MINE MONITORING FOR SAFETY AND HEALTH

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PREFACE

In 1994, as a prelude to privatisation, the British Coal Corporation closed its Technical Services and Research Executive (TSRE). This brought to an end a forty-seven year period during which Britain's state owned coal industry had carried out its own research into mining related problems.

The amounts of money spent had been huge. For example, in one arbitrarily chosen year, 1988/9, it was £16m (1). Whilst some went on projects that had a direct impact on the productivity of mines, for example the development of improved coal getting machines, some was also spent on more philanthropic activities. Examples included investigations of the underground environment and its impact on the safety and health of miners. As part of these studies many new and improved instruments were produced for the assessment of atmospheric 'pollutants'. For the purposes of this monograph all such devices will be called 'environmental instruments', or 'environmental monitors'.

In 1974 I joined an expanding team of physicists at the NCB's Mining Research and Development Establishment (later to become TSRE) to work on environmental monitor development. Some twenty years later, when redundancy occurred, I felt the need to look back at what I had done and to ask why and so what? Only when these ghosts had been exorcised would I be able to move forward with confidence to a new and exciting career.

This monograph is the result of my research. In it an attempt is made to answer a number of questions:

* What underground environmental factors have an adverse impact on the safety and health of coal miners?
* How were these hazards discovered, investigated and controlled?
* What influence did the availability of appropriate monitoring instrumentation have on this process?
* Were there any underground environmental hazards that required (in 1994) continued research into their control and monitoring?
* Were there (in 1994) any environmental monitoring or control procedures that could be relaxed?

Before considering the history of environmental hazards in coal mines, this monograph begins with chapters containing general background information for the discussions that follow; Chapter 1 looks at the attitudes of colliery management and governments towards underground safety and health and how they affected the introduction of hazard control measures; Chapter 2 outlines the development of mining technology, showing how it led to the appearance of new pollutants and sources of danger. Environmental hazard control has frequently been achieved by ventilating the workings. Chapter 3 contains a brief review of technology applied.

Following these general reviews are chapters that consider the identified hazards. These include: Blackdamp - Chapter 4, Firedamp - Chapter 5, Gaseous products of explosions and fires - Chapter 6, Shot firing - Chapter 7, Diesel engines - Chapter 8, Respirable dust - Chapter 9, Ionising radiation - Chapter 10, Heat and humidity - Chapter 11, Lighting - Chapter 12, Noise - Chapter 13. Answers to the questions identified above are given as a set of general conclusions in Chapter 14.

Although falls of ground have been a major danger underground, they are usually considered a 'geological' hazard rather than environmental. Consequently the subject has not been reviewed in this monograph.

I D Unwin
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Reference

1. British Coal Corporation. Report and Accounts 1988/89.

Chapter 1 The management of the environment and safety and health in coal mines

In Roman times, men working below ground experienced hazardous environments created by the presence of noxious gases. In response, they developed monitoring and control techniques, as evident from Agricola (1). He reports that in the first century AD Pliny had noted that 'aluminous or sulphurous fumes dangerous to diggers' sometimes occurred in wells. They were detected by observing the behaviour of a dog or lighted candle when lowered down the shaft. They were removed by directing a current of fresh air into the workings. That is through the application of ventilation.

In Britain, the first coal mines were formed from shallow pits dug into seams exposed at the surface. Sometimes the air in these workings became so stagnant that men could not breathe and candles would not burn. Such conditions were said to be caused by the presence of a gas given the descriptive names 'chokedamp' or 'blackdamp'. The danger this gas has represented to miners is discussed in Chapter 4.

By the seventeenth century a rising demand for coal had resulted in the construction in Britain of relatively large mines. In some places two shafts were sunk, linked underground by the workings. As described in Chapter 3, such an arrangement could lead to the spontaneous flow of a current of air. This reduced the likelihood that blackdamp would appear.

