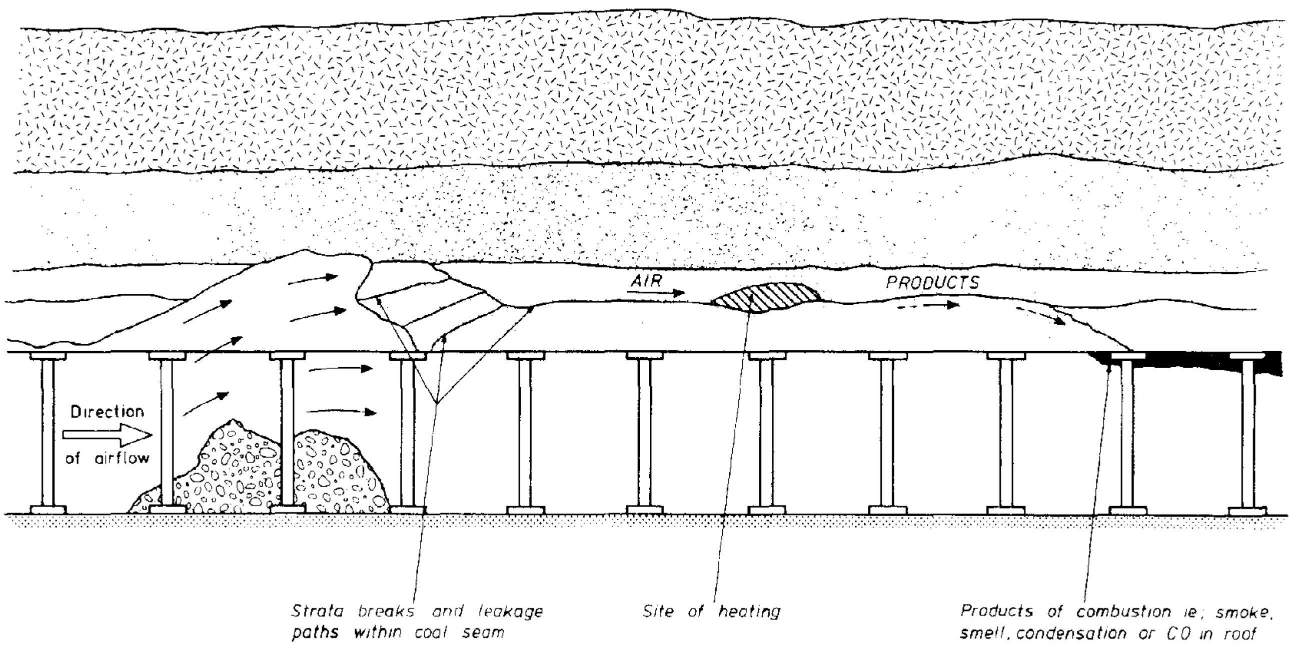
PLATE 5

TYPICAL FAULT PATTERN AND ASSOCIATED LEAKAGE PATHS IN MULTI LIFT LONGWALL WORKING



TYPICAL LEAKAGE PATHS AND RESULTANT HEATING ASSOCIATED WITH A ROOF FALL



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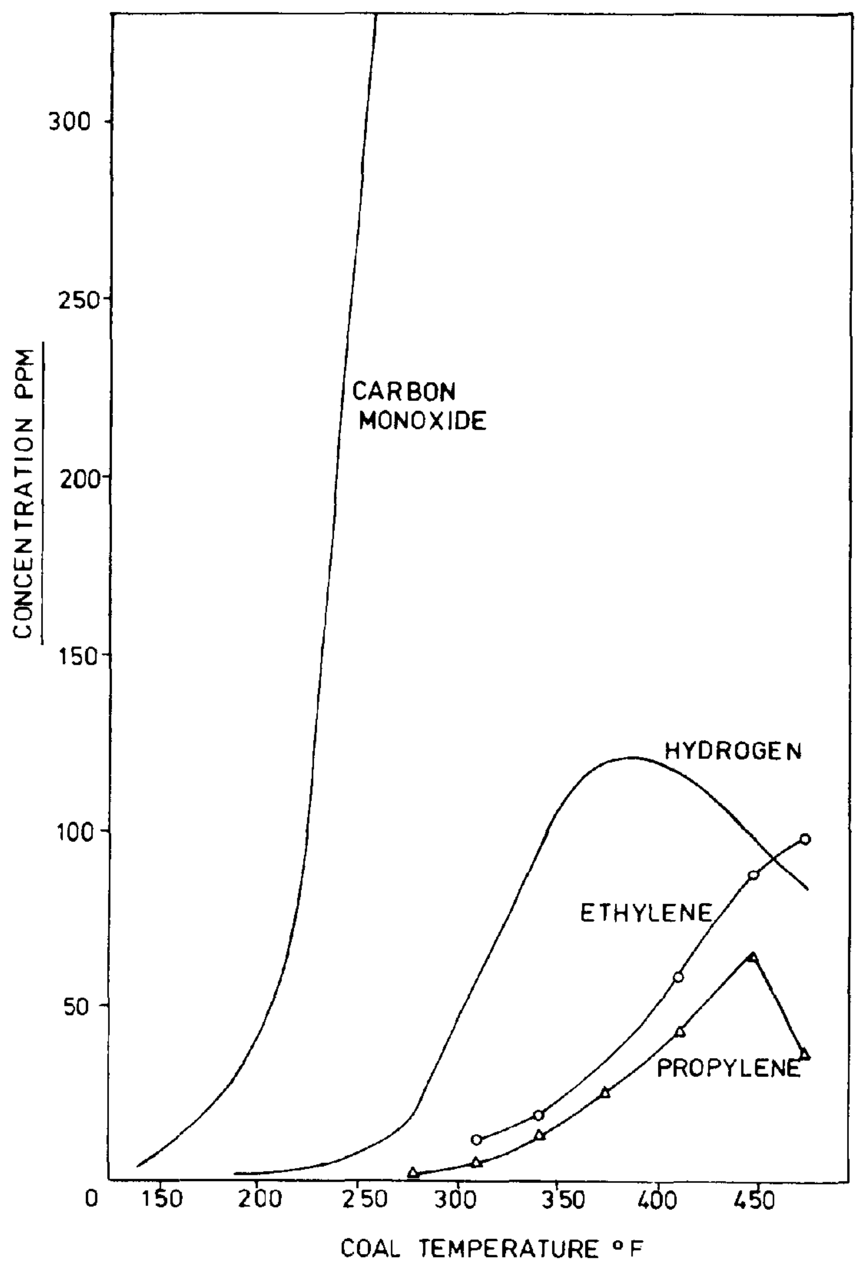
G.C.	Aug. 78	647/6

A TYPICAL DYNAMIC OXIDATION TEST
GAS CONCENTRATION v TEMPERATURE



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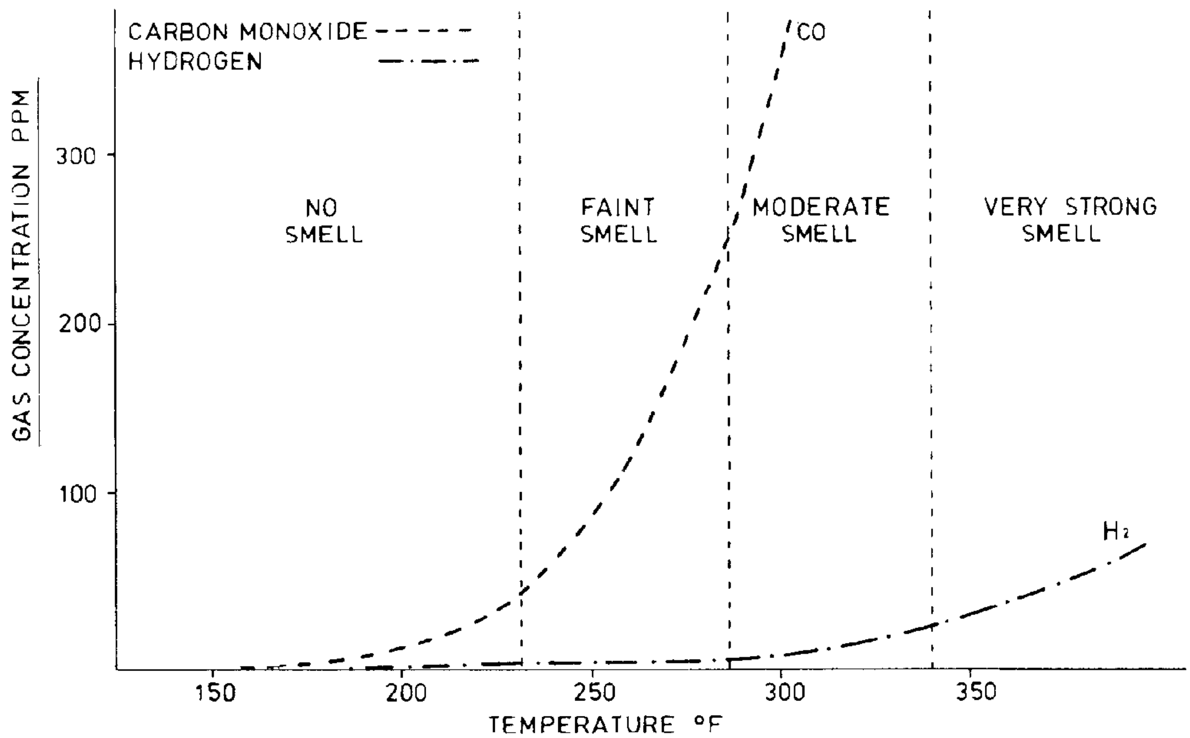
Source: ref. 93

DEVELOPMENT OF SMELL WITH TEMPERATURE
(FOR A UK MEDIUM VOLATILE COAL)



Source : ref 110

PD-NCB Consultants Ltd. London		
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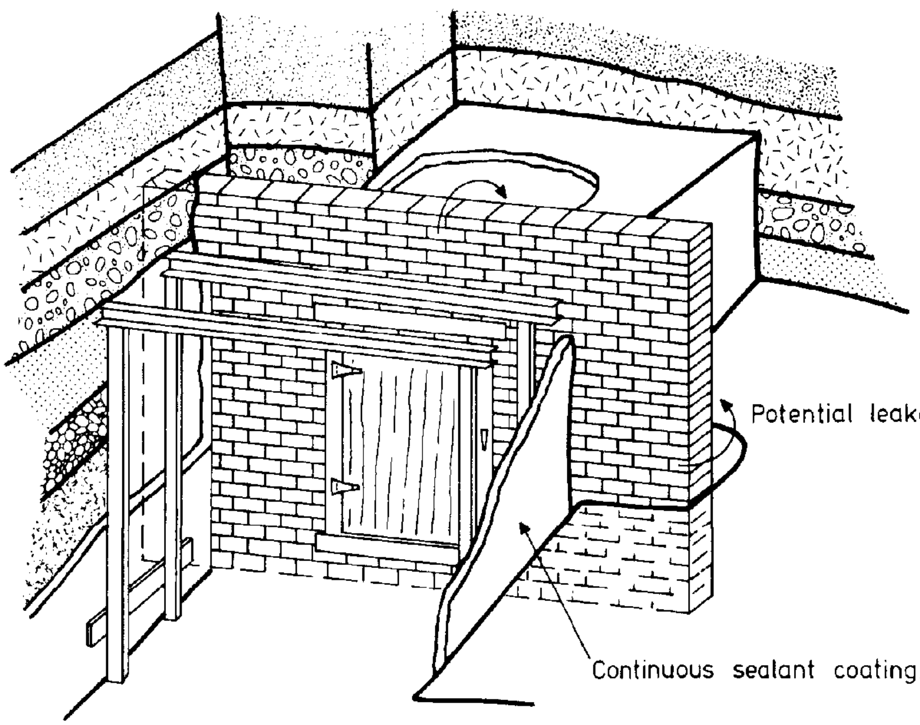
SEALING OF DOORS AND REGULATORS