From about the middle of the seventeenth century the presence of another gas began to be noted in some of the deeper coal mines. Rather than preventing candles from burning, it caused their flames to grow. Sometimes violent explosions occurred, leading to massive devastation underground and large loss of life. Given the name 'firedamp', the danger this gas has represented to coal miners is considered in Chapter 5.

A feature of the early blackdamp hazard was that if its appearance did lead to any fatalities, they tended to be few in numbers. Further, there was no structural damage caused to the mine. Consequently the events were rarely noted outside the immediate locality. Explosions of firedamp, on the other hand, were very different. By the beginning of the eighteenth century the devastation being caused was sufficiently newsworthy for descriptions to begin appearing on a wide scale. This early bias in the reporting of mining accidents towards explosions eventually led to the widely held theory that such events were the main danger in coal mining. It was not until after 1850 that the fallacy of this view was demonstrated and other hazards, such as falls of ground, demonstrated as causing greater loss of life amongst underground workers.

Irrespective of its danger relative to other hazards, by the late eighteenth century explosions of firedamp were killing a large number of coal miners. Faced with this fact some colliery owners simply chose to ignore it. Alternatively, others took a more proactive approach, voluntarily instigating explosion prevention measures. These either involved the use of ventilation to dilute the flammable gas with fresh air, or attempting to remove all potential sources of ignition from the underground workings. As described in Chapter 12, the latter primarily led to the replacement of naked flames used to illuminate the workings with safer alternatives.

Despite this early application of firedamp explosion prevention measures, they continued to kill miners. In one horrific accident ninety-two men and boys died at Felling Colliery near Gateshead-on-Tyne in 1812. A local parson, the Reverend Hodgson, was so affected that he set about publishing the circumstances behind the incident. This was done 'contrary to the feelings of the coal owners' (2). On seeing the details, a London barrister named Wilkinson suggested that a society be formed with a view to preventing anything similar from occurring in the future. The first meeting of the Sunderland Society was held on 1 October 1813.

One of the communications received by the Sunderland Society was from the eminent mining engineer John Buddle. His view was (3) that the application of even the best mine ventilating techniques then available would not remove the danger from firedamp. Instead, he felt that the only alternative was to change the gas chemically such that it was harmless in the presence of naked flames. In saying this, Buddle was probably referring to an idea due to a Dr Trotter in 1805. He claimed that the explosive power of firedamp could be removed by 'fumigating' the workings with oxymuriatic gas. That the Society accepted this view is indicated by the fact that they subsequently approached the eminent chemist Sir

Humphrey Davy for help. Around 1810 he had conducted an extensive study of the properties of oxymuriatic gas and shown it to be chlorine (4).

As Buddle had done, Davy also seems to have given due consideration to the ideas of Trotter. In a report of his studies (5) it is noted how he looked for a room temperature reaction between chlorine and firedamp. He found none. During subsequent research, Davy observed, as others had done before (6), that explosions would not propagate through long narrow tubes. He also found that they would not pass through fine wire sieves or gauzes either. So, rather than change the properties of firedamp, from these findings Davy was able to produce an enclosure for a naked flame that made it incapable of igniting an explosive concentration of gas that may appear in the surroundings. This led to the now famous 'Davy flame safety lamp'. It went into production in 1816. Considering its work done, the Sunderland Society disbanded itself.

At almost exactly the same time, the mining engineer George Stephenson produced his own flame safety lamp. Operating on similar principles to Davy's, the early versions included long thin tubes to provide the protection from explosions. Gauze was used later.

Soon after they had been developed, both the Davy and Stephenson safety lamps had become very popular with colliery operators. However, despite their undoubted safety relative to naked flames in flammable atmospheres, the number of explosions continued to rise. It is alleged (7) that some owners tried to hide this fact by preventing the publication of reports of accidents. Further, the Government was reluctant interfere in the matter and play any part in attempting to make coal mines safer for those employed underground.

Attitudes began to change in 1834 when the MP for South Durham, a Mr Peace, introduced a petition before Parliament requesting that action be taken over the number of accidents in coal mines. In response the House of Commons set up a select committee to study the problem. Although the report (8), published in 1835, made no recommendations as to how accidents in coal mines could be avoided with certainty, it did suggest they should be reported to the Home Secretary. No immediate action in this respect was taken.

Over the next four years there were about three hundred coal mining fatalities and nothing was seemingly done to prevent even more from occurring.

In June 1839 fifty-two men and boys were killed in an explosion at St Hilda Colliery, County Durham. A member of the local community, a wine merchant named James Mather, was so moved that he suggested that a committee be formed to study the prevention of accidents in coal mines. The resulting group was called the South Shields Committee.

As a review of coal mining practices and safety, the report subsequently published (9) was a classic. In it the authors stressed the importance of maintaining good ventilation standards. Also, they made a point of suggesting that scientific instruments such as anemometers, barometers and thermometers could be usefully employed underground as aids to safety. Unfortunately it seems that comments such as these were largely ignored by the coal mining industry.

According to Galloway (2), up to the 1830's the more devastating colliery accidents tended to occur around Newcastle upon Tyne and Durham whereas after they became more widespread. He believes that this fact 'encouraged' the Government to begin taking a greater interest in coal mine safety than hitherto. Ignoring any debate over the validity of this view, from 1845 onwards they did commission numerous official investigations into the subject. These revealed that whilst the safety standards applied in areas such as the North East of England were the best possible given the level of knowledge available, in other areas they were not. Further, within those mines in which standards were low many operators seemed unwilling to make any improvements. Consequently it became apparent that the only way of getting majority acceptance of 'best mining practice', particularly from a safety point of view, was to introduce legislation governing underground operations.

The first Coal Mines Act of this kind was passed in 1850. This created a Mines Inspectorate with powers to enter any workings and draw the attention of the manager to any dangerous conditions found therein. Also, the Act required that all fatal accidents be reported to the Home Office within twenty-four hours of occurring.

Although the 1850 Act was not particularly far reaching, the requirement that accidents be reported was an important aid to their reduction in coal mines. To see why, it is necessary to briefly detail the mechanism by which a system, including underground environmental hazards, can be controlled. This is a five stage process (10):

i) Set a performance target;

ii) Measure the actual system performance;

iii) Compare the actual performance against the target;

iv) Interpret any discrepancies;

v) Devise and then apply appropriate remedial measures.

In the present context, target (i) is zero deaths, injuries or cases of industrial disease, the actual performance (ii) the number occurring, and the remedial measures (v) the safety measures adopted.

If the actual performance assessments in the control mechanism are in error the remedial measures adopted as a result may be inappropriate, or a major hazard remain uncontrolled. An example of this is firedamp and its relative importance to other mining hazards.

It has already been noted how a bias in the collection of early accident data led to the widely held view that explosions of firedamp resulted in more coal mine deaths than any other single cause. Data that became available after the passing of the 1850 Act, with its requirement that accidents be reported to the Home Office, revealed that this was not the case. For example, between 1875 and 1885, only about 23% of the 12,315 recorded deaths were due to explosions. Of the remainder by far the greater proportion, about 41% of the total, were caused by falls of ground (11). This does not mean that steps taken to limit the numbers of underground explosions were inappropriate, since such incidents were claiming many hundreds of lives. However, with incomplete accident data being collected, other potentially serious hazards had the potential for being overlooked or ignored. Blackdamp is a case in point. As will be described in Chapter 4, this was often a problem in mines left unventilated because they did not contain firedamp.

An attempt at actually trying to reduce the number of coal mining accidents by more than just collecting data was made with the introduction of the 1855 Coal Mines Act. This made it a requirement that all collieries adopt a general safety code along with an approved set of ‘special rules’ designed for the local conditions. The latter largely incorporated ‘best mining practice’ from the North East coal field around Newcastle-upon-Tyne and Durham.