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USE OF CONTINUOUS TUBE AT REGULATOR LOCATION

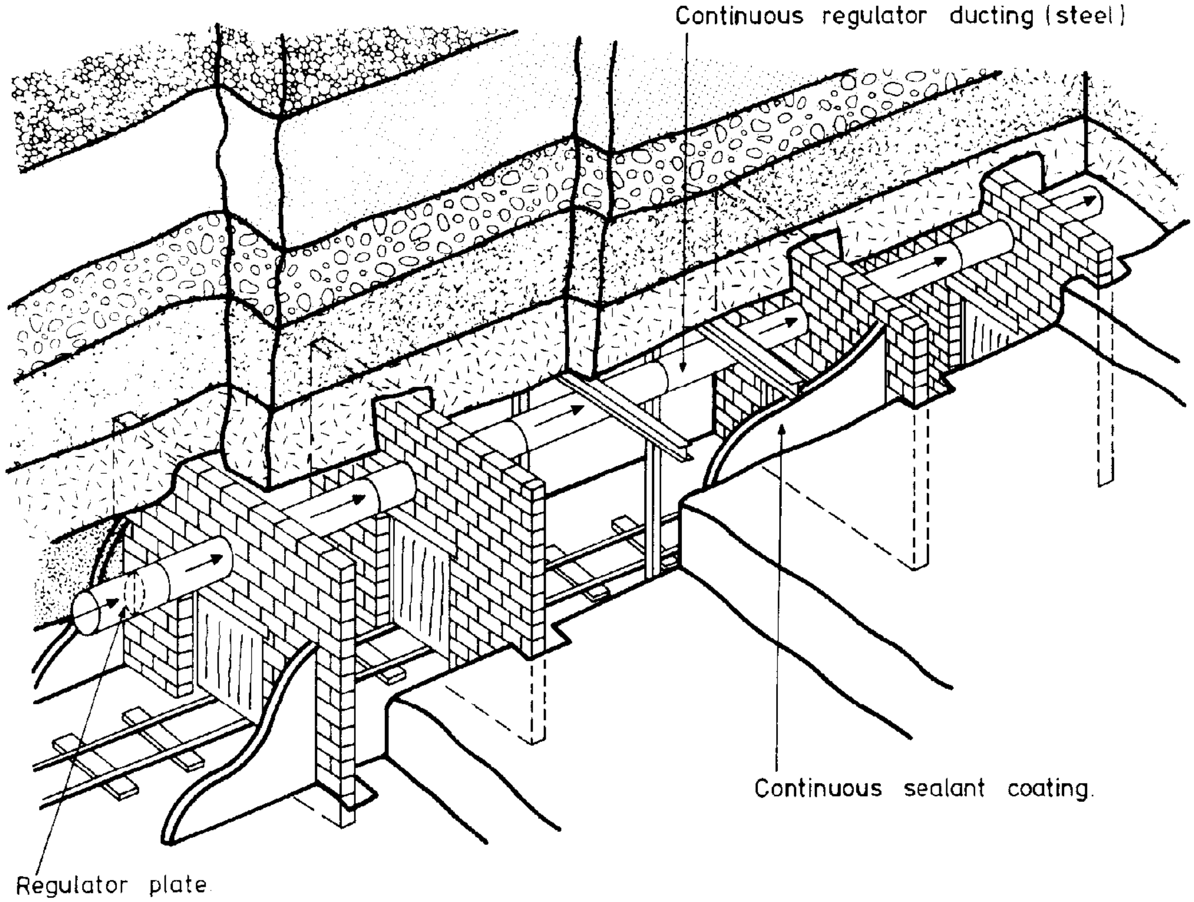

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PLATE 11

GENERAL CONCEPT -
AIR LEAKAGE - LONGWALL RETREATING FACE

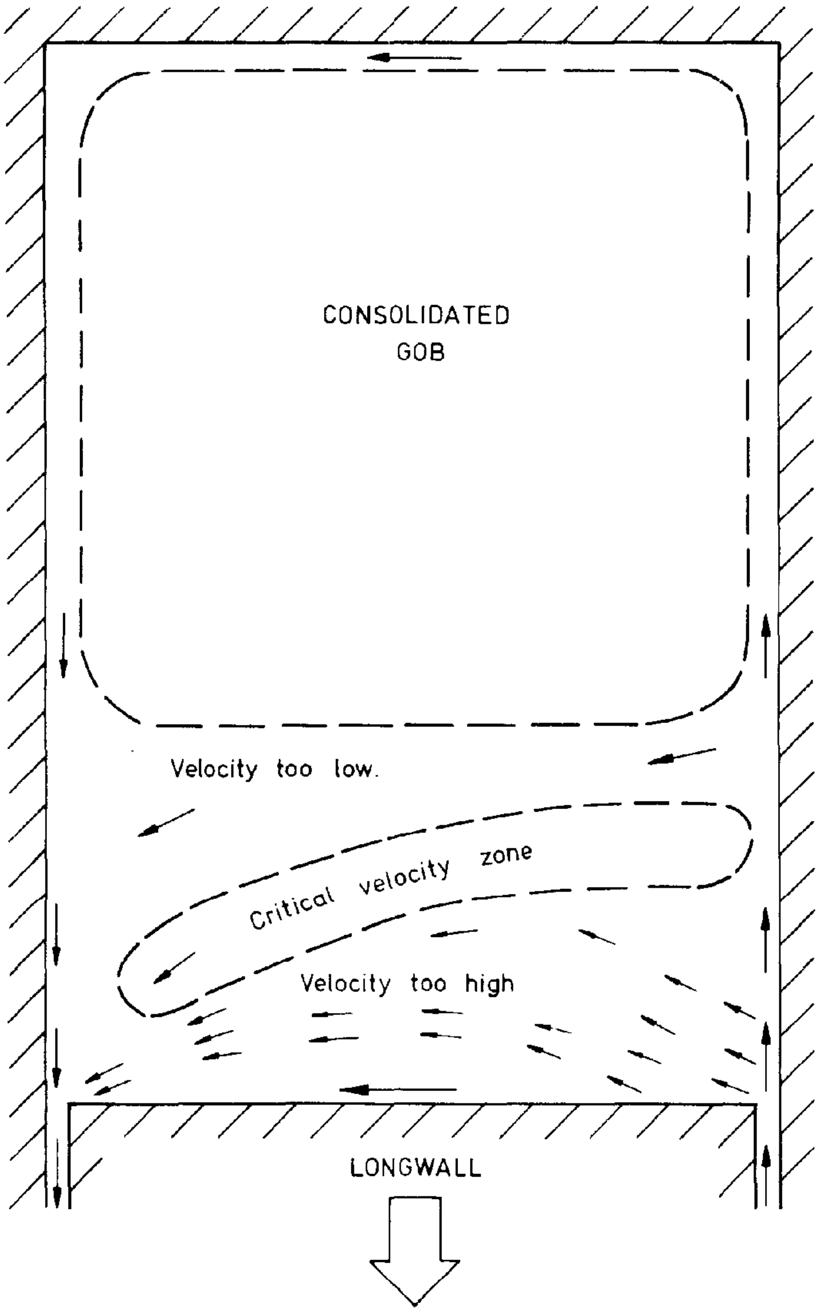

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PLATE 12

GENERAL CONCEPT -

AIR LEAKAGE - LONGWALL ADVANCING FACE

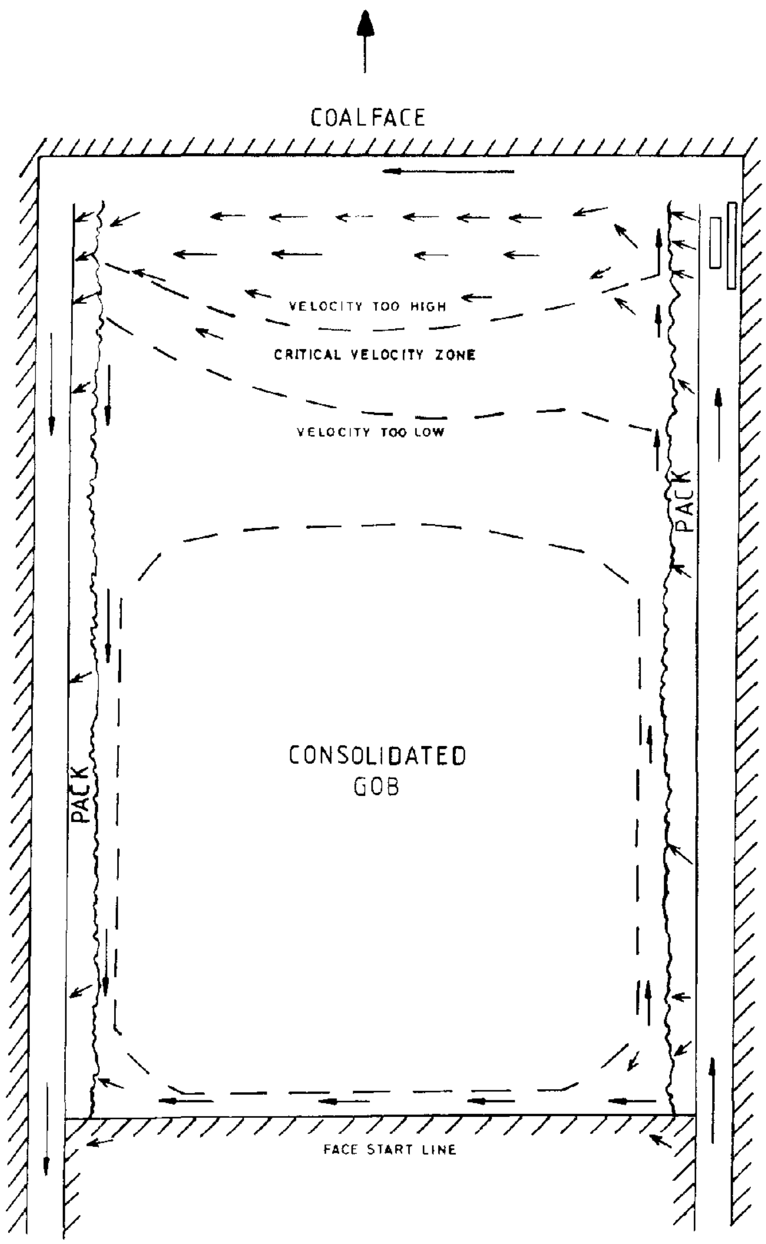

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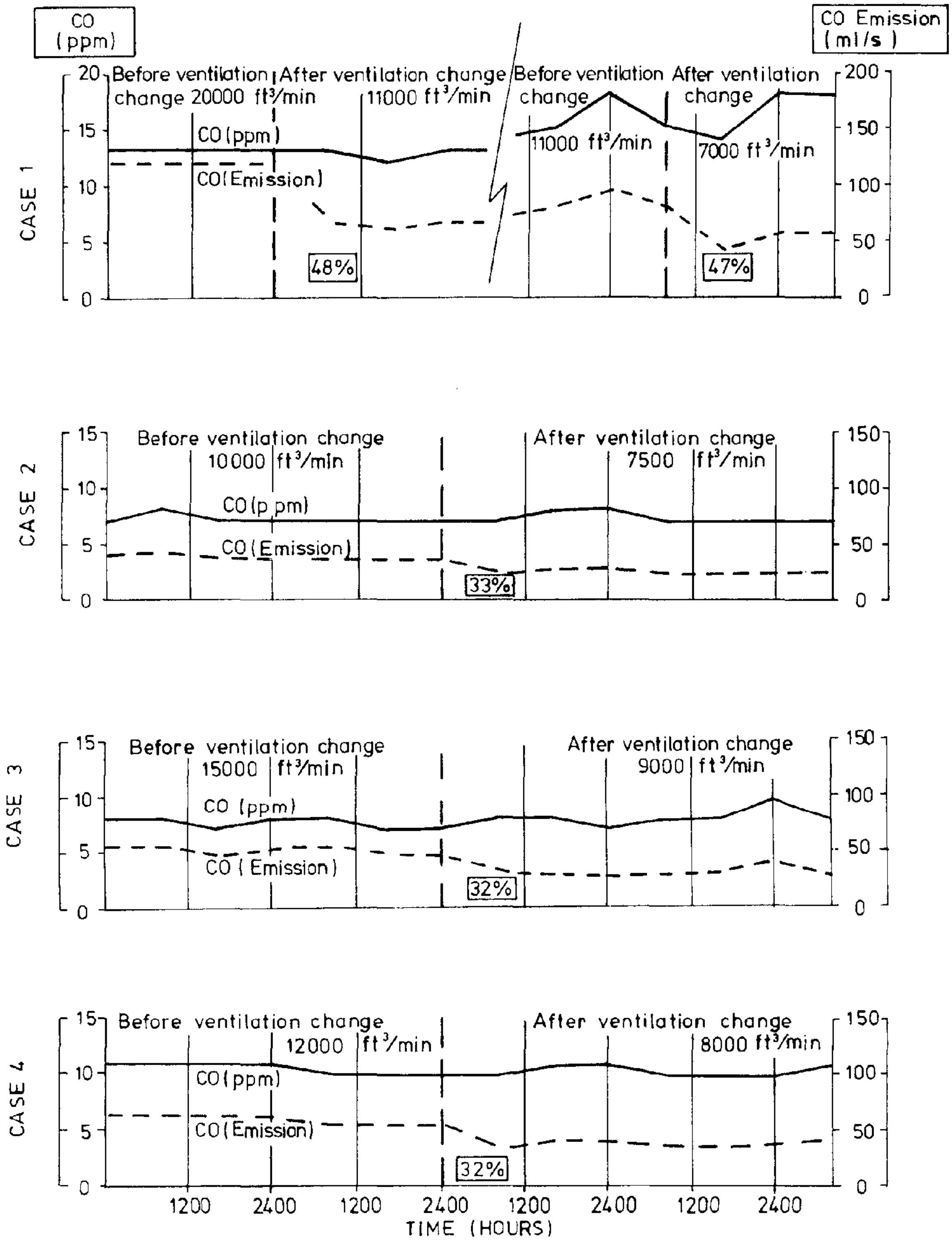
PLATE 13

GRAPHS SHOWING HOW THE EMISSION OF CARBON MONOXIDE VARIES WITH CHANGE OF DISTRICT AIR QUANTITY



[%] Refers to percentage reduction in emission of carbon monoxide

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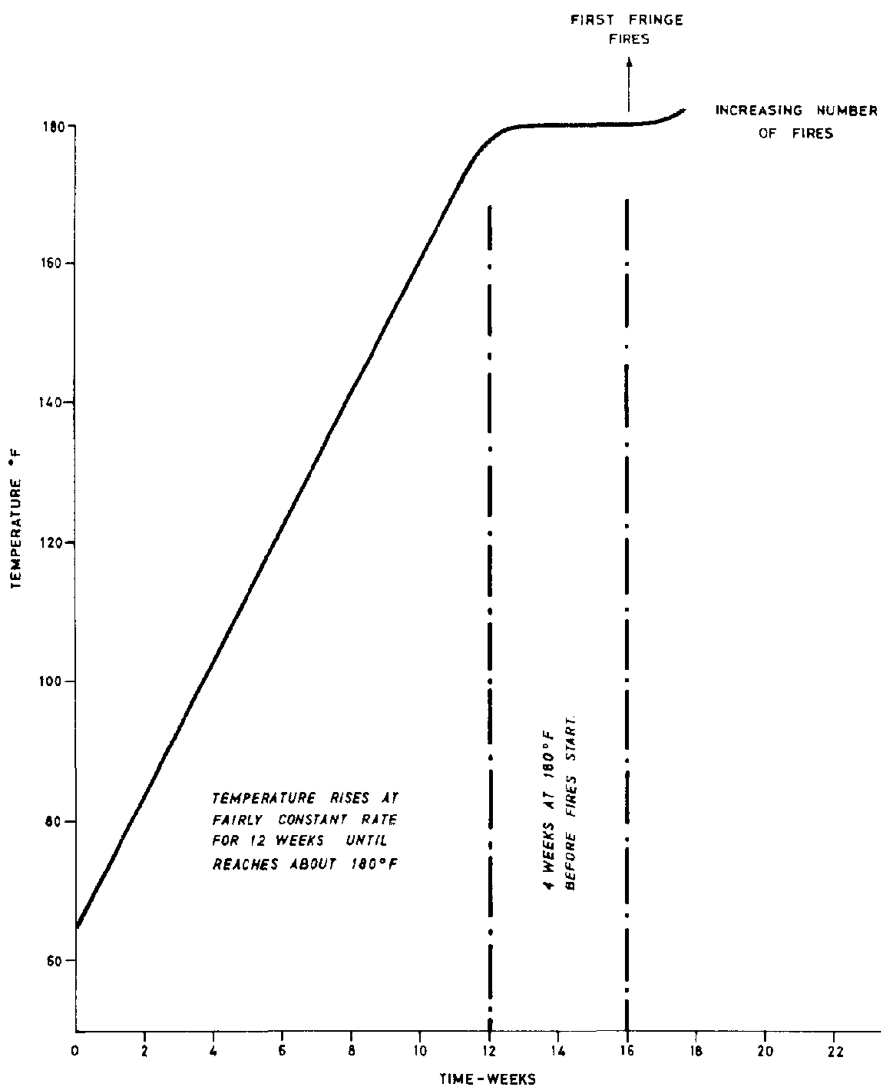
TEMPERATURE RISE IN 400 TON EXPERIMENTAL HEAP OF UNCONSOLIDATED COAL.



Source: PD-NCB Data.

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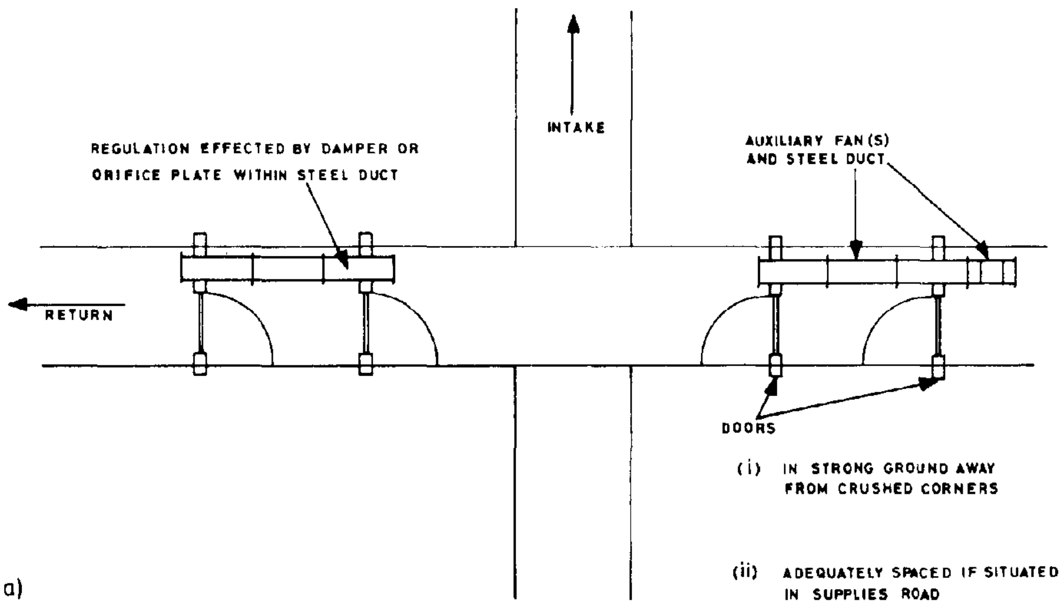
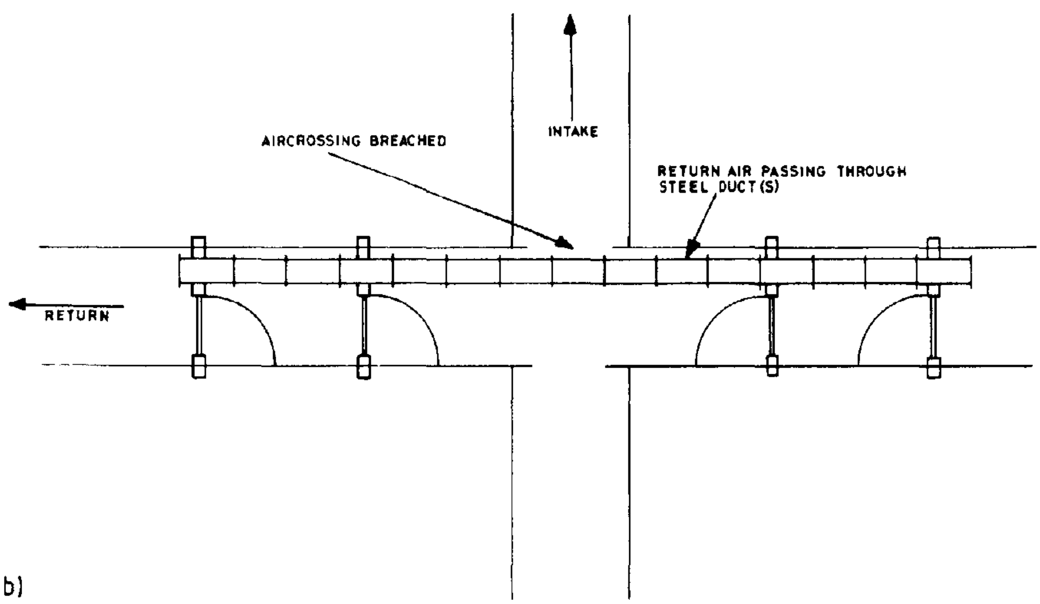
METHODS OF RELIEVING VENTILATION PRESSURE ACROSS AN AIRCROSSING



(a)



(b)

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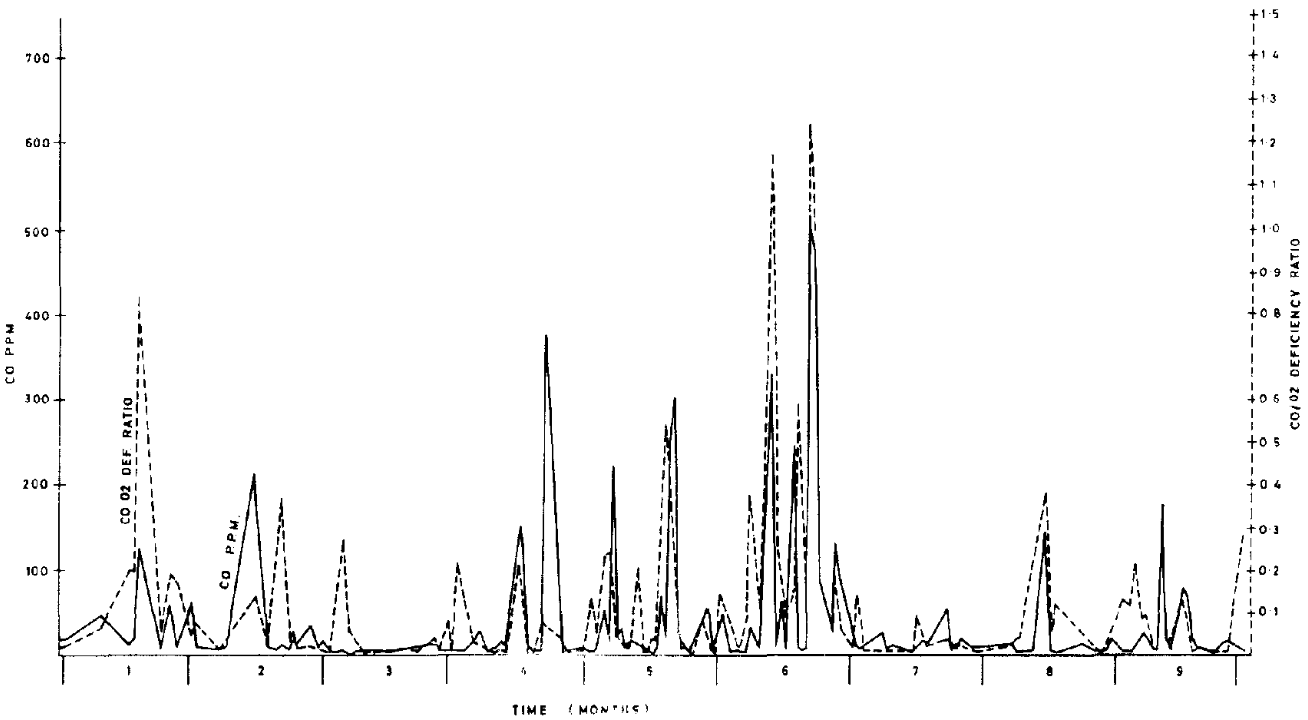
EXAMPLE OF GAS SAMPLES
FROM SEALED OFF SECTION OF A MINE



Source . PD - NCB Data.

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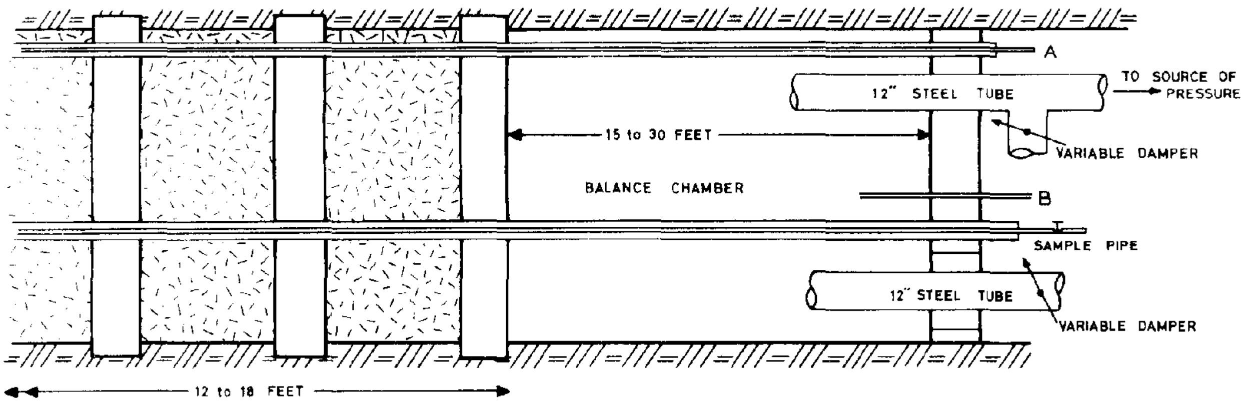
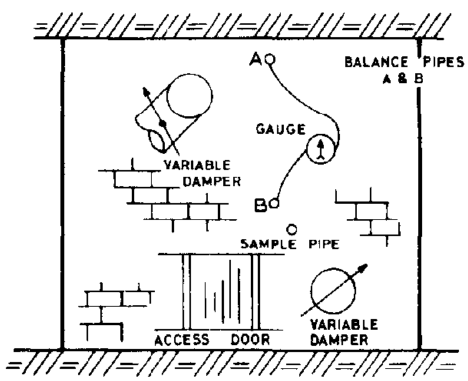
SKETCH OF TYPICAL BALANCE CHAMBER



Section on chamber.



Front elevation.

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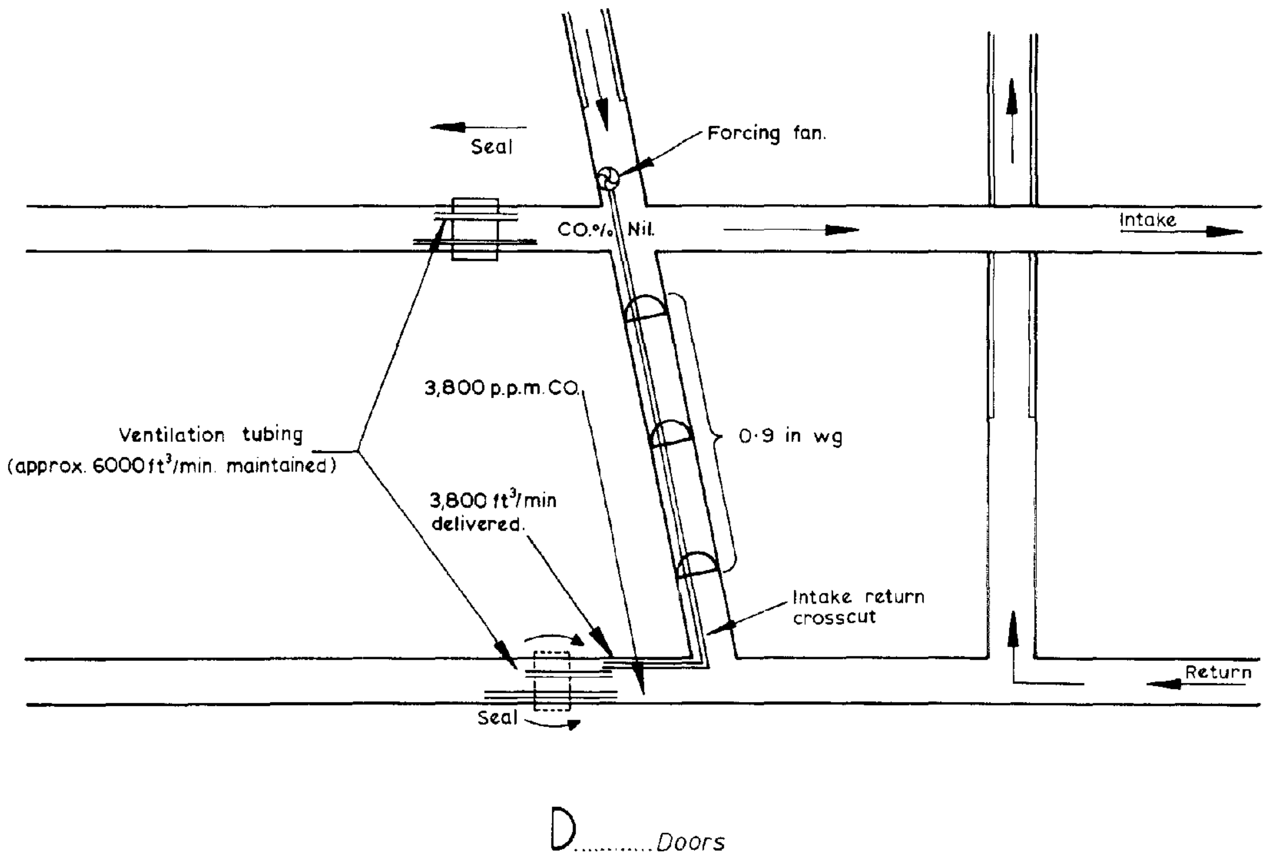
VENTILATION ARRANGEMENTS WITH DOORS IN CROSSCUT



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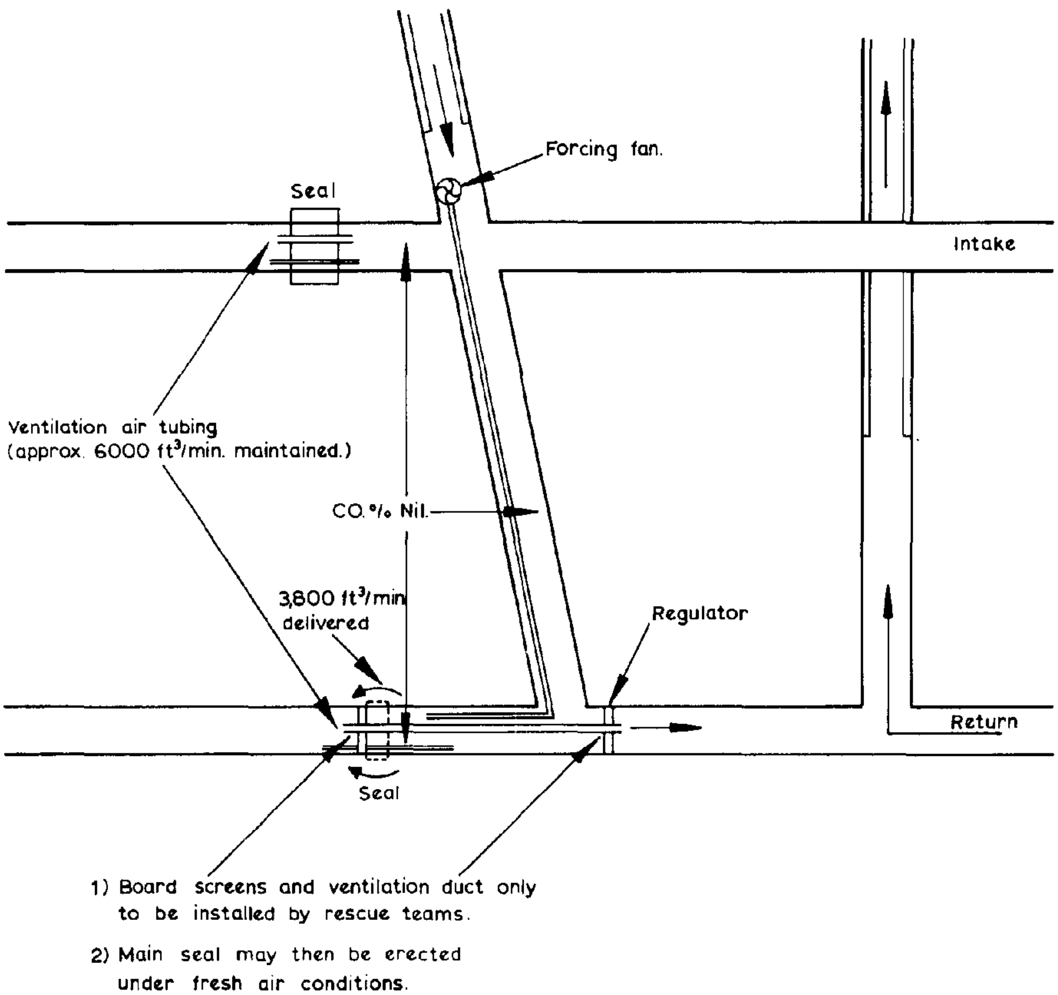
VENTILATION ARRANGEMENTS ENABLING RETURN STOPPING TO BE CONSTRUCTED UNDER FRESH AIR CONDITIONS



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TYPICAL EMERGENCY ORGANISATION IN THE EVENT OF A MAJOR INCIDENT

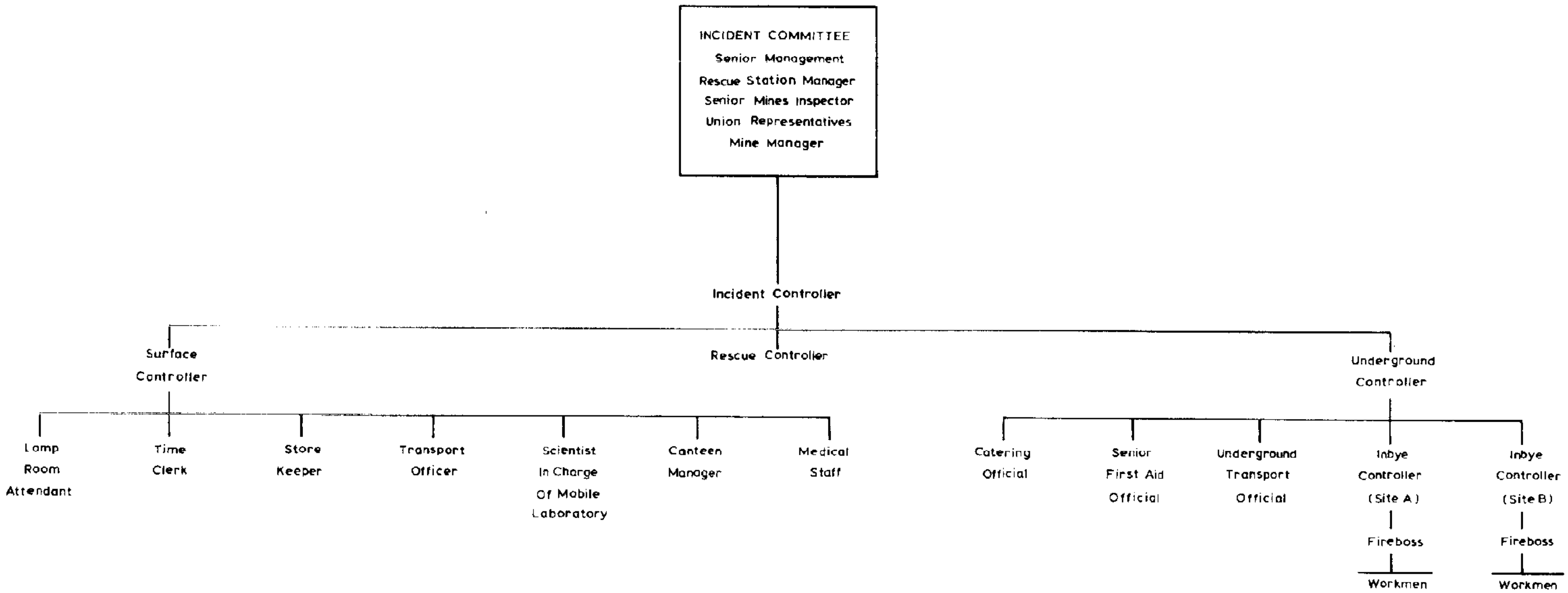

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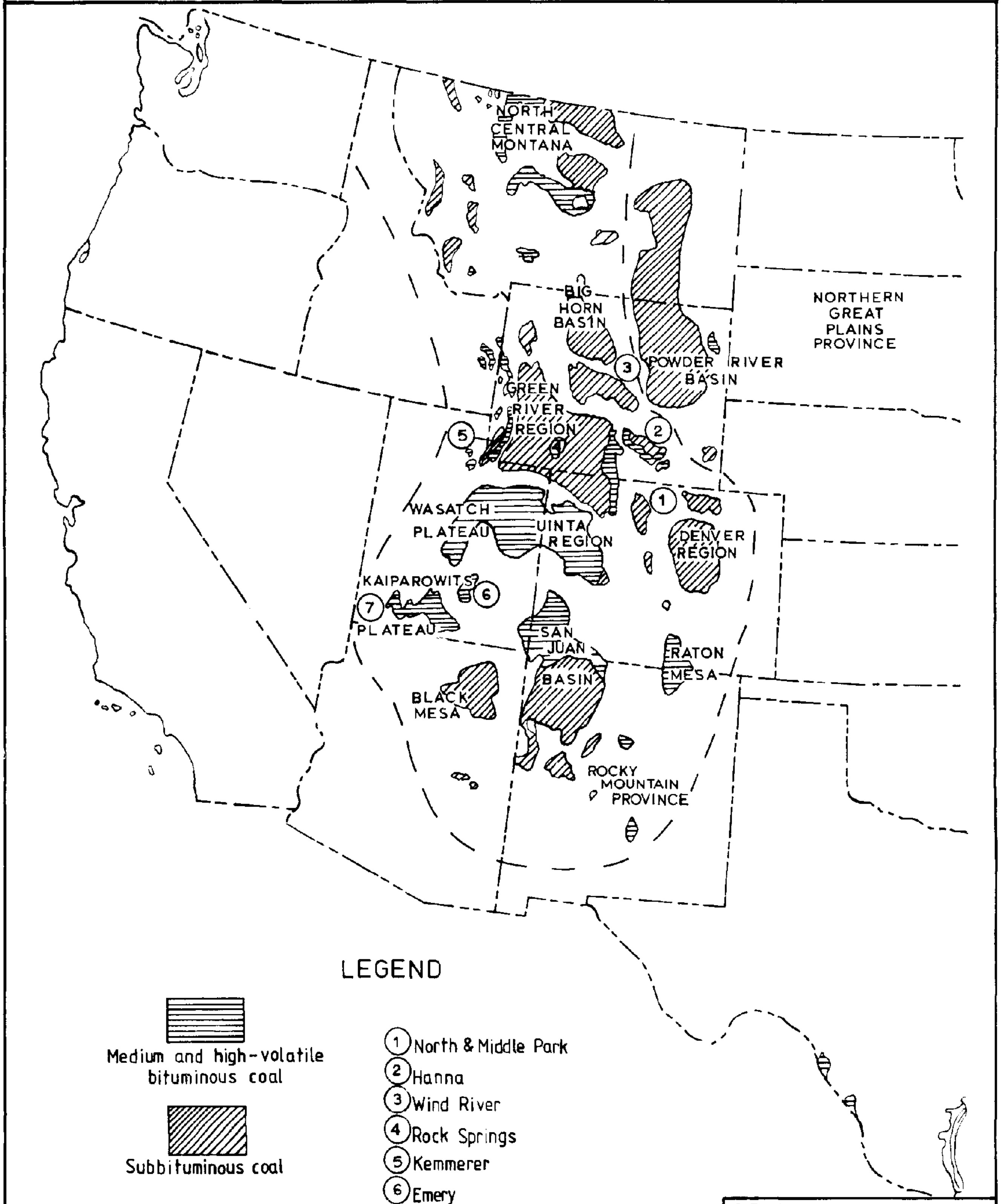
PLATE 20

BITUMINOUS COAL FIELDS OF THE WESTERN UNITED STATES



LEGEND

Medium and high-volatile bituminous coal

Subbituminous coal

1 North & Middle Park
2 Hanna
3 Wind River
4 Rock Springs
5 Kemmerer
6 Emery
7 Knab Kolob

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UNDERGROUND COAL MINES AND COALFIELDS OF COLORADO

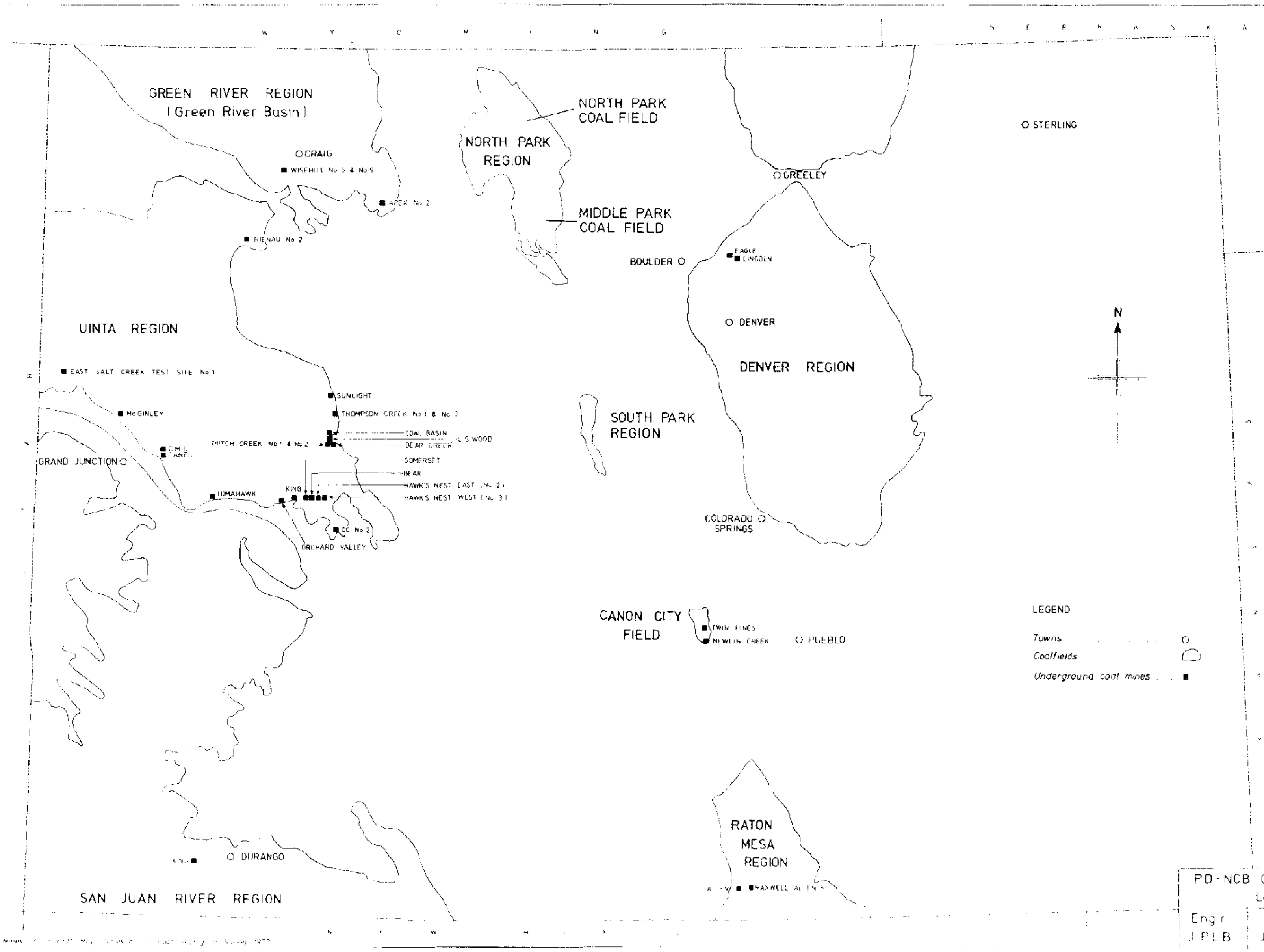

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PLATE 22

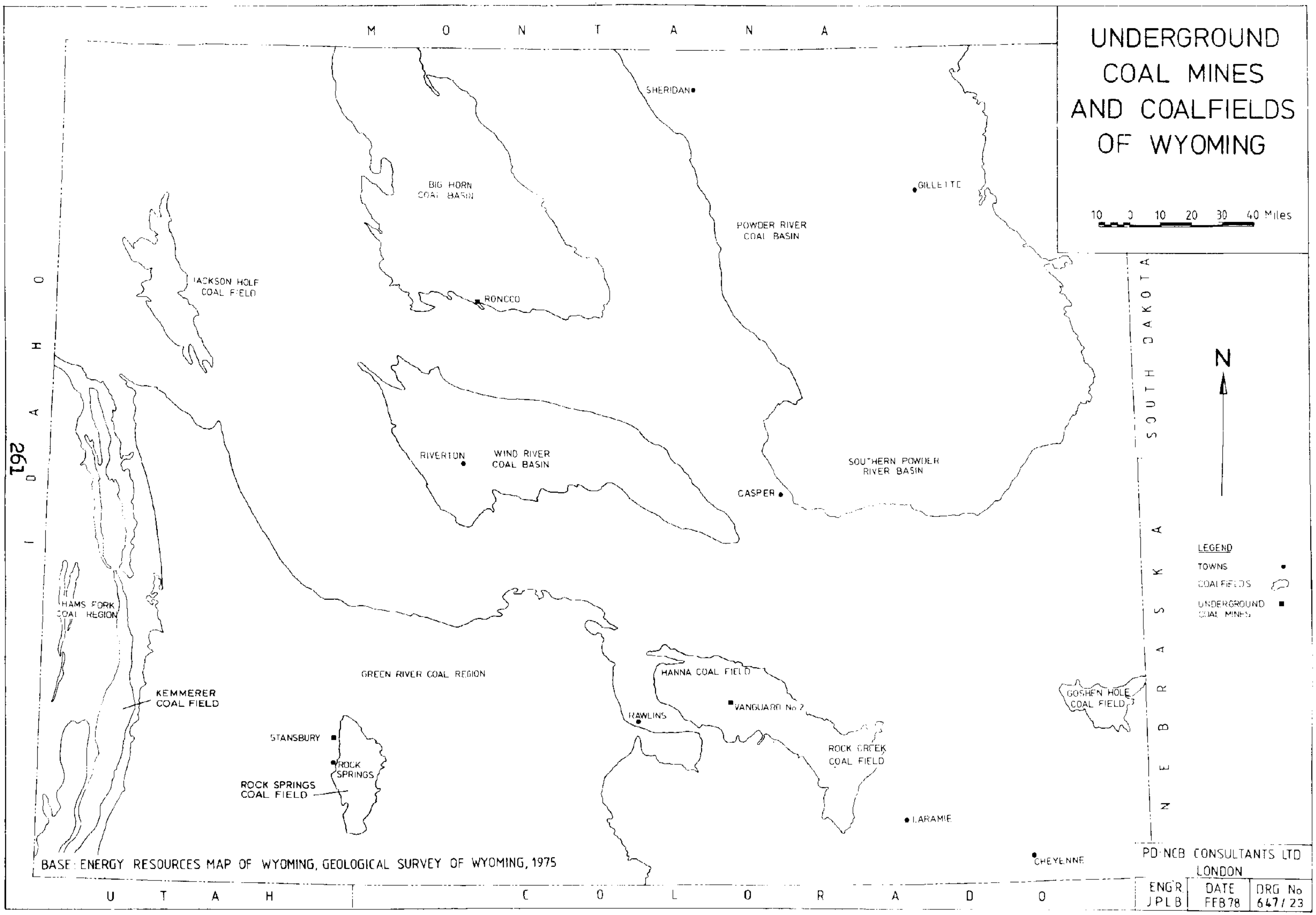
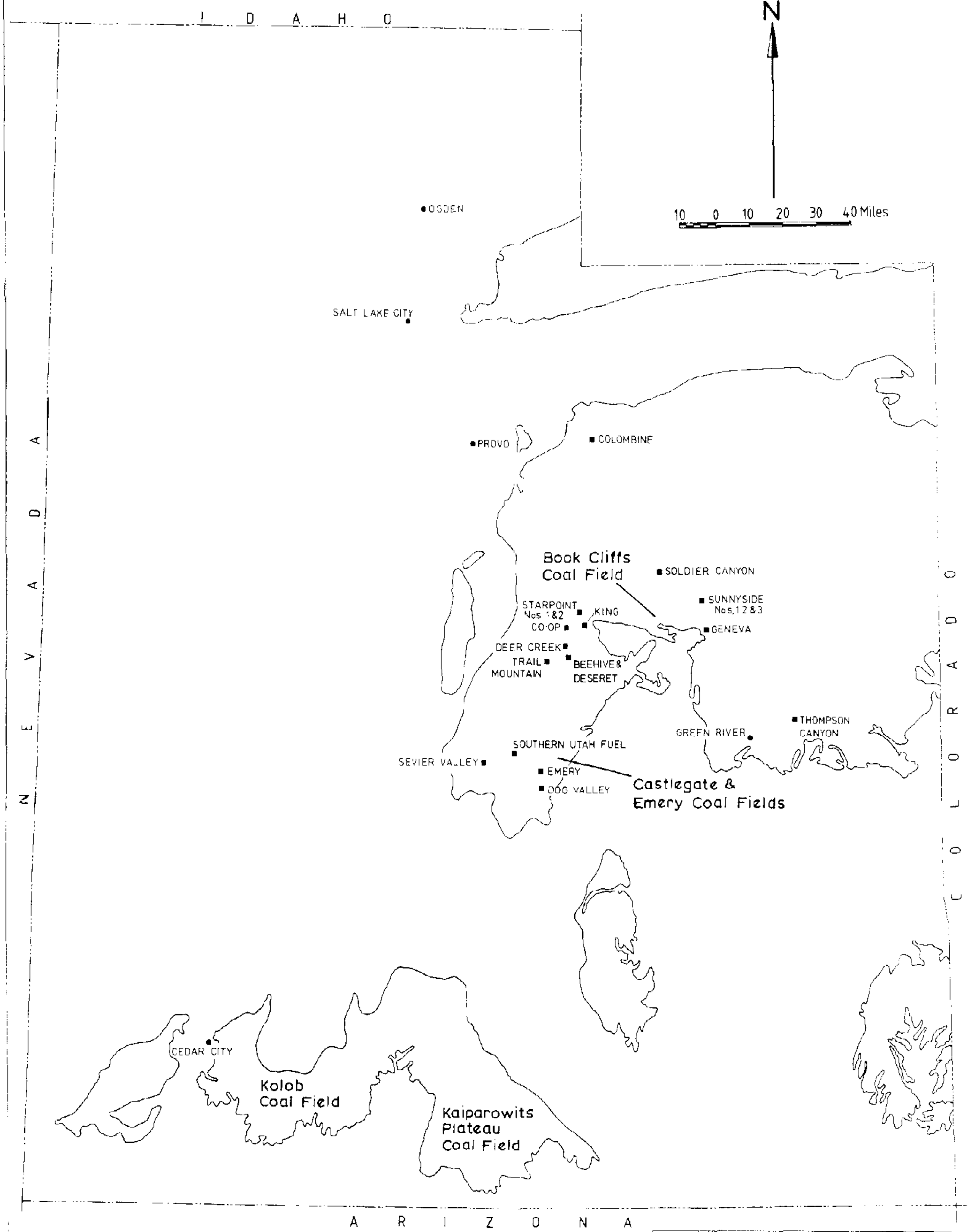