Not all colliery operators appreciated this interference in what they saw as exclusively their affairs. Many were outwardly hostile to the idea. In two areas, North and South Staffordshire, defence committees were set up during the 1860’s to protect their members from prosecution (12).

In other areas the attitudes were more positive. Instead of forming societies to fight the legislation, institutes were formed to discuss common problems. One of the earliest, dating from 1852, was the ‘North of England Society for the prevention of accidents and for other purposes connected with mining’. In subsequent years similar groups appeared in other districts. In 1889 they were federated to form the Institution of Mining Engineers. Besides acting as a forum for discussion this new grouping sponsored research. Its results were published in transactions.

The Institution of Mining Engineers was not the only group formed from the mid-nineteenth century onwards that had an interest in the study of mining problems. Others included: mining universities and colleges (Royal School of Mines, London opened 1850); colliery owners’ associations (Mining Association of Great Britain founded in 1854, began sponsoring research 1908); the Safety in Mines Research Board (SMRB) (set up by the Government in 1921). In addition, a few colliery companies conducted research in their own laboratories, although these were more typically used for carrying out routine scientific work, such as mine air gas analysis.

Despite the existence of a large number of organisations with interests in coal mining research, as late as 1945 doubts were expressed as to the value of their efforts. For example, Reid notes (13) that many coal owners financed work for commercial reasons, keeping the results to themselves rather than publishing it for the benefit of all. Even the information that did enter the public domain was only likely to be noted by the few who attended the presentations (14). The result was that the activities undertaken were not leading to as large a general improvement in the conditions underground as might have been expected or desired.

Although the research carried out in the pre-1945 era may not have had as large an impact on underground safety as desired, it will be evident from the discussions that follow that there was an increasing awareness of the problems and dangers associated with coal mining. It is not unreasonable to suggest that this was due to the existence of the groups listed above and the work they carried out. The result was the introduction of increasingly stringent legislation, some clauses of which were related to the health and safety of those employed underground.

At colliery level it was the responsibility of the manager and his deputies to ensure compliance with the law. This required that they provide themselves with level data on the parameters that defined the hazard the rules were intended to combat. Until relatively recently, such could only be obtained by sending men underground with hand held instruments to take ‘spot’ measurements. Typically, this was done once or twice a working shift. However, many of the parameters under consideration were known to change significantly over a relatively short period of time. Consequently, it was often difficult to obtain accurate hazard assessments by this means, making the appropriateness of any subsequently adopted control measures uncertain. Unfortunately, there were frequently no alternatives to the adoption of this methodology.

Despite an increasing awareness of the environmental dangers associated with coal mining, even during the early decades of this century, some managers operated their collieries with a complete disregarded for the safety of their employees. Even the presence of the legislation failed to make any difference. Its requirements were simply ignored. Consequently, the potential for disaster was very real as evident from the worst accident in British coal mining history. This was an explosion that occurred at Senghyndd Colliery, near Pontypridd in South Wales on 14 October 1913. In total, 439 persons were killed. The subsequent enquiry revealed that before the accident happened there had been around fourteen breaches of the regulations, most of which were intended to prevent such an occurrence (15).

During debates on safety and health in coal mines that followed the Senghyndd and other similar disasters, some of the Labour Party felt that the only way of improving matters was to nationalise the coal industry. Despite objections from the coal owners, this occurred on 1 January 1947 with the formation of the National Coal Board (NCB). Significantly, a statement was included in the associated Act of Parliament that the Board was to carry out its duties of mining coal with due regard to the safety, health and welfare of persons in their employment.

Within the NCB, the coal mines in Britain were collected into forty-eight ‘areas’. These were grouped into eight ‘divisions’, each with its own management board. In pursuance of its health and safety responsibilities, the NCB:

* Set up a standing committee to consider safety and health within the industry;
* Set up a network of area, division and colliery safety officers;
* Set up a comprehensive health service headed by the Chief Medical Officer;
* Created a network of scientific laboratories to provide a service to collieries in respect of, for example, statutory mine air analyses and lamp testing.