UNDERGROUND COAL MINES AND COALFIELDS OF WYOMING
10 0 10 20 30 40 Miles
M O N T A N A
I D A H O
S O U T H D A K O T A
N E B R A S K A
U T A H
C O L O R A D O
SHERIDAN
GILLETTE
BIG HORN COAL BASIN
POWDER RIVER COAL BASIN
JACKSON HOLE COAL FIELD
RONCCO
RIVERTON
WIND RIVER COAL BASIN
SOUTHERN POWDER RIVER BASIN
CASPER
N
LEGEND
TOWNS
COALFIELDS
UNDERGROUND COAL MINES
HAMS FORK COAL REGION
GREEN RIVER COAL REGION
HANNA COAL FIELD
KEMMERER COAL FIELD
VANGUARD No 2
RAWLINS
GOSHEN HOLE COAL FIELD
STANSBURY
ROCK SPRINGS
ROCK SPRINGS COAL FIELD
ROCK CREEK COAL FIELD
LARAMIE
CHEYENNE
BASE: ENERGY RESOURCES MAP OF WYOMING, GEOLOGICAL SURVEY OF WYOMING, 1975
PD-NCB CONSULTANTS LTD LONDON
ENG'R JPLB
DATE FEB78
DRG No 647/23

PLATE 23

UNDERGROUND COAL MINES AND COALFIELDS OF UTAH



LEGEND

TOWNS •

COALFIELDS

UNDERGROUND COAL MINES ■

BASE ENERGY RESOURCES MAP OF UTAH MAP 36, UTAH GEOLOGICAL SURVEY, 1975

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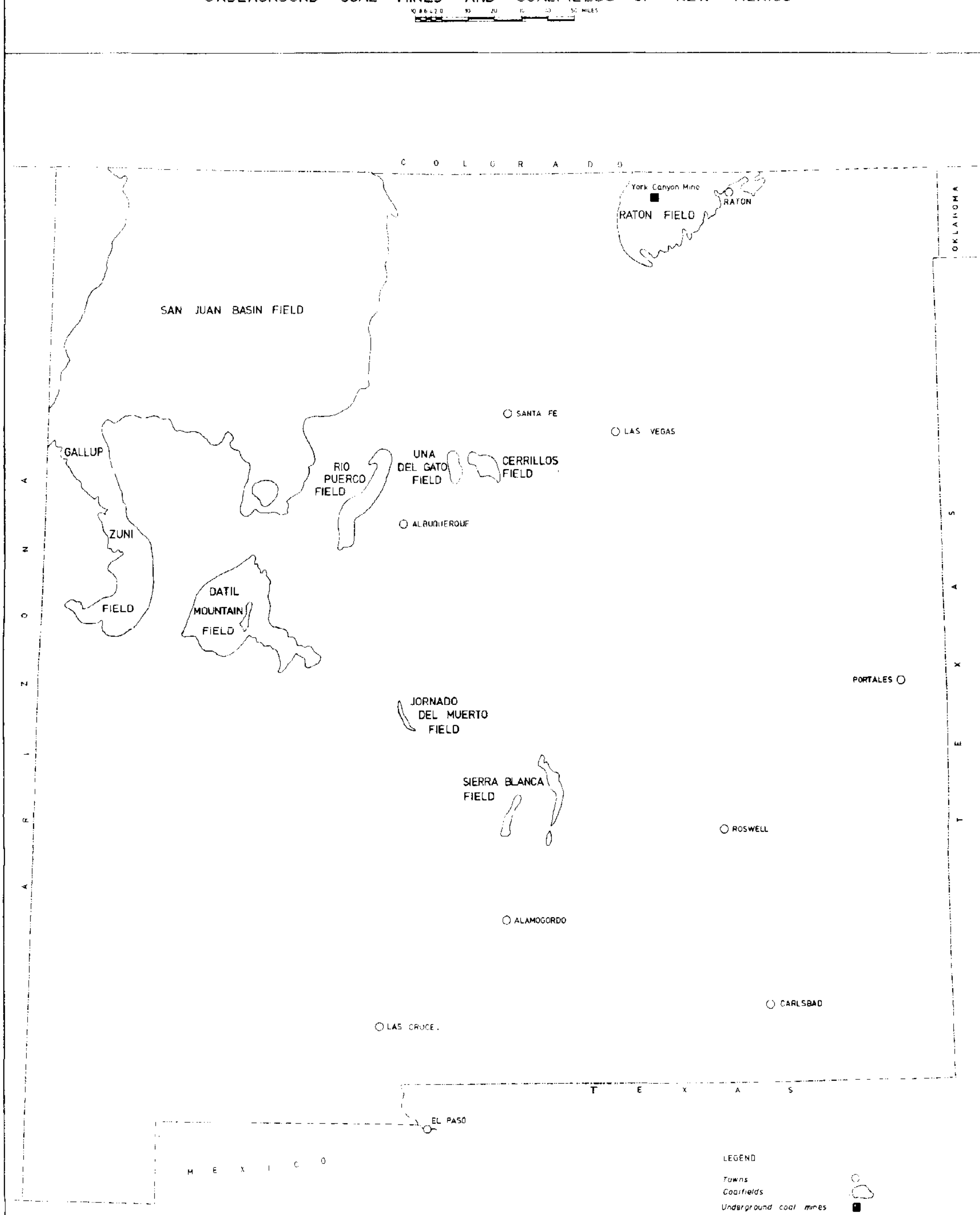
UNDERGROUND COAL MINES AND COALFIELDS OF NEW MEXICO



BASE New Mexico Energy Resource Map No 2 New Mexico Bureau of Mines and Mineral Resources 1974

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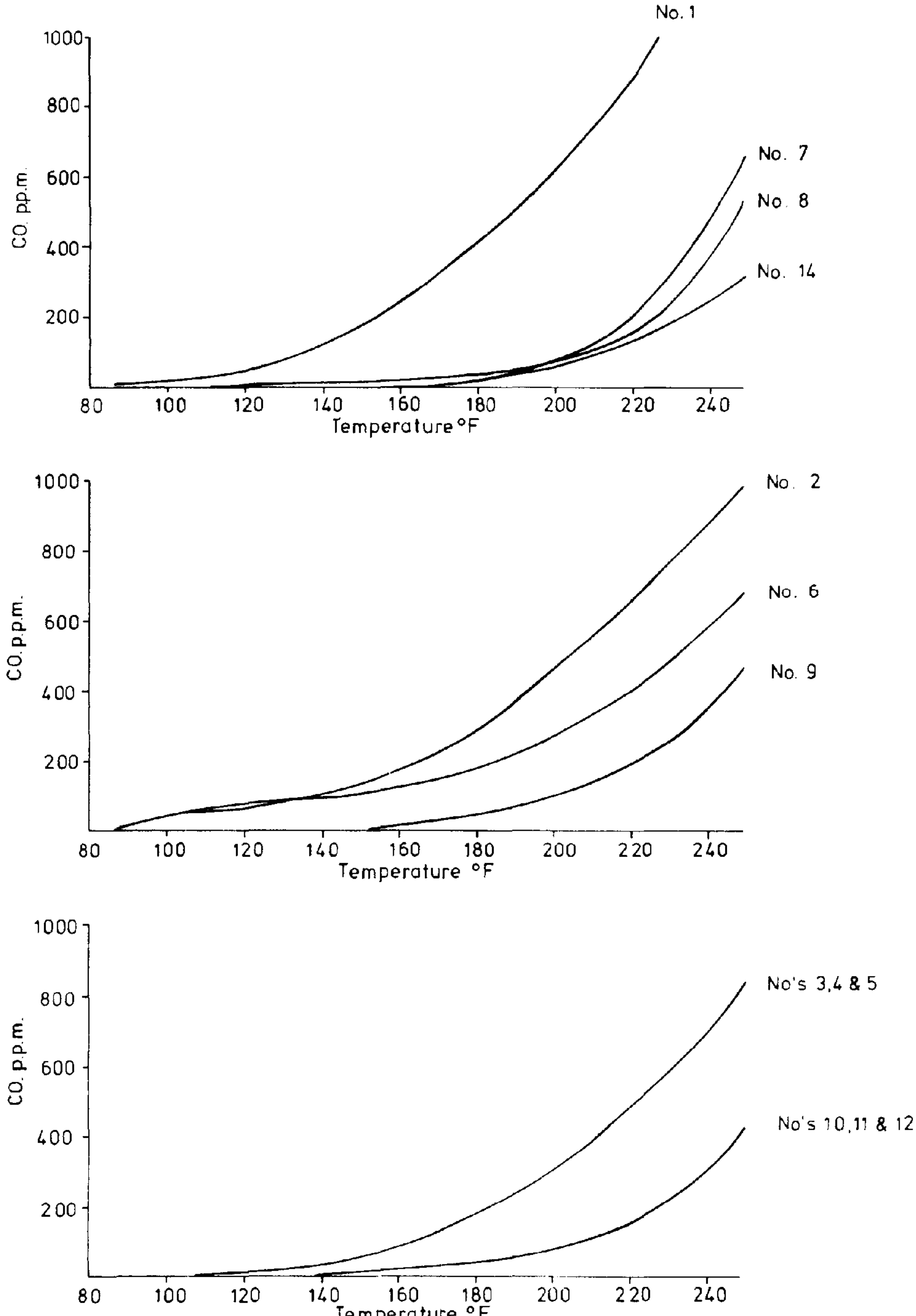
PLATE 26

CO PRODUCTION IN NCB OXIDATION TEST FOR THE 14 SAMPLES



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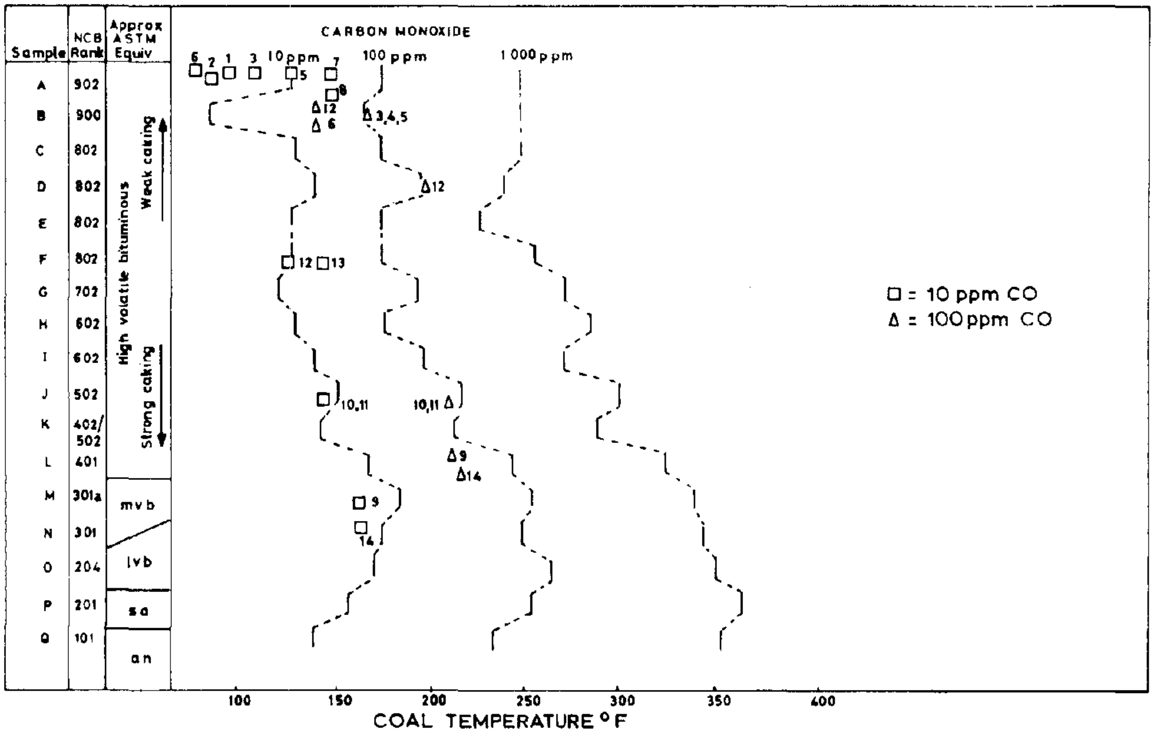
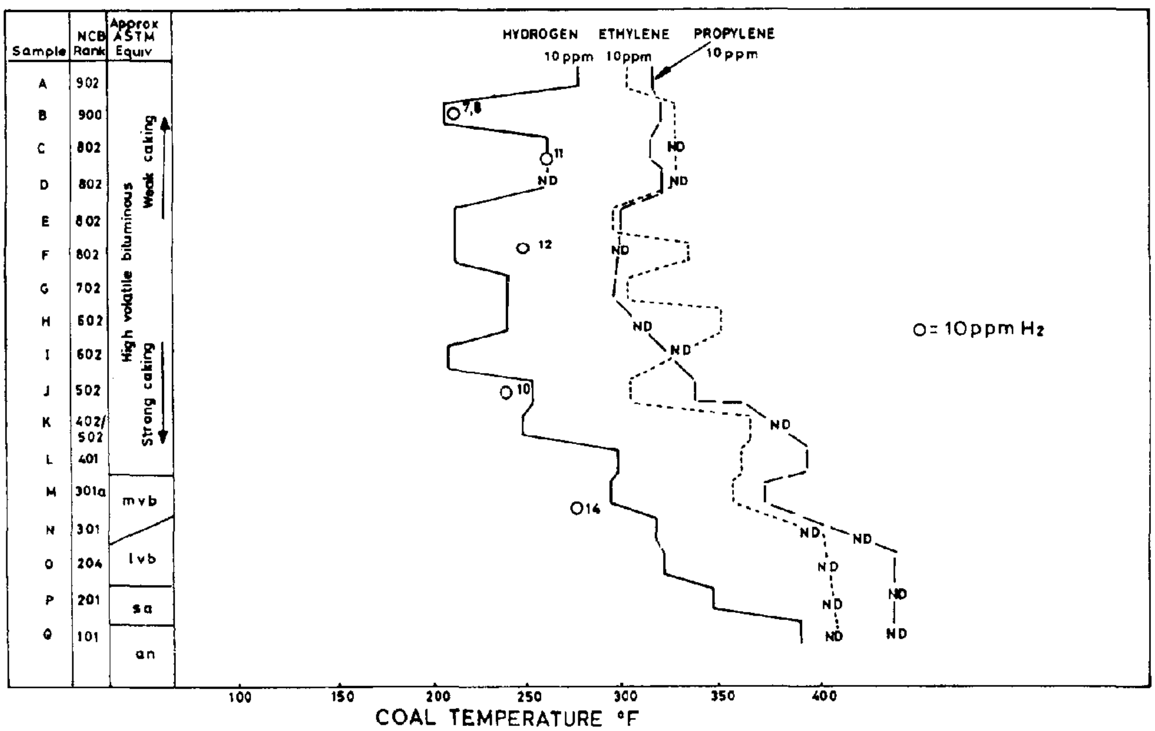
COAL TEMPERATURES AT WHICH VARIOUS GAS LEVELS ARE REACHED
(SAMPLES OF WESTERN COALS SUPERIMPOSED ON DIAGRAMS FOR BRITISH COALS)





NOTE: FOR DEFINITION OF SAMPLE NOS 1-14 SEE TABLES VI AND VII.

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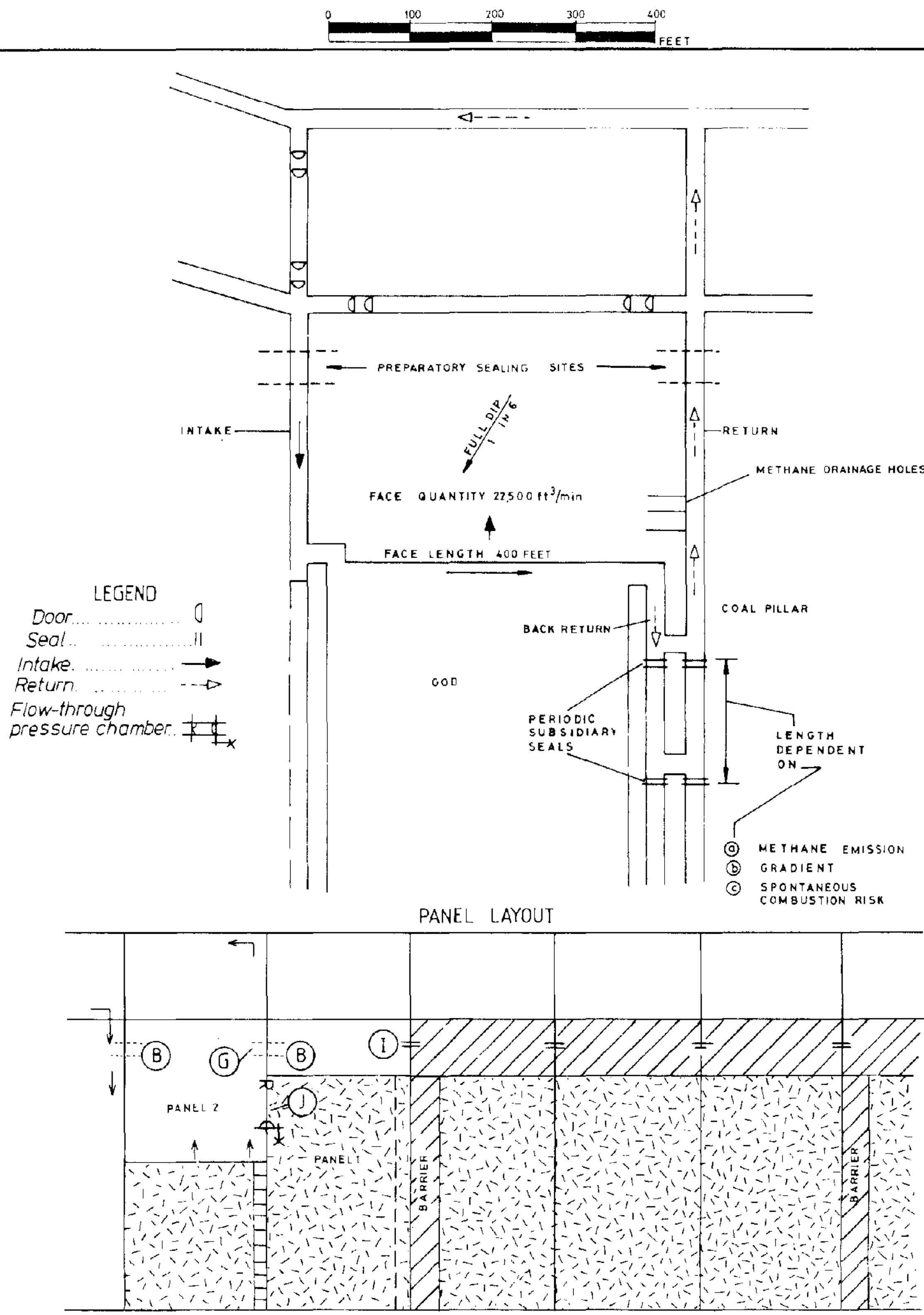
RETREAT LONGWALL FACE LAYOUT AND VENTILATION



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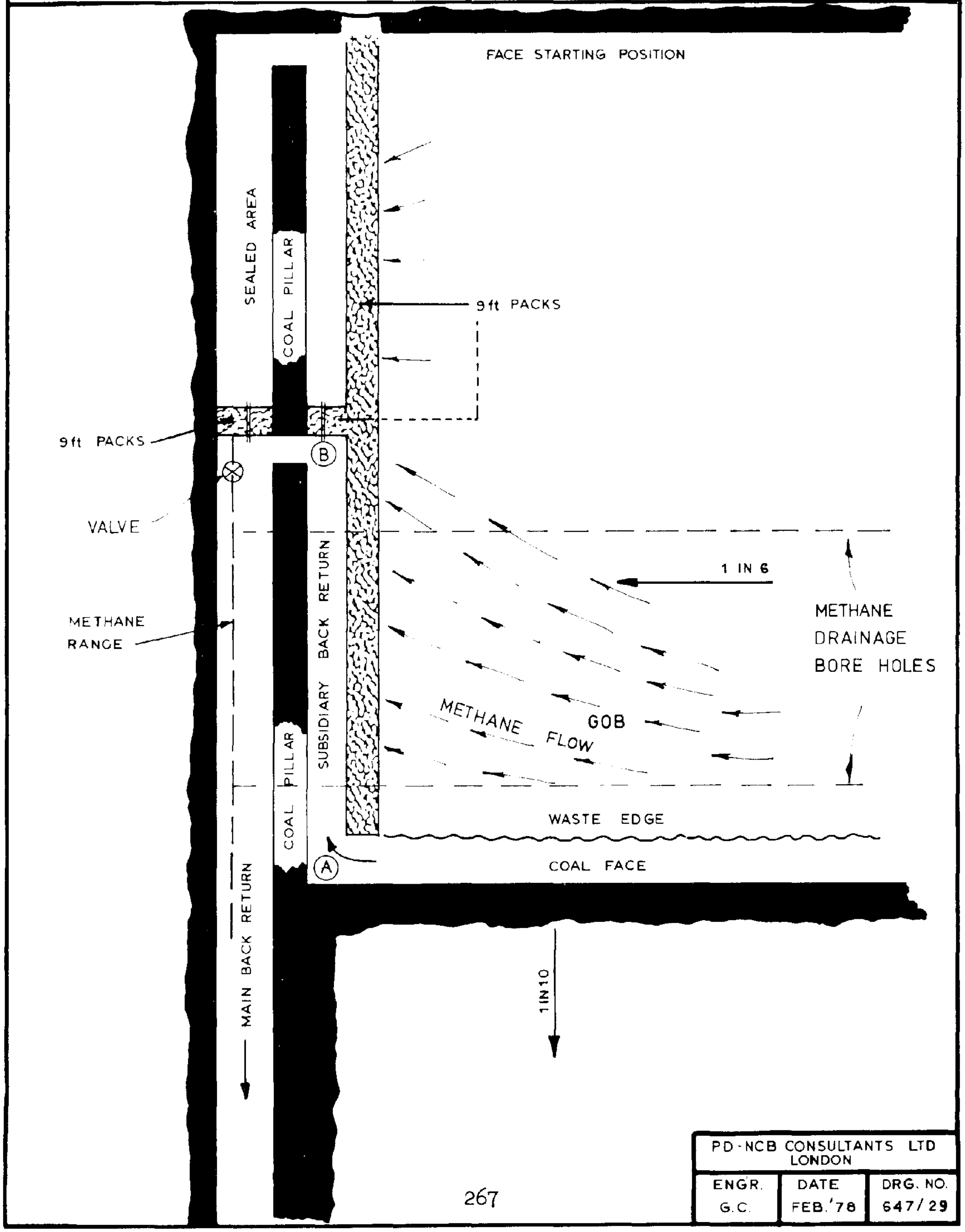
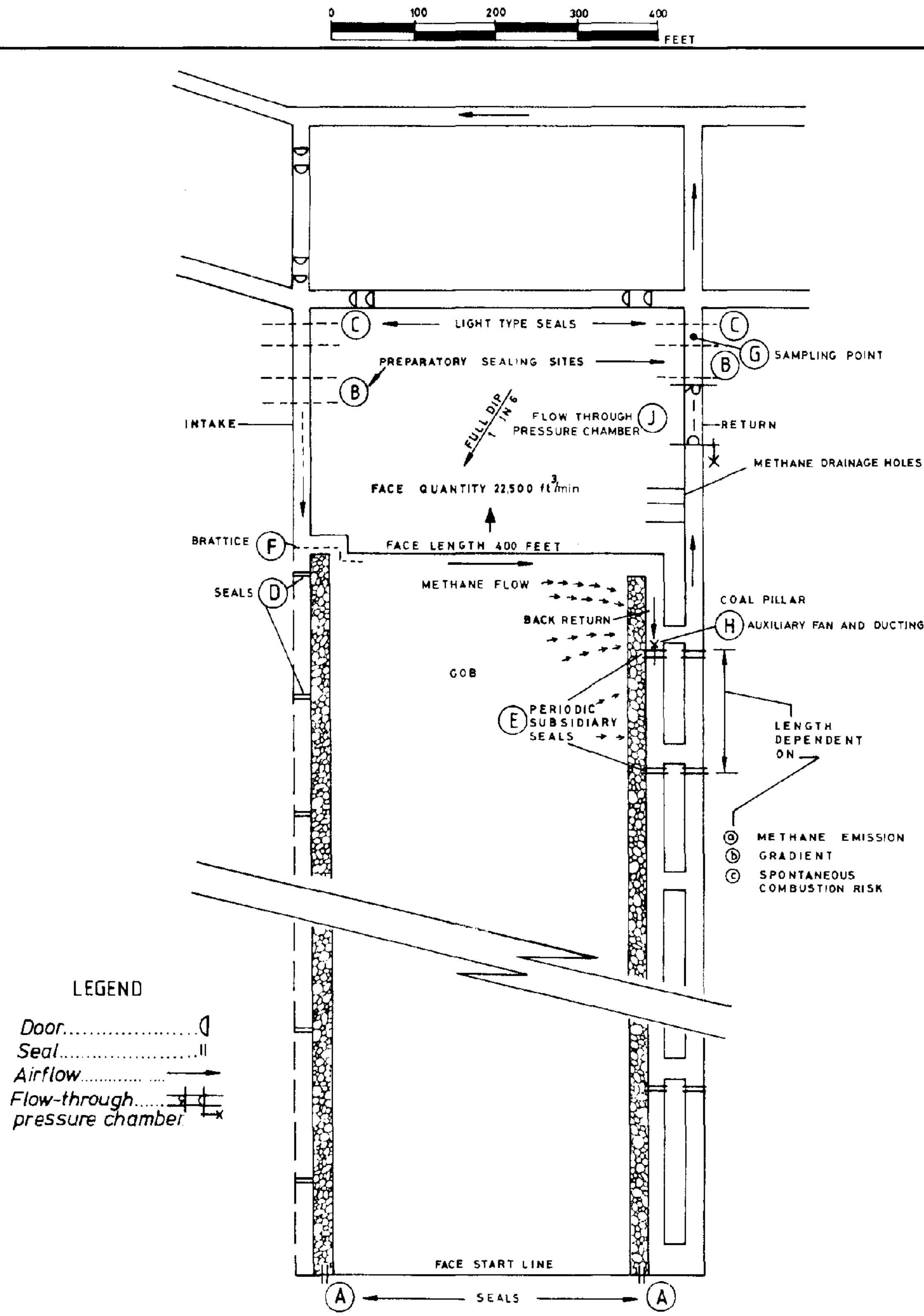
RETREAT LONGWALL FACE-"BACK RETURN" VENTILATION SYSTEM

NOT TO SCALE



RETREAT LONGWALL FACE SPONTANEOUS COMBUSTION PRECAUTIONS



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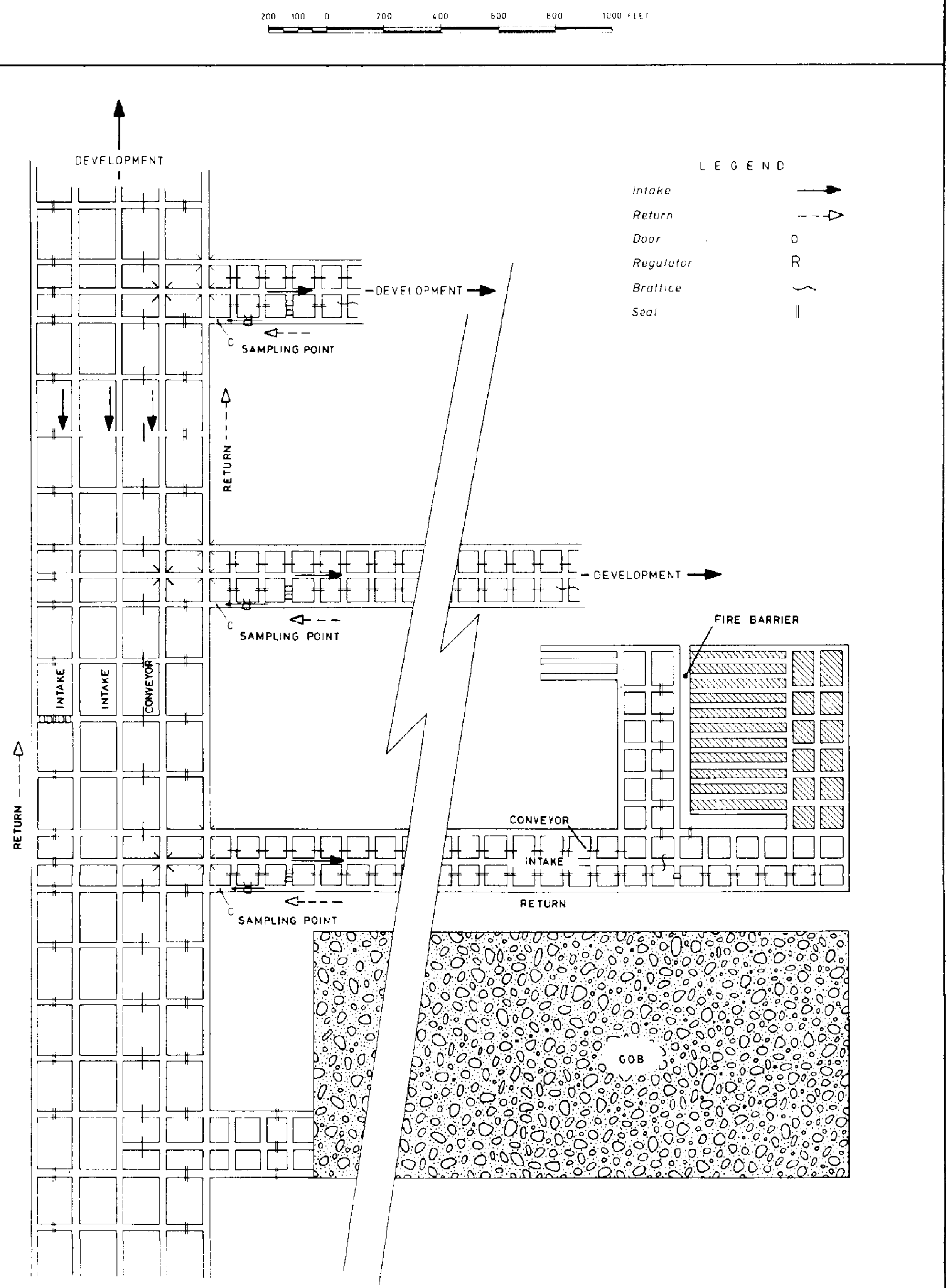
ROOM AND PILLAR MINING LAYOUT AND VENTILATION PLAN



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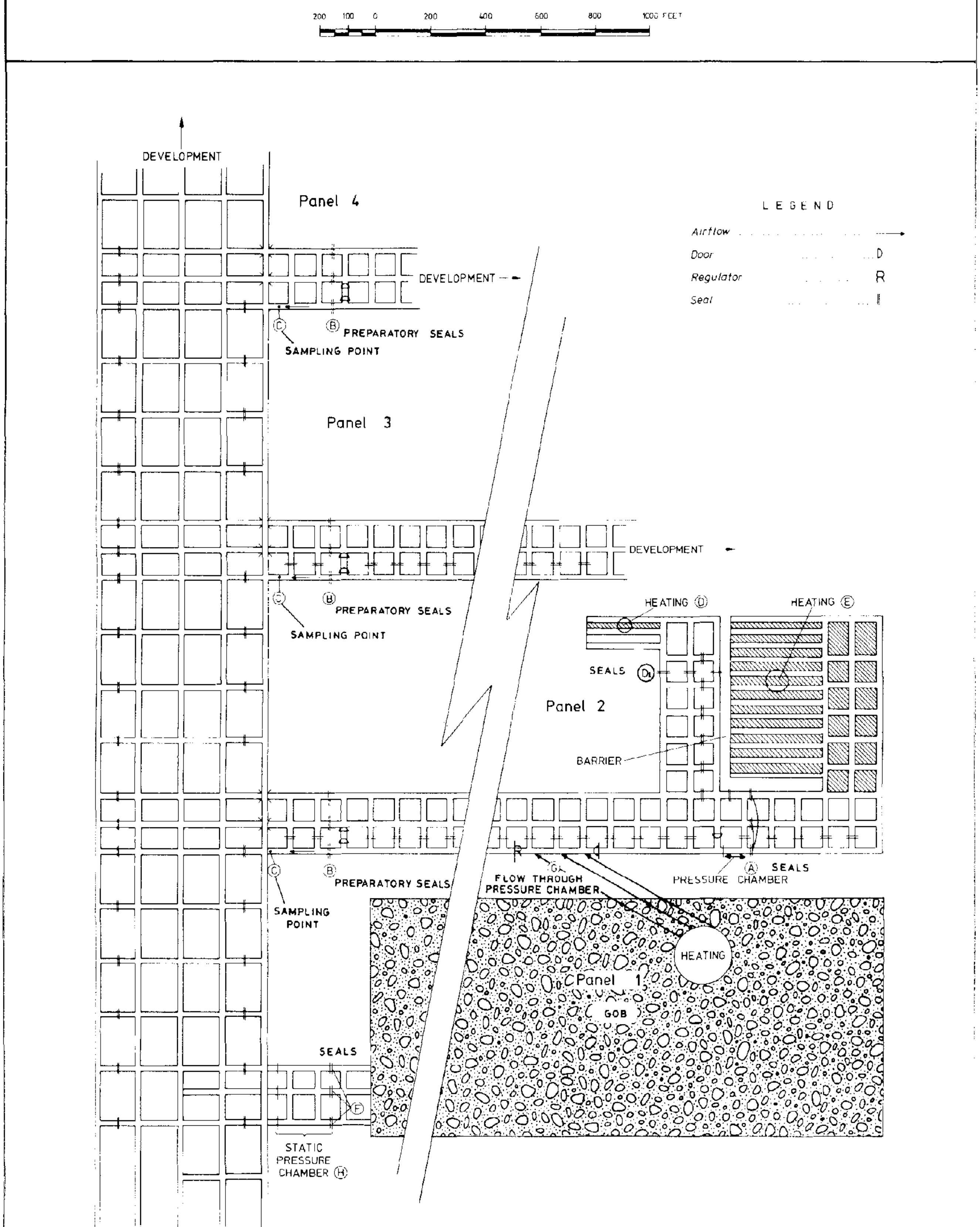
ROOM AND PILLAR MINING - SPONTANEOUS COMBUSTION PLAN



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SUB-LEVEL CAVING BY PILLAR EXTRACTION VENTILATION AND LAYOUT PLAN

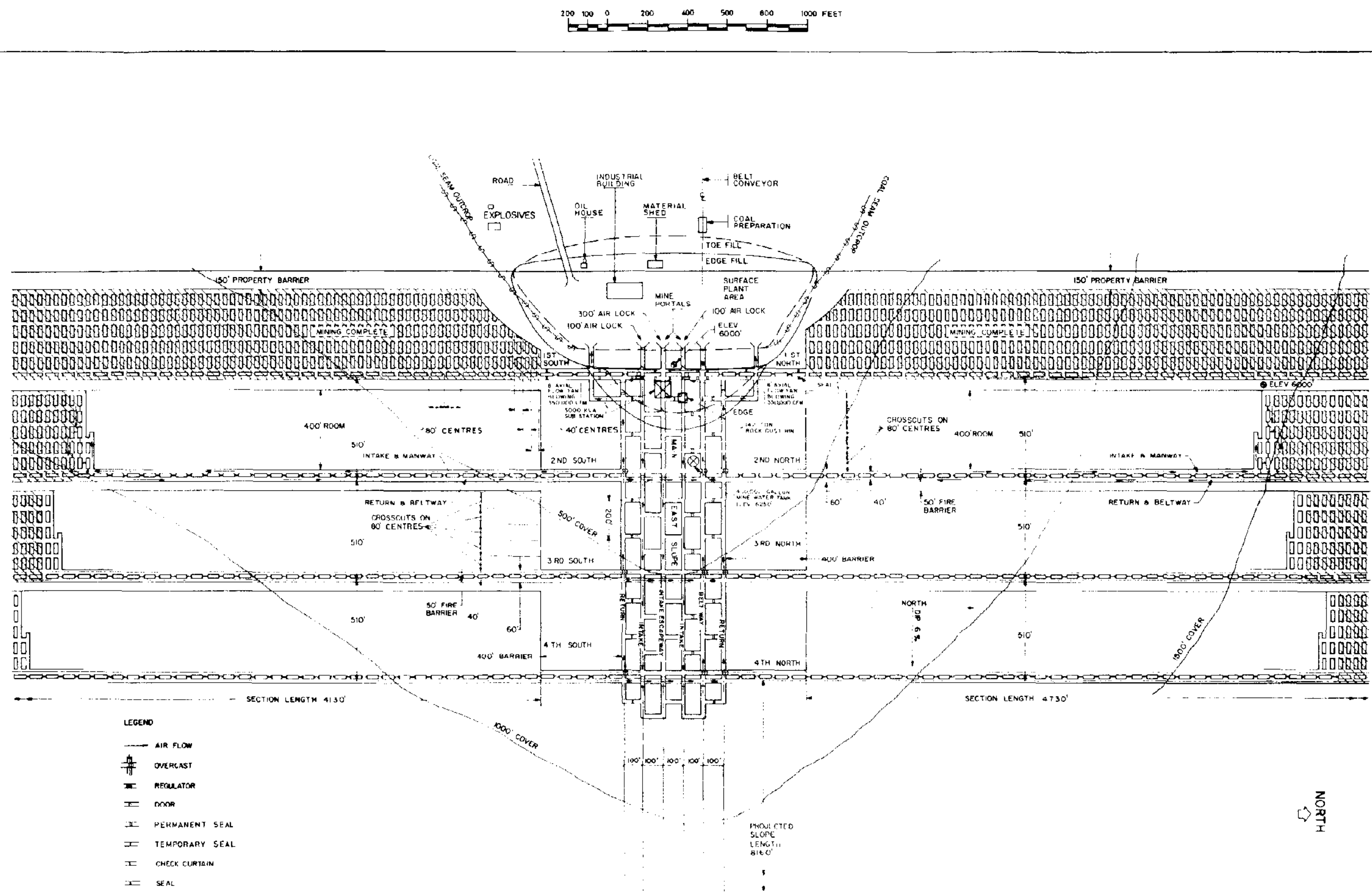

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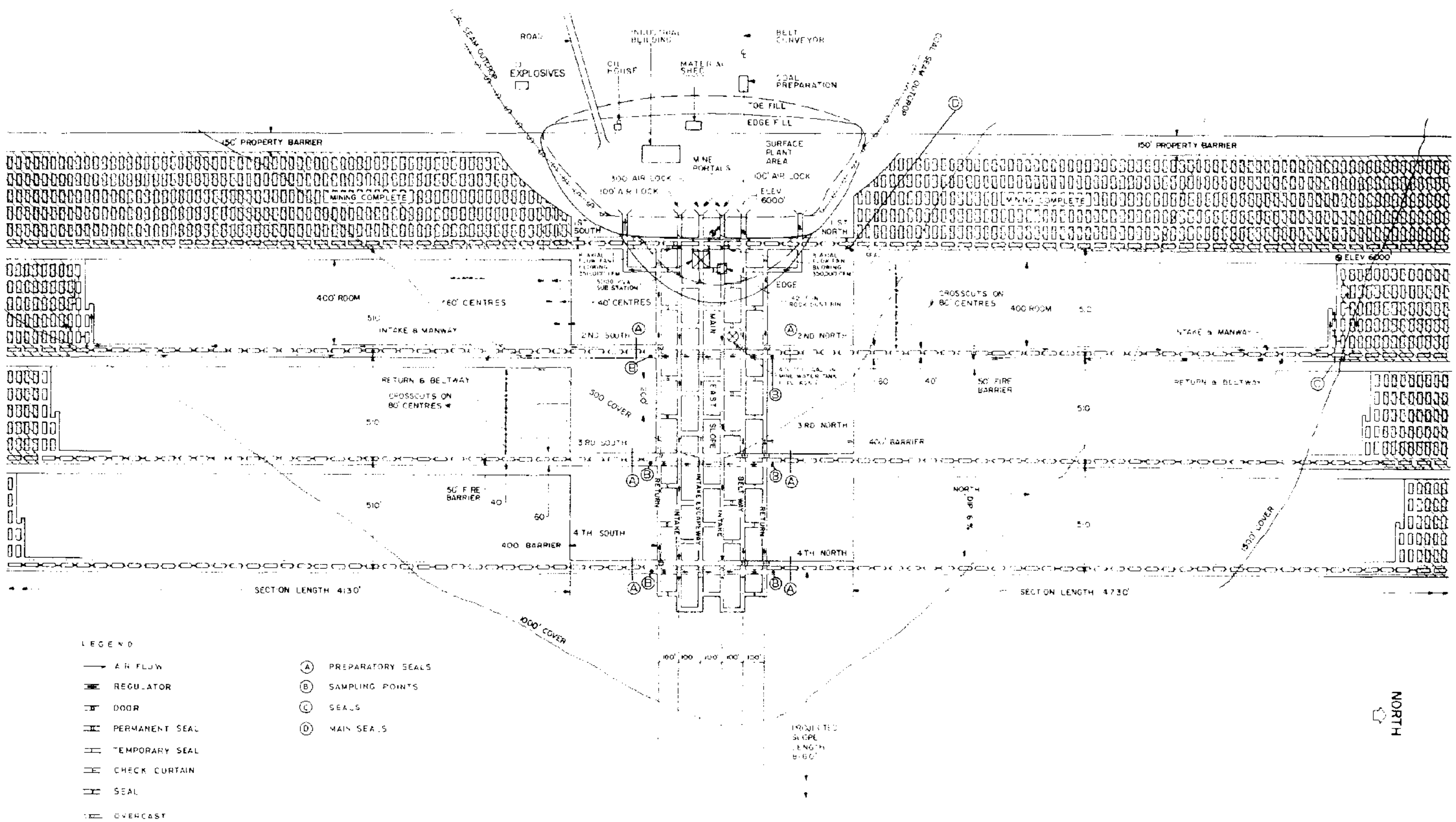
PLATE 33

SUB-LEVEL CAVING BY PILLAR EXTRACTION - PRECAUTIONS AGAINST SPONTANEOUS COMBUSTION

200 0 200 400 600 800 1000 FEET



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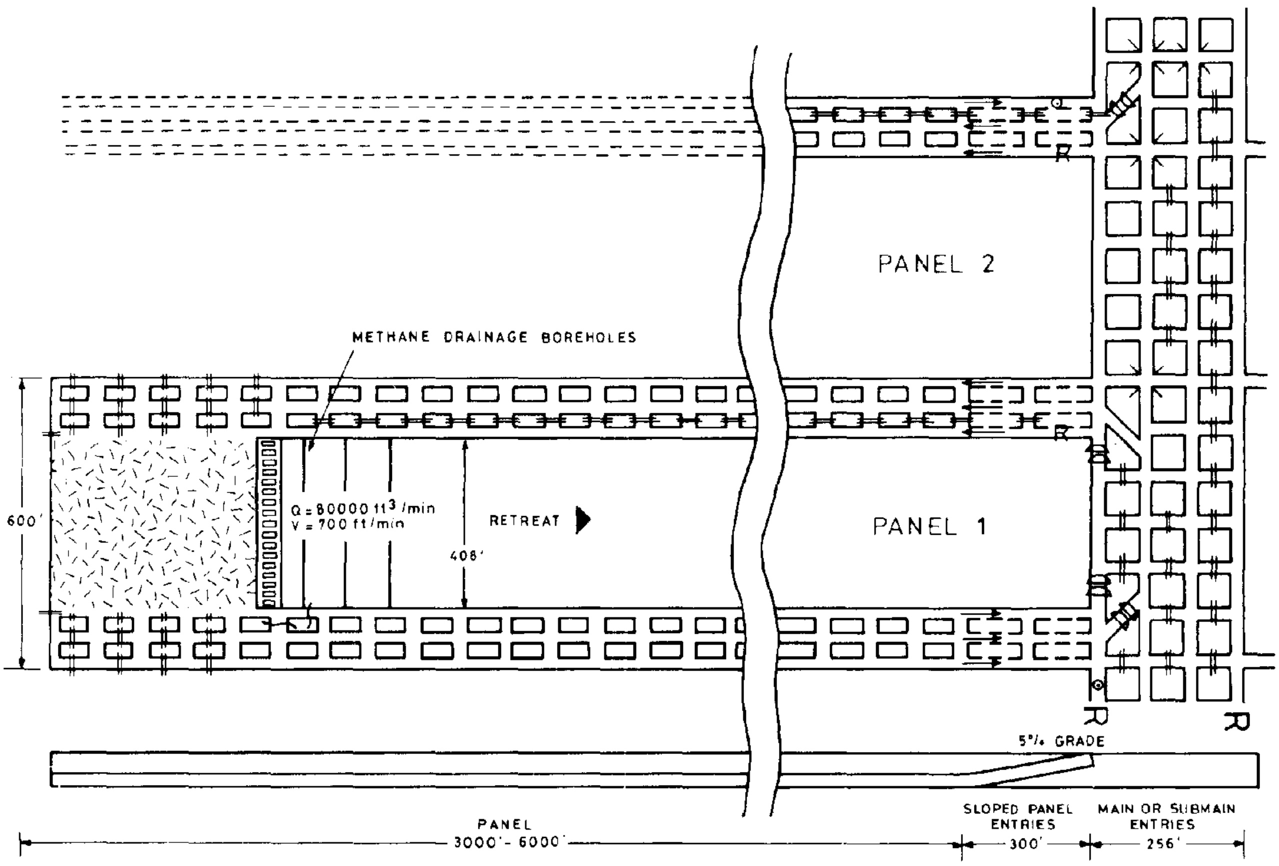
LONGWALL CAVING - MINING DESIGN

100 0 100 200 300 400 500 ft

PLAN VIEW



SECTION VIEW

INTAKE ....