From the NCB’s first annual report in 1947 (16), the coal mining industry was paying out about £10 million annually as compensation to victims of accidents and industrial diseases. Thus it is not surprising that rapid consideration was given to ways in which this drain on financial resources could be reduced. The work was to be undertaken by an NCB operated research function. Initially this was located at the Coal Research Establishment (CRE). This was established in 1948 near Cheltenham. Within a few years expansion had led to the additional creation of the Mining Research Establishment (MRE) near London. In 1969, MRE was merged with the NCB’s Central Engineering Establishment (CEE), near Burton upon Trent, Staffordshire to form the Mining Research and Development Establishment (MRDE). Subsequent contraction of the coal industry resulted in name changes, first to the Headquarters Technical

Department (HQTD) and latterly to Technical Services and Research Executive (TSRE). This was closed in April 1994.

On the Government's side, the responsibility for conducting research into safety and health in coal mines was delegated to the Safety in Mines Research Establishment (SMRE). This was formed from the SMRB. It worked with the Mines Inspectorate.

Under the pre-nationalised coal industry doubts had been raised over the relevance of some of the research undertaken and the ability of the industry as a whole to make best use of its results. With the new national organisation, programs of investigation could be formulated using data from every colliery in Britain, irrespective of who had owned it previously. Further, reports of results could be passed back down the integrated management chain to those with operational responsibilities.

Despite potential improvements in the efficiency with which research data could be transferred from source to user, in the immediate post nationalisation period the bulk of the underground environmental state information fed to mine management still came from men taking spot measurements. In many cases the instruments and methodologies used were virtually identical to those from nearly a century earlier. Whilst these may have been adequate to ensure compliance with the law, since this tended to be formulated to incorporate existing assessment methodologies to minimise the potential for avoidance, the results were not always ideal for use in the effective control of mining hazards. Some of these could appear extremely rapidly. Instead, systems were required that provided continuous readings of the significant hazard variables at a central location on the surface. Such information would enable any rapidly developing underground dangers to be promptly identified and appropriate control measures applied, possibly before a critical situation had arisen that necessitated the halting of coal production.

Recognising facts such as these, by the middle 1950's the NCB was considering the development of schemes that improved underground information collection. This was to be achieved through the application of multiplexed data transmission systems. Further, it was found that the same ideas had the benefit of reducing operating costs through manpower savings (17). They also removed the need to send men into potentially dangerous conditions to take spot measurements.

The first such data transmission system applied in coal mines was called ELSIE (Electronic Signalling and Indicating Equipment). Introduced in 1957, it could transmit the status of switches controlling underground plant to indicators in a central control room on the surface. Although the early versions were primarily used with coal cutters and conveyors, safety devices were included later. Early examples were air flow switches designed to show the continuity of the underground ventilation, the primary method of controlling underground pollutant levels.

A major limitation of ELSIE in the control of environmental hazards was its inability to transmit continuously varying analogue signals. However, even had it had this capability there were simply no reliable monitoring instruments that could have been used with it. Recognising both these shortcomings, from the 1960's onwards MRE and its successor organisations carried out an extensive environmental monitoring development program. As seen from the chapters that follow, the results included a range of continuously operating instruments for permanent installation underground. Also, new portable devices for taking spot readings of pollutant levels were also produced.

Since ELSIE could not be used, the analogue state signals from each of the new monitoring instruments installed underground were transmitted to indicators on the surface of the mine via a pair of wires. However, it was found that with large systems too much data was being provided. This made it difficult for officials to fully appreciate the actual state of a mine's environment and consequently determine the best control measures to be applied in response to a given set of conditions.