RETURN ....

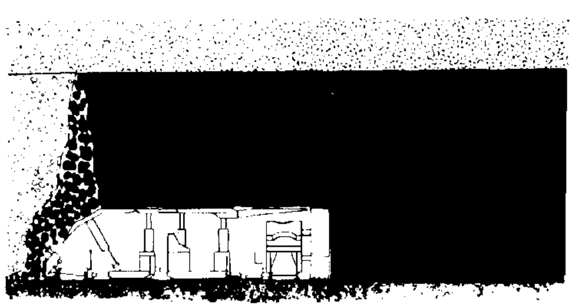
DOOR .... D

REGULATOR ...... R

SEAL .... ||

CURTAIN .... ∫

SAMPLING POINTS o



SECTION ACROSS FACE

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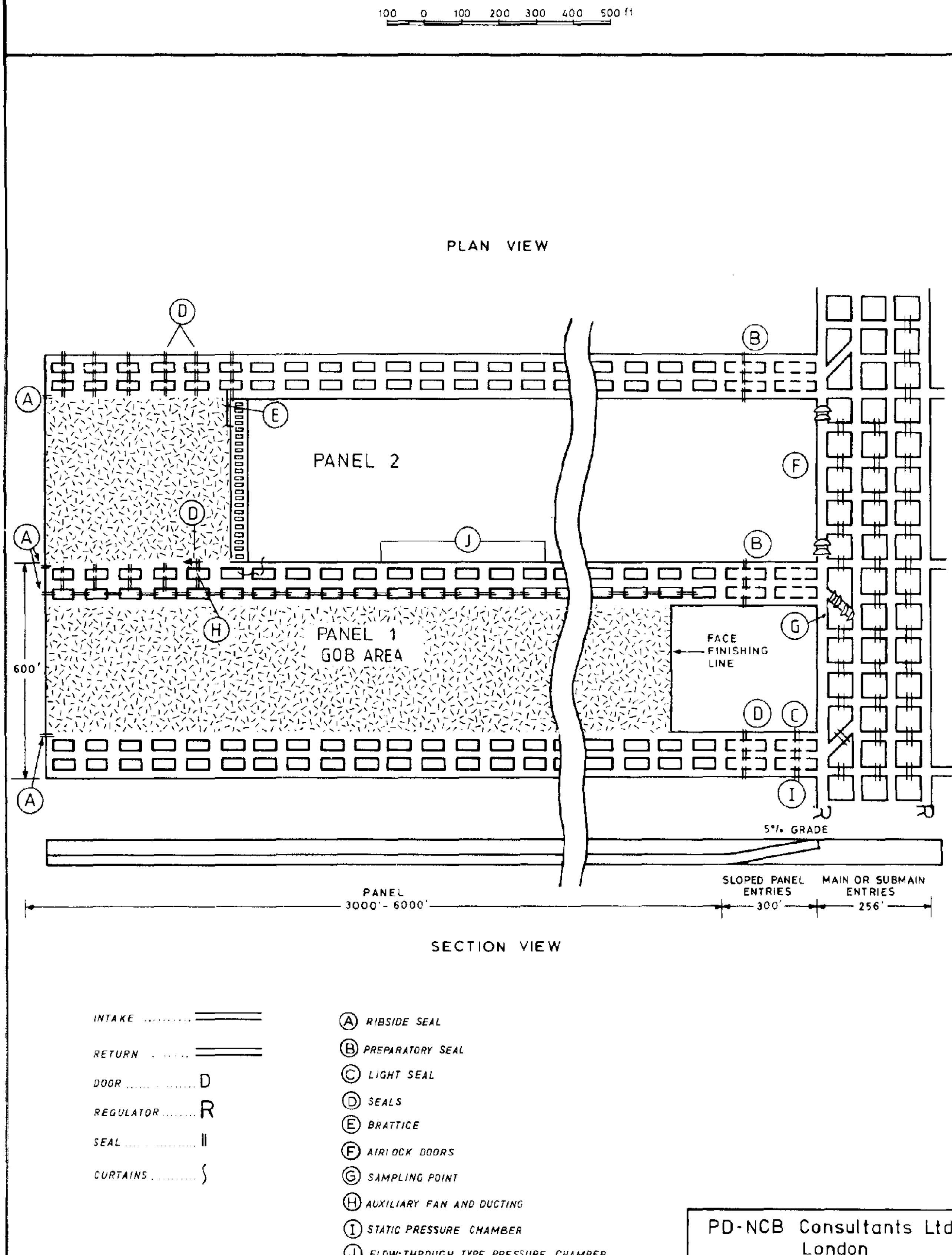
LONGWALL CAVING
PRECAUTIONS AGAINST SPONTANEOUS COMBUSTION



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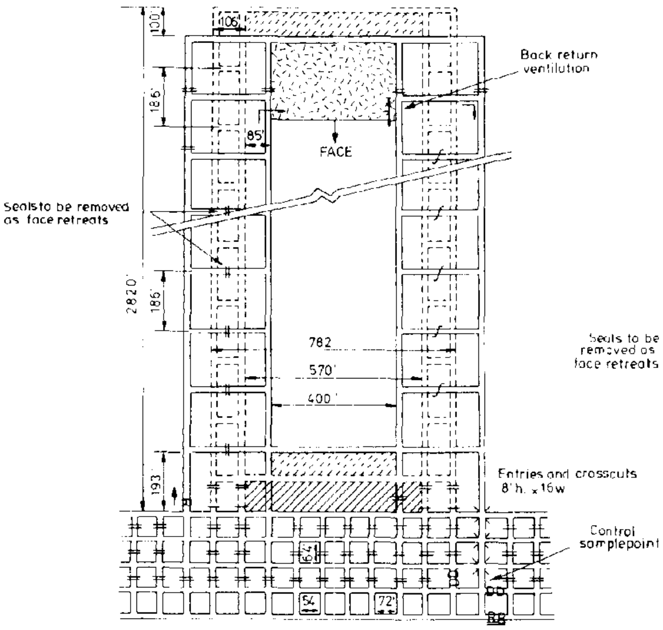
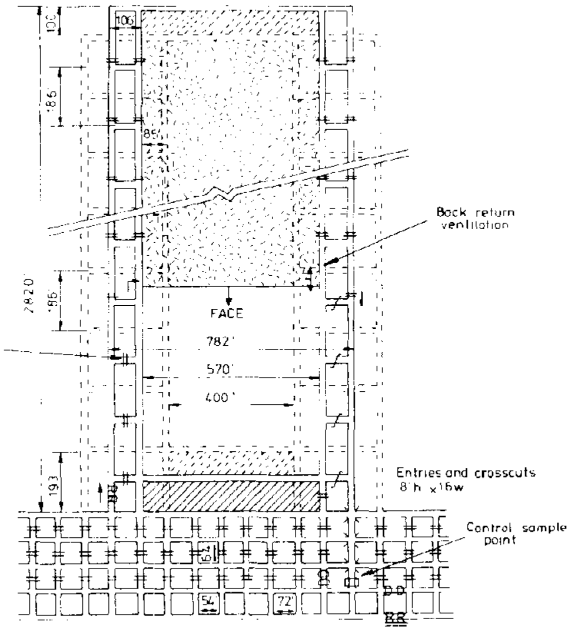
Eng'r. G C.	Date Feb. 78	Drg. No. 647 / 36

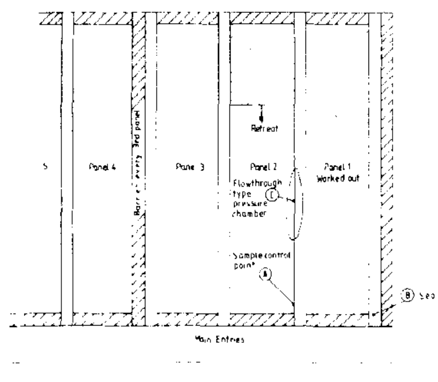
LAYOUT AND VENTILATION FOR TWO-ENTRY MULTILIFT MINING



LOWER LIFT EXTRACTION



UPPER LIFT EXTRACTION



PANEL LAYOUT

KEY
RR = Regulators
D = Doors
X = Air crossing
= = Seal
/ = Curtain

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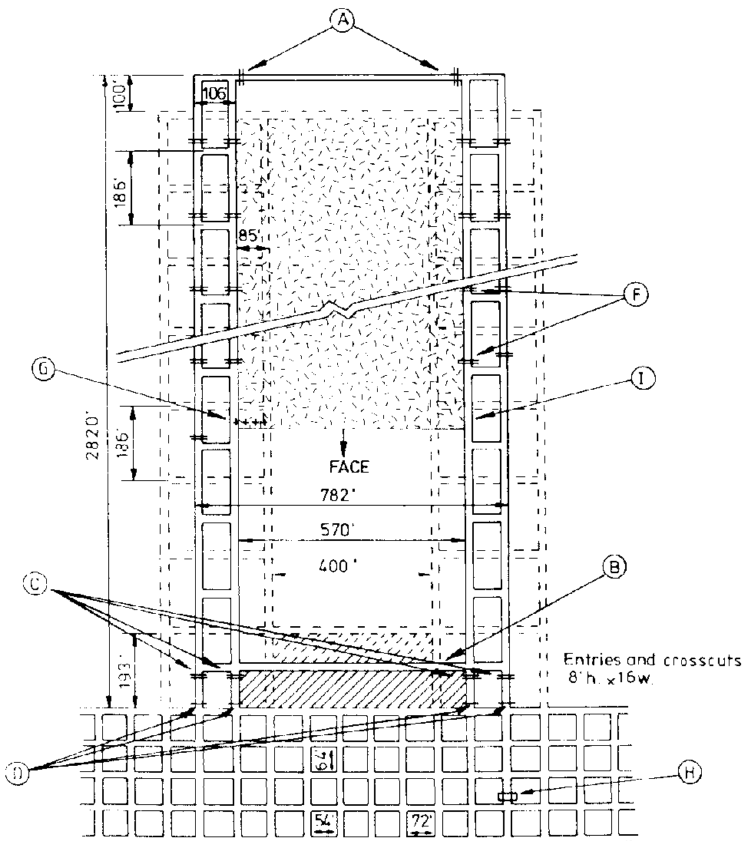
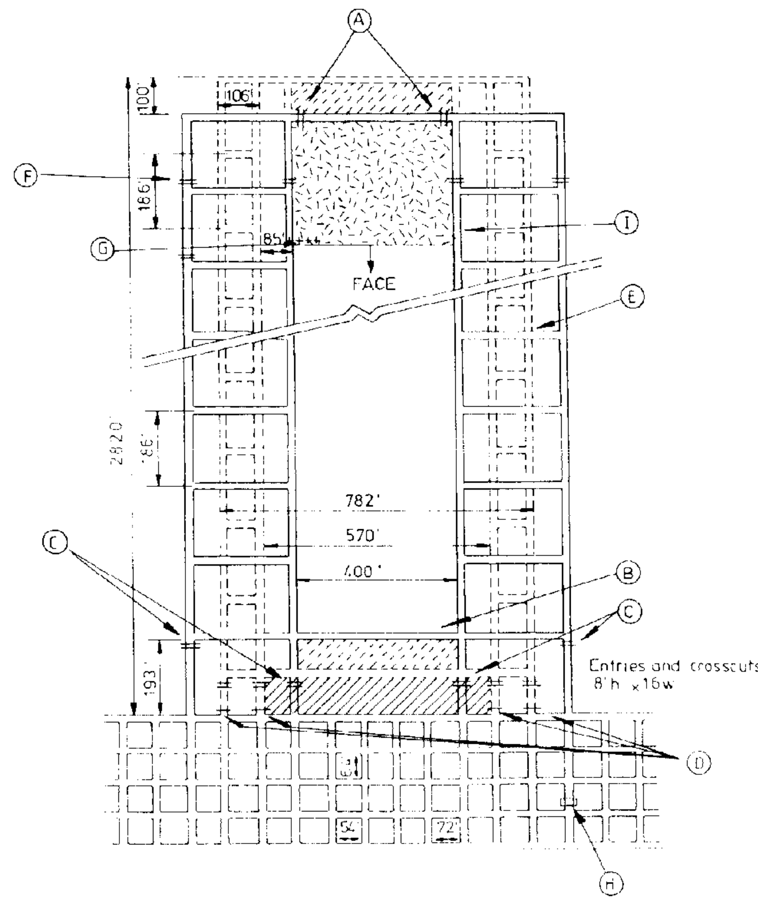
LAYOUT FOR TWO ENTRY MULTILIFT MINING – PRECAUTIONS AGAINST SPONTANEOUS COMBUSTION

LOWER LIFT EXTRACTION



UPPER LIFT EXTRACTION



(A) Ribside seal
(B) Face finishing line
(C) Preparatory seal
(D) Light seal
(E) Cross over point
(F) Seals
(G) Brattice
(H) Sampling point
(I) Auxiliary fan and ducting

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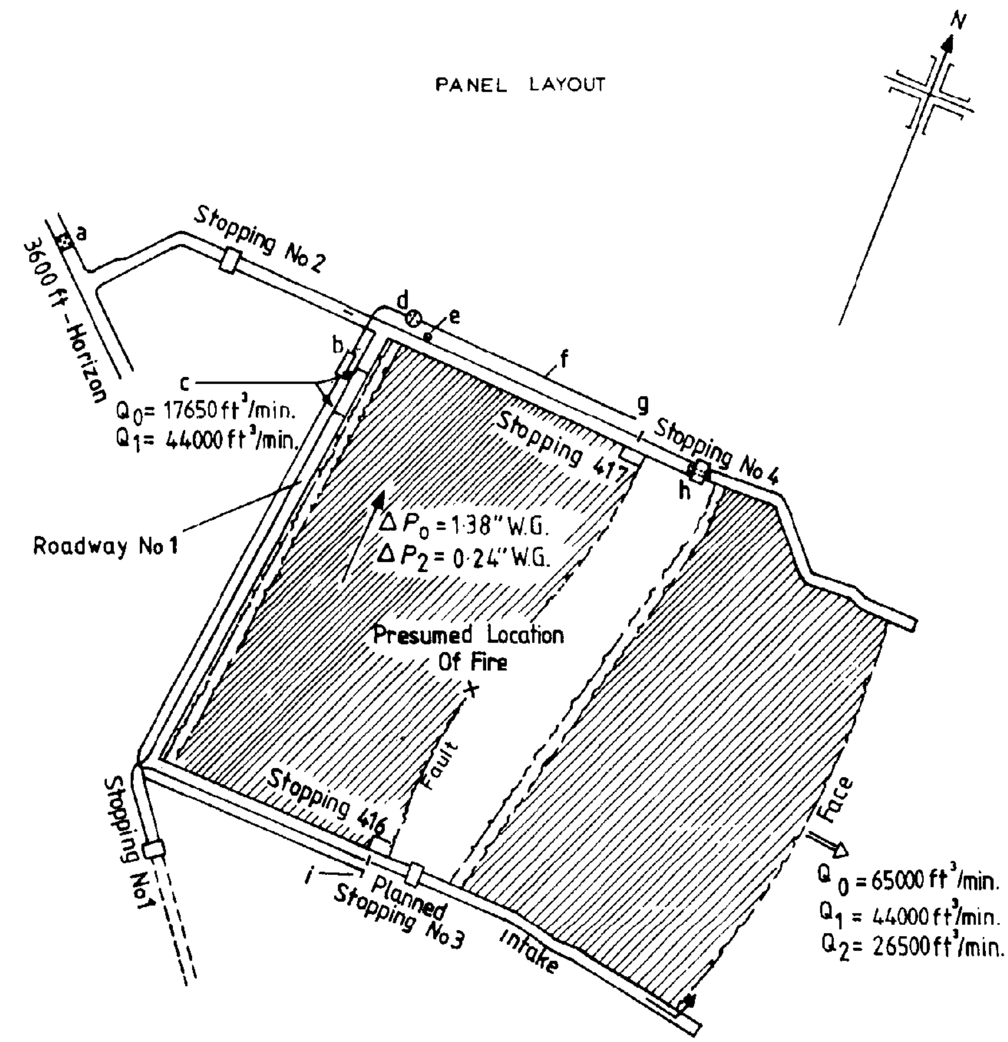
JC	Sept '78	[illegible]

PLATE 38

CASE 1 - GERMANY

Scale 1:4000 approx.



a Intake point for CO Unor device.
b Inclined-tube manometer.
c Ventilation doors in use.
d Intake points for CH_4 and CO Unor instruments.
e Regulator to control pressure at face.
f Tubing for pressure measurements.
g Exit point of combustible gases.
h Fan to raise pressure.
i Entry point of short-circuited air.

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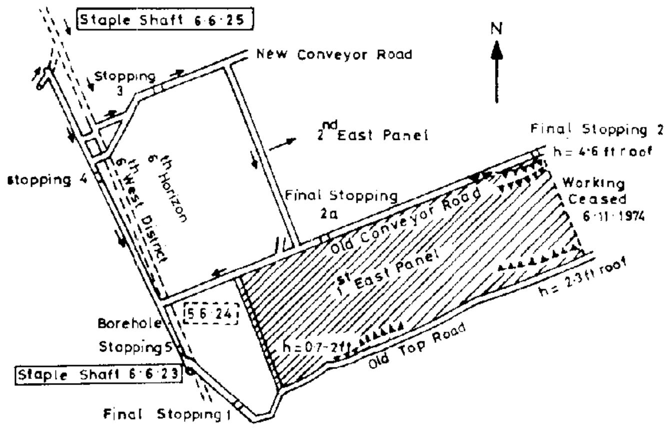
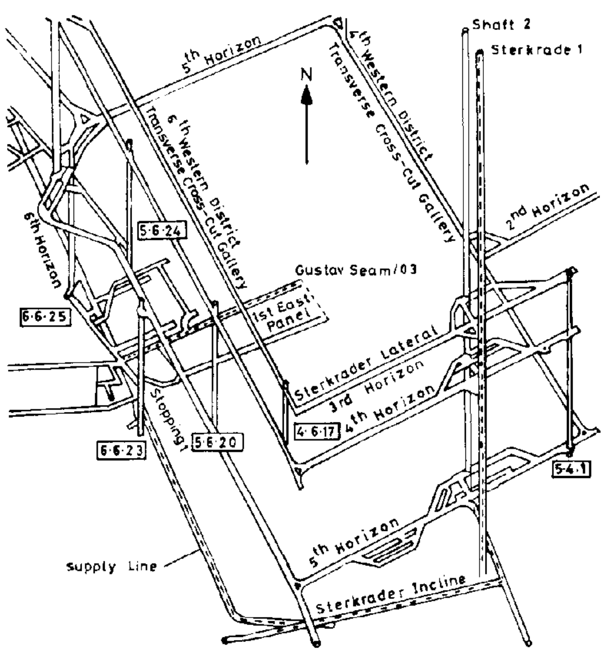
CASE 2 - GERMANY



LEGEND

Fault............. ▼▼▼▼▼▼

(a) Scale 1:10000 approx.
Cross-section of workings in the Gustav seam.



(b) Not to scale.
Layout of delivery lines used in the neutralization procedure.

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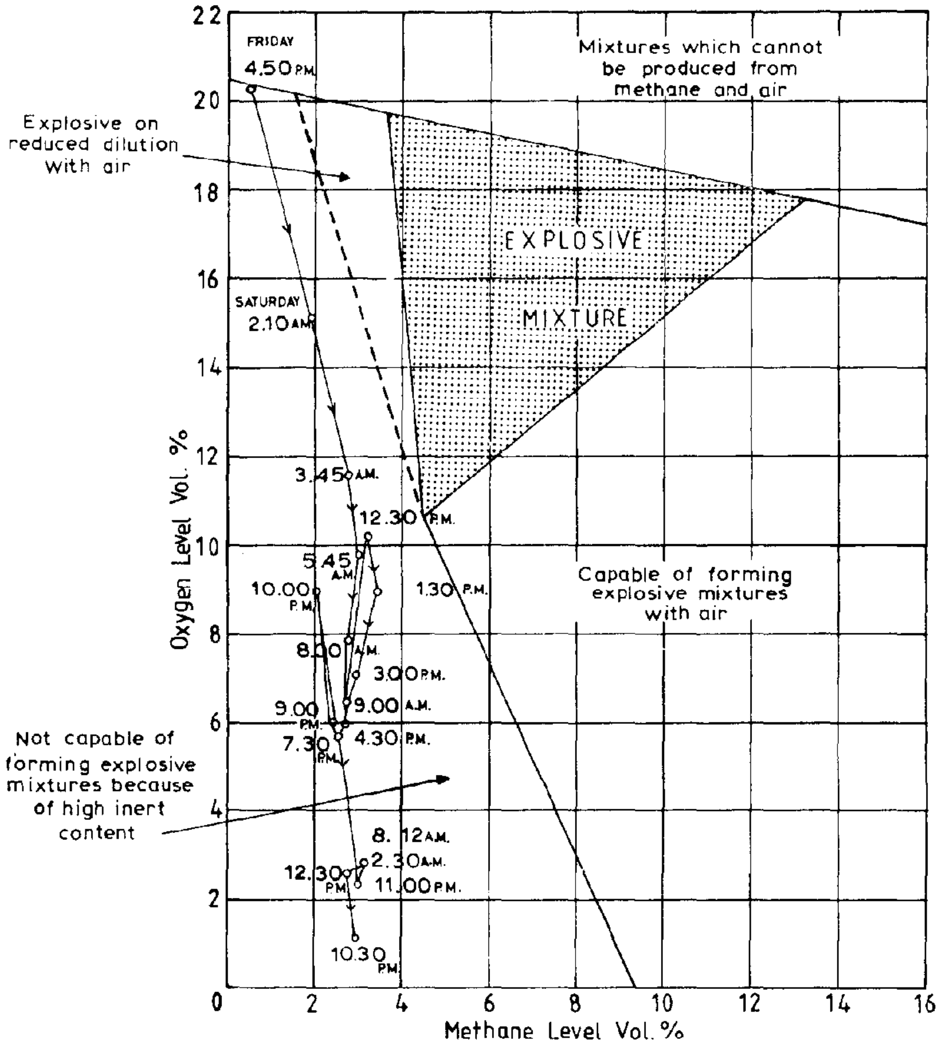
CASE 2 - GERMANY

THE COMPOSITION OF THE GAS SAMPLES TAKEN FROM EAST OF STOPPING 2a AND THEIR RELATIONSHIP TO THE EXPLOSION TRIANGLE.



Friday - 6th December 1974
Saturday - 7th December 1974

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CASE 4-CANADA

Hydraulic Mine Layout

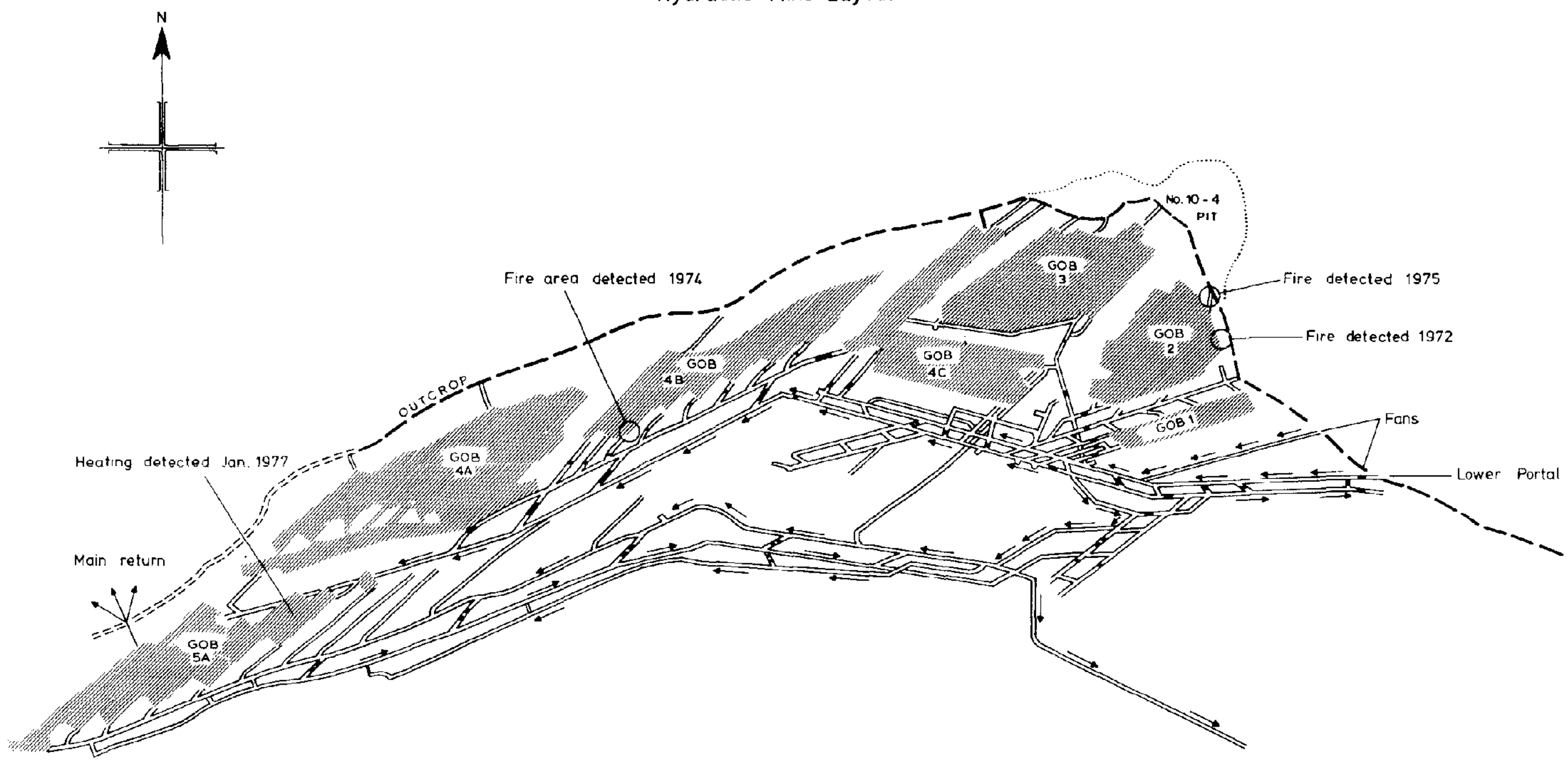

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PLATE 42

CASE 5-U.K.
SHAFT AREA

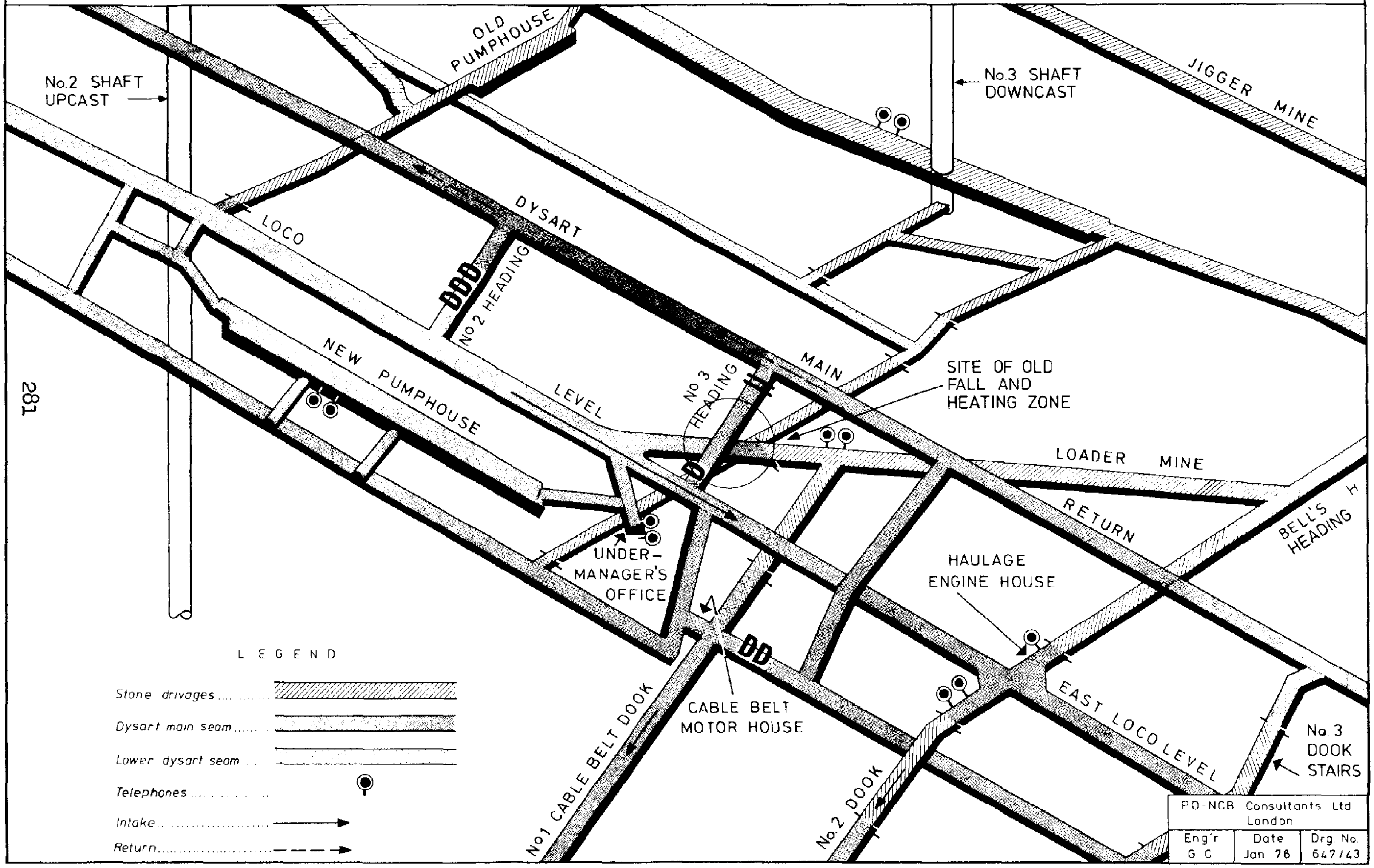
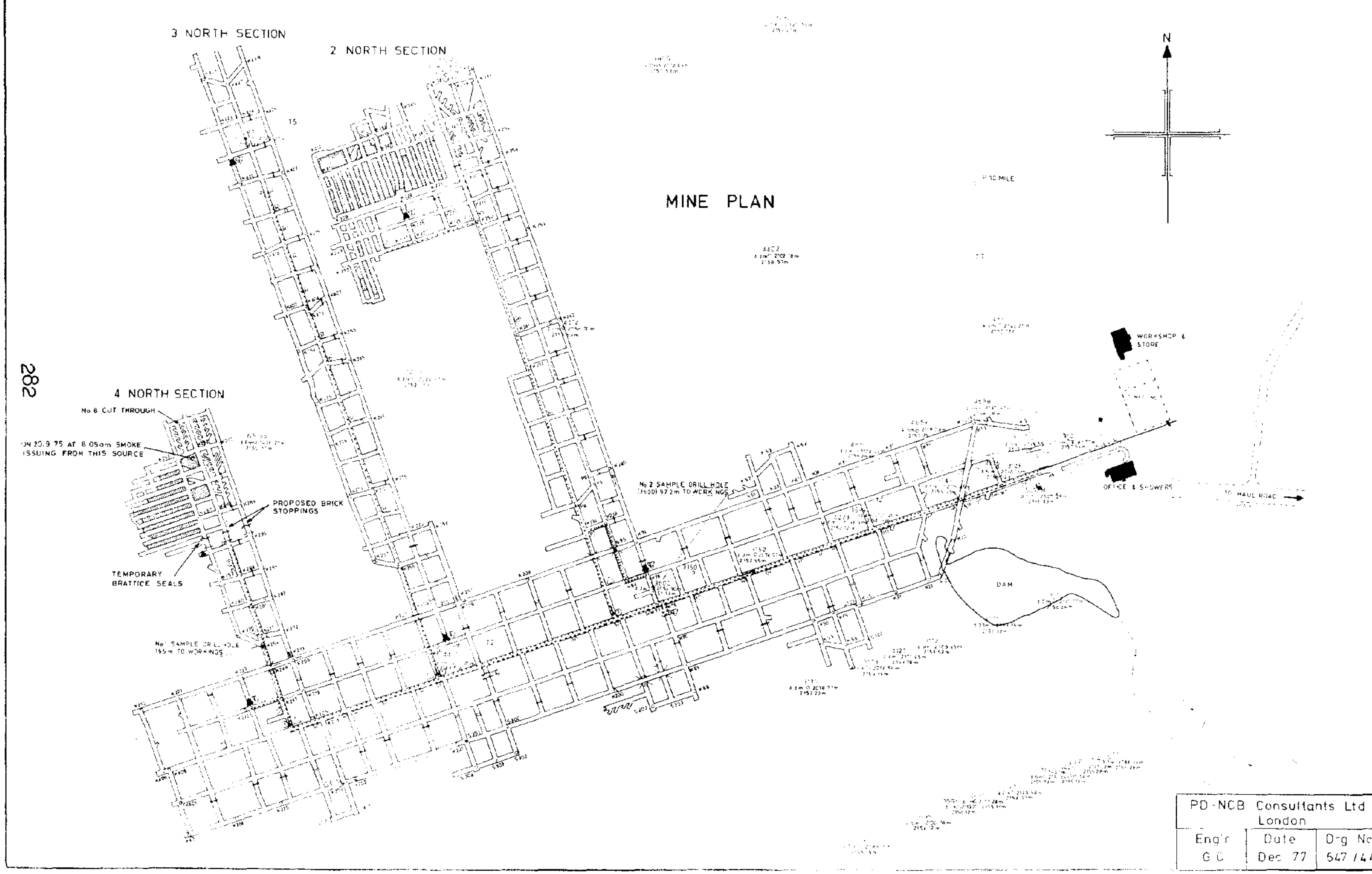


PLATE 43

CASE 6 - AUSTRALIA

Scale 1:7500 approx.



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G C	Dec 77	547/44

CASE 7-U.S.A.

Scale 1:4000 approx.

SECTION PLAN

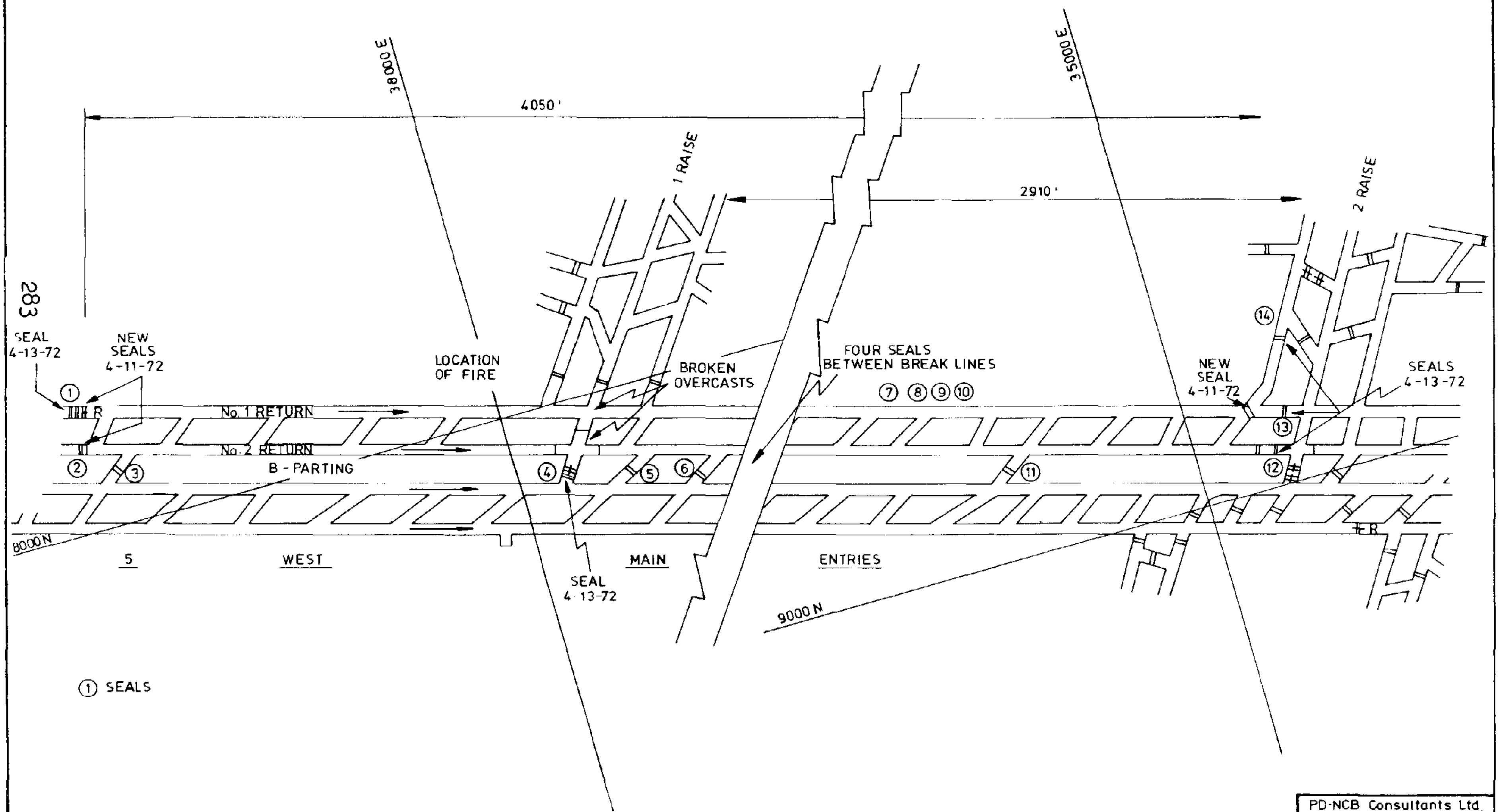

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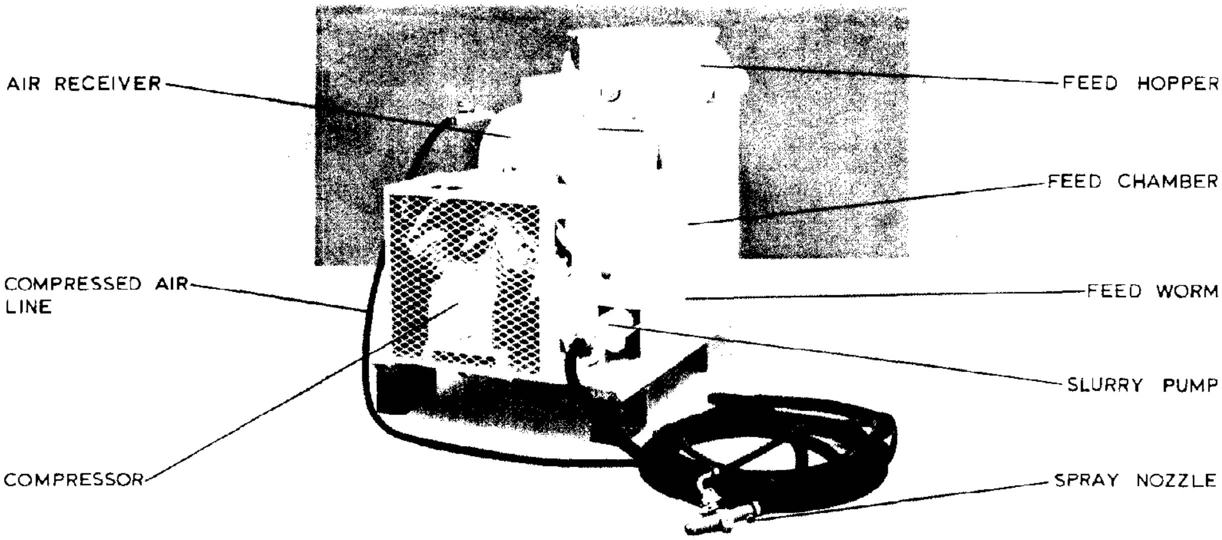
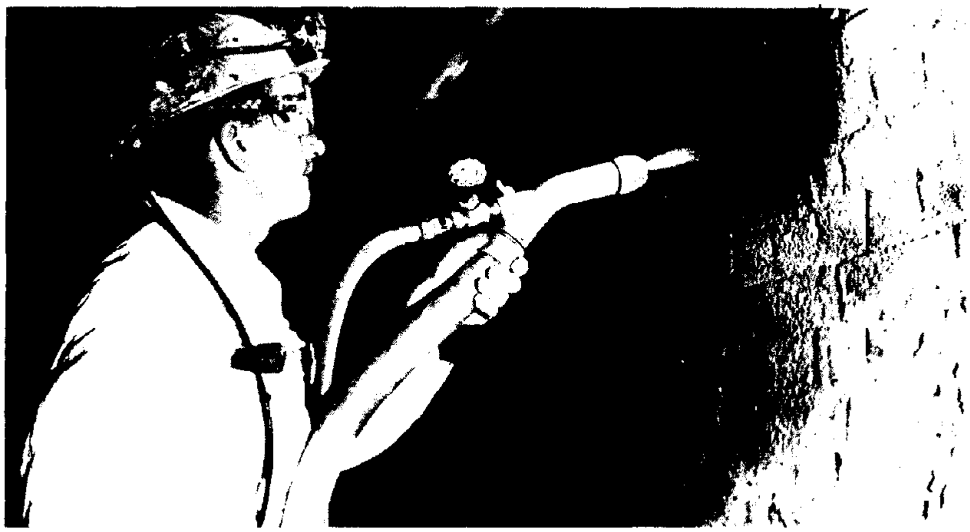
PLATE 45