A solution was provided by the development at MRDE of a computer based monitoring and control system called 'MINOS' (MINe Operating System). Originally designed for the automated operation of conveyor belt systems, by 1975 versions were available to collect underground environmental data and to display an analysis of it on the surface. This was done by connecting the analogue outputs from groups of monitors to local 'out-stations'. These sequentially converted the sensed signals into a digital format for multiplexed transmission along a data highway to the surface. Here the received information was fed into a computer for analysis and display on a VDU. This was normally placed in a continuously manned colliery control room. Each of the instrument readings could be connected to an alarm unit that operated when it fell outside a pre-set range. To ensure rapid and correct response when officials were not present, operator action messages could be presented on the screen. Also available from MINOS were summary displays that highlighted trends in significant environmental variables. By this means officials were provided with data in a form that enabled them to make well informed and timely management decisions that maximised the effectiveness of the control measures subsequently applied to the environment.

By the time the British coal mining industry was once again put into private ownership, it had been provided with powerful systems capable of automatically monitoring the state of the underground environment. This meant that hazard assessments could be made without necessarily having to put the lives of men at risk during the taking of measurements. Attitudes of mine management towards the safety and health of workers also seem to have improved. It is postulated that a reduction in the ambiguity of the law and the consequential increased risk of successful prosecution by the injured parties and the Government's Health and Safety Executive may have been an influence on this.

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Chapter 2 Coal mining technology

This chapter reviews the technical development of the coal mines, including the shape and size of the underground workings and the ways mineral has been extracted and transported to pit bottom.

2.1 The shape and size of mines

Coal has been used in Britain since Roman times. Then it was simply gathered from the surface. By the twelfth century it was being excavated, by either tunnelling into seams exposed on the side of hills or by digging shallow 'bell' pits. Workings with two entrances were in existence by the fourteenth century. Here one arrangement consisted of a near horizontal gallery, or adit, driven into the side of a hill to intersect with a vertical shaft, or pit. It seems reasonable to suggest that when a coal seam accessed by this arrangement was worked out new reserves were found by digging in the bottom of the pit. Once located, tunnels would then be driven back towards a second but very much shallower shaft sunk close to the mouth of the old adit. By this method a mine would consist of two shafts, one deeper than the other. The significance of this as regards the provision of a ventilating current of air through the workings is outlined in Chapter 3.

Data showing how the depth of coal mines has varied is provided by Galloway (1). He states that at the start of the eighteenth century most pits in the North East of England were between 120 and 180 ft (37 and 55 m) deep. During the 1760's, Walker-on-Tyne Pit reached 600 ft (183 m), in 1782 Hebburn Colliery 775 ft (236 m), and in 1843 Hutton Pit 1460 ft (444 m). Later the deepest mines were around Manchester; in 1858 Astley Deep Pit, Dunkinfield, was at 2100 ft (640 m), and in 1869 Rosenbridge was at 2500 ft (746 m). In the 1990's British coal mines were between about 300 and 920 m deep.

The working of ever deeper seams had a number of impacts on the working environment underground. These included the appearance of firedamp, the effects of which are described in Chapter 5. Also, the workings got hotter due to a rise in the natural temperature of the strata. The effects this had on the safety and health of those employed underground are considered in Chapter 11.

The shallow pits of the seventeenth and eighteenth centuries were small. Mineral extraction started near the shafts and gradually moved outwards. When the cost of underground haulage became too expensive, or the ventilating current incapable of removing any firedamp that appeared, another shaft was sunk. Typical shaft to shaft distances were between 90 and 180 m.

During the nineteenth century there was a dramatic rise in the demand for coal. In response the size of the coal industry increased rapidly; in 1831 it employed 109,300 men (2), by 1913 it was over a million. To create sufficient underground work places meant that either new shafts had to be sunk, or the size of existing mines increased. Since the former option was slow to implement, the latter was frequently adopted. To give an idea as to the consequences in terms of mine layout, it is stated (3) that in 1812 Killingworth Colliery near Newcastle upon Tyne had 160 miles (256 km) of 'galleried workings'. The impact such road lengths had on the ventilation of the mines is discussed in Chapter 3.