SEALANT COATING MIXING AND SPRAYING MACHINE



Electric spraying machine



Spraying Gypseal

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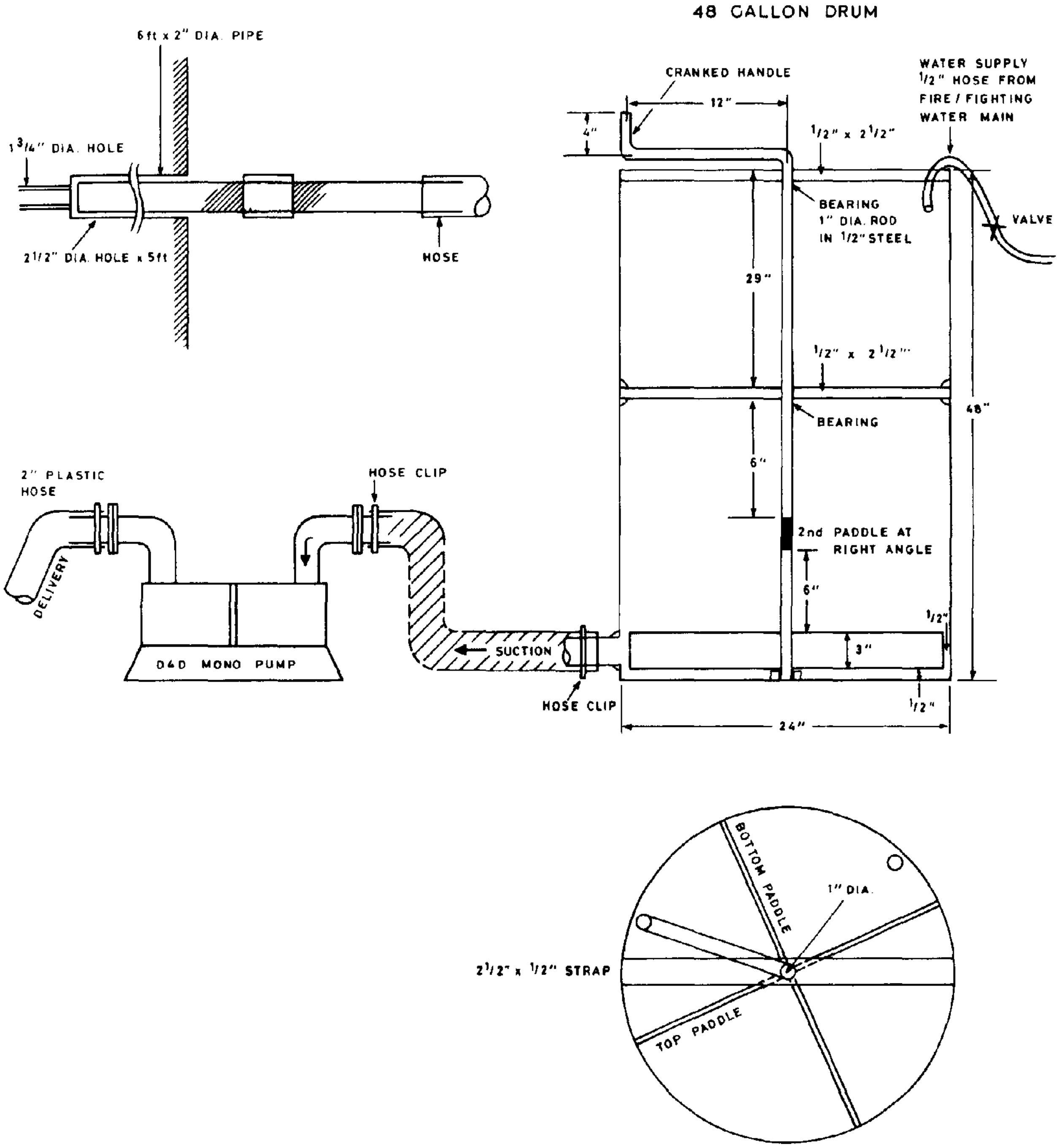
PORTABLE SEALANT MIXING AND INJECTION / PLACING MACHINE



PLAN VIEW OF DRUM

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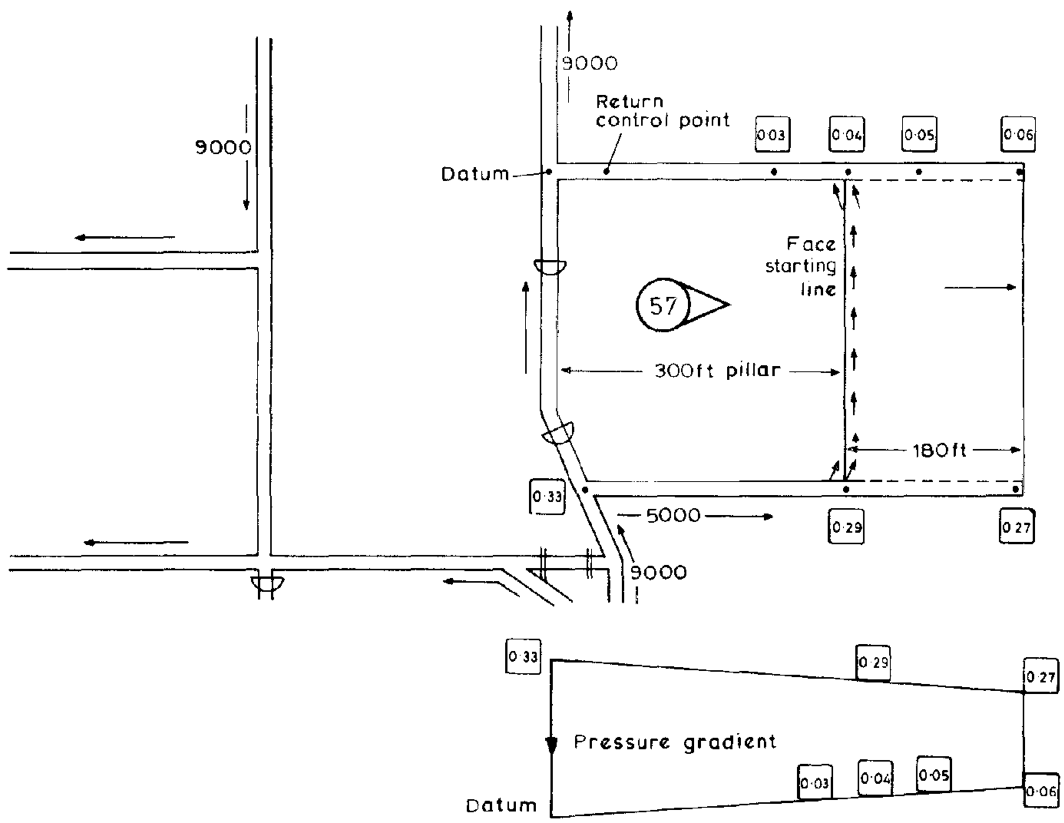
S.B.L.	Feb. 78	647 / 47

57's DISTRICT

PRESSURE DISTRIBUTION BEFORE INSTALLATION OF PRESSURE CHAMBER



Ventilation pressure in lb / ft² .... 0·04

Air quantity in ft³/min .... —9000→

Day No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
C.O. P.P.M.	12	11	12	12	11	–	13	14	10	10	–	125	115	29	25	22	22	20	20	18	16	16
CO/O_2 def Ratio	·25	·27	·20	·24	·23	·24	·24	·24	·24	·22	··	1·28	1·48	·36	·40	·37	·34	·33	·25	·28	·24	·25

RETURN CONTROL POINT SAMPLE RESULTS

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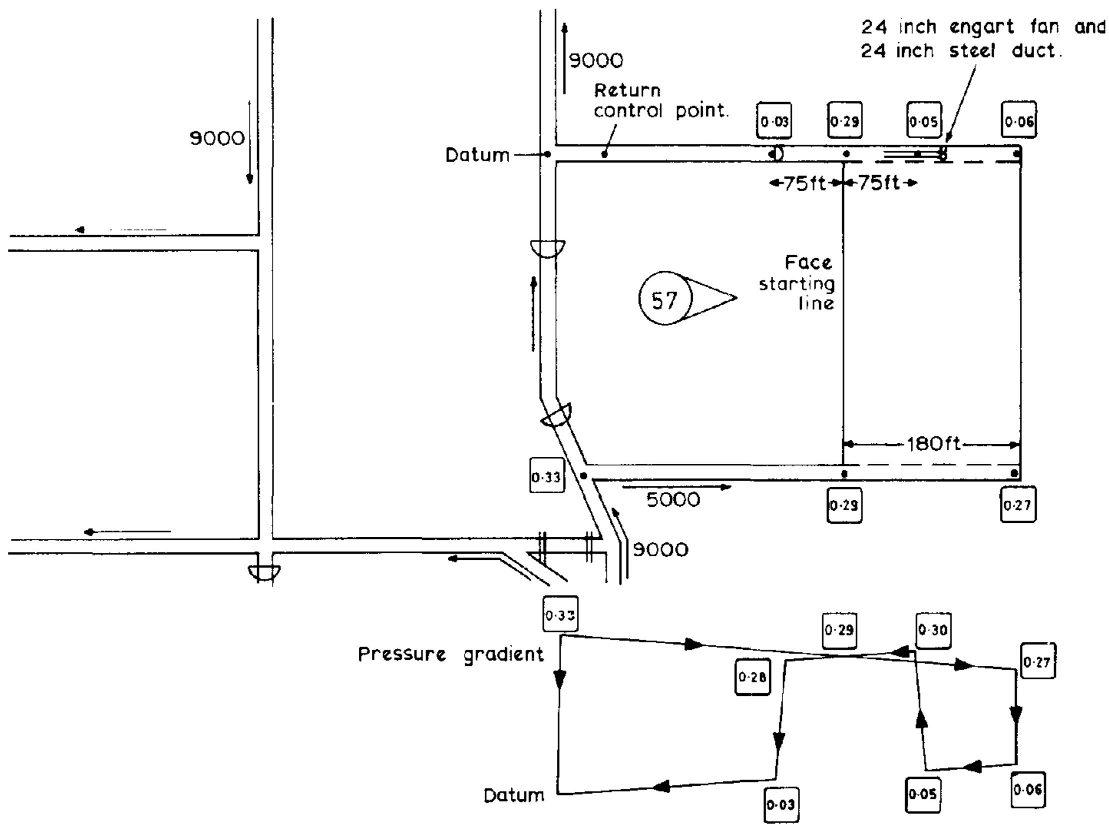
57's DISTRICT

PRESSURE DISTRIBUTION AFTER INSTALLATION OF PRESSURE CHAMBER



Ventilation pressure in lb/ft² .... 0·29

Air quantity in ft³/min .... 9000 ⟶

Day No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
C.O. P.P.M.	12	11	12	12	11	—	13	14	10	10	—	125	115	29	25	22	22	20	20	18	16	16
CO/O_2 def. Ratio	.25	.27	.20	.24	.23	.24	.24	.24	.24	.22	—	1.28	1.48	.36	.40	.37	.34	.33	.25	28	.24	.25

RETURN CONTROL POINTS SAMPLE RESULTS

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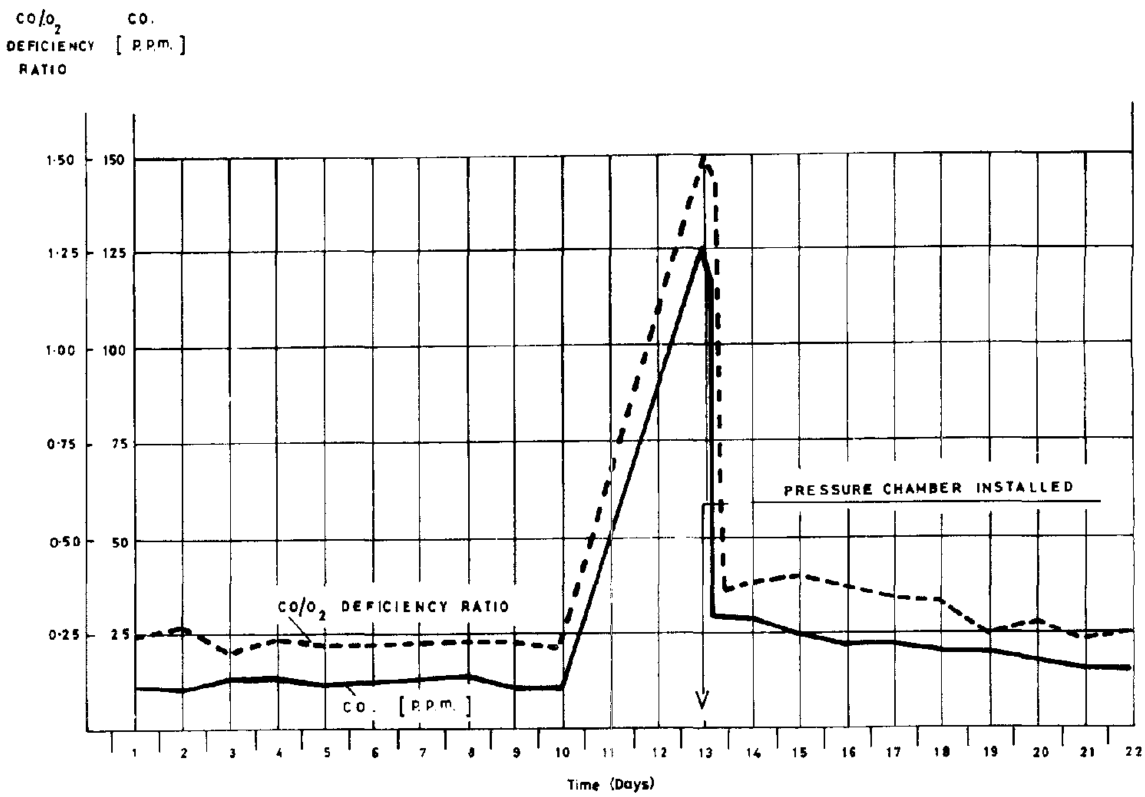
Eng'r.	Date.	Drg. No.
S.B.L.	Feb. 78	647/49

57'S RETURN CONTROL POINT



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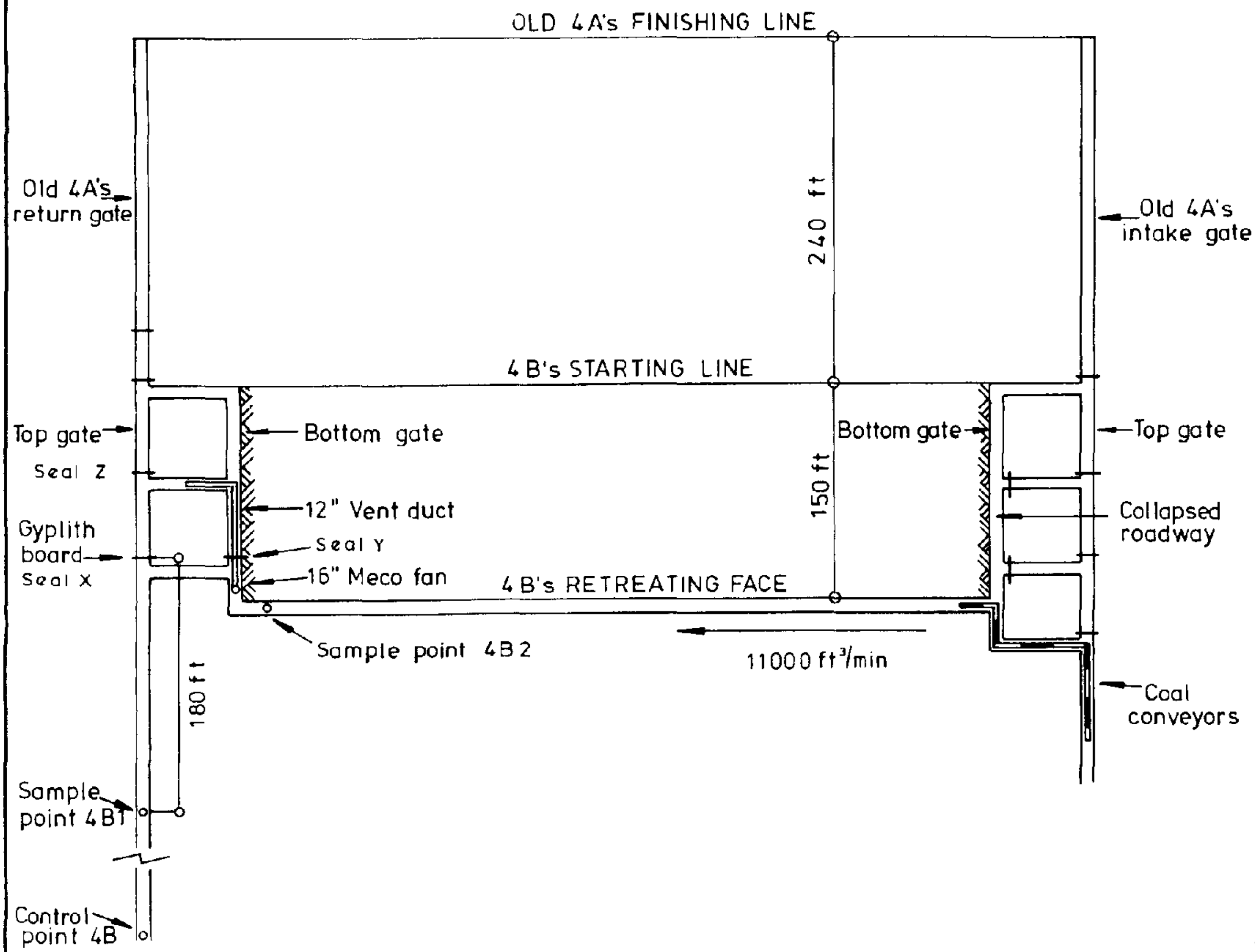
Eng'r. S.B.L.	Date Jan. 78	Drg. No. 647/50

4B's HEATING-DIAGRAM TO ILLUSTRATE VENTILATION ARRANGEMENTS



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London

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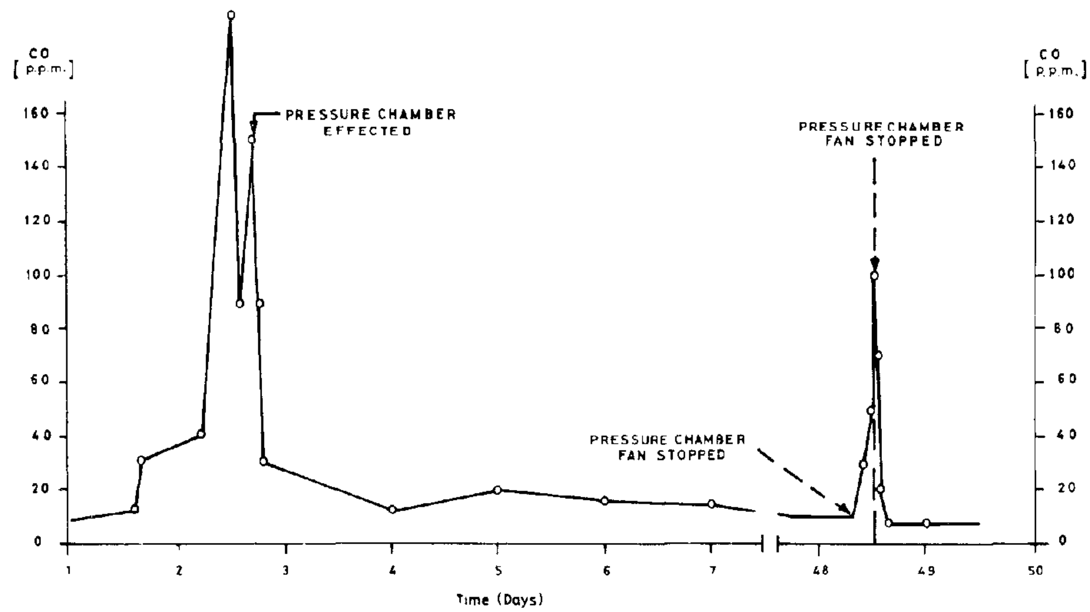
4B's HEATING-CO p.p.m. READING AT 4B's SAMPLE POINT



P D-N C B Consultants Ltd., London.		
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