Between 1913 and the mid-1940's the demand for coal fell by about 30%. Also, there was considerable debate as to the merits of nationalising the industry. The consequence was that the owners were reluctant to invest in the redevelopment and modernisation of their collieries. So by the end of this period many coal faces were large distances from the pit bottom. They were also at the end of old, narrow and undulating interconnecting roadways (4). Such arrangements would have led to relatively high day to day transportation and ventilating costs.

The existence of mines with long and narrow pit bottom to face roadways also made it difficult to increase output in times of high demand. The effects of this became evident when, during the winter of 1947 to 48, resulting fuel shortages led to a wholesale disruption of British industry. In an attempt to prevent this from recurring, the Government, which now had control of the mines following nationalisation, initiated a program of colliery reconstruction (5). Primarily this involved increasing the use of underground machinery to cut the coal and then transport it away from the face. To maximise the benefits from these changes, the quality of the underground roadways needed to be improved. Typically this involved making them larger and straighter. The former was to allow for higher ventilation rates necessary to counteract any increases in the firedamp concentration associated with the anticipated higher coal outputs. Straight roads were required for the new haulage systems, notably locomotives and conveyor belts (see Section 2.4). These could not operate efficiently in the presence of sharp curves and uneven gradients.

Since 1956, under pressure from other fuels, sales of coal in the United Kingdom have continued a decline begun in 1913. Initial attempts at reducing the rate of fall involved accelerating the pace of mechanisation of mines. This was seen as a means of cutting costs through increased productivity. An indication of the improvements achieved can be obtained from output per man shift (OMS) figures. In 1950 this stood at 1.23 tonnes. By the time the benefits of mechanisation were being realised, 1970/71, the corresponding figure was 2.24 tonnes (6). However, this rate of improvement was not maintained. In an attempt to change this, the levels of colliery automation were increased. This led to the development and introduction of the MINOS system mentioned Chapter 1. The benefits of this approach are indicated by the fact that by 1992/93 the output per man shift had risen to 6.34 tonnes.

Figures from 1995, the time of privatisation, show that a single colliery employed about 15% fewer men than it did on nationalisation in 1947, but produced 6.3 times as much coal. The attainment of such a large improvement was associated with considerable changes to the way mines were laid out. Whilst the coal faces were further from pit bottom, the interconnecting roadways were straighter and larger.

2.2 Sinking shafts and driving roadways

Coal concealed below the surface cannot be extracted without sinking shafts and driving access tunnels through other rocks. These may be relatively hard and some proved difficult for early miners to penetrate using the available hand tools. Under these conditions a technique called ‘fire setting’ was sometime used. Here, pieces of wood and other combustible material were placed against the rock face and set alight. When the ground had heated up the flames were rapidly doused. The resulting thermal stresses fractured the rock, making it easier to remove. Disadvantages with this method included its slowness and the fact that the fire consumed the oxygen in the workings. The safety and health implications of this are described in Chapter 4.

A faster method of breaking ground was to use explosives. Gunpowder was being used in British coal mines by the mid-eighteenth century. Later, more powerful explosives became available. In 1913, nearly forty-nine million shots were fired (7). The impact such activities can have on the underground working environment is described in Chapter 7.

To break ground, explosive charges are placed down holes in the strata. Originally these were drilled using hand tools, but by the last quarter of the nineteenth century compressed air and electric drills had been developed. Unlike their predecessors, these operated at high speeds and produced clouds of fine dust. The impact this had on the health of miners is described in Chapter 9.

In recent years the use of explosives in coal mines has declined. In part this has been due to the development of machines capable of cutting through hard rock. However, these have their own environmental impact, particularly concerning the heat, dust and noise they create.

2.3 Extracting coal

The most commonly used layouts of the ‘faces’ at which coal is removed from the solid have been called ‘short wall’, or ‘pillar and stall’, and ‘long wall’.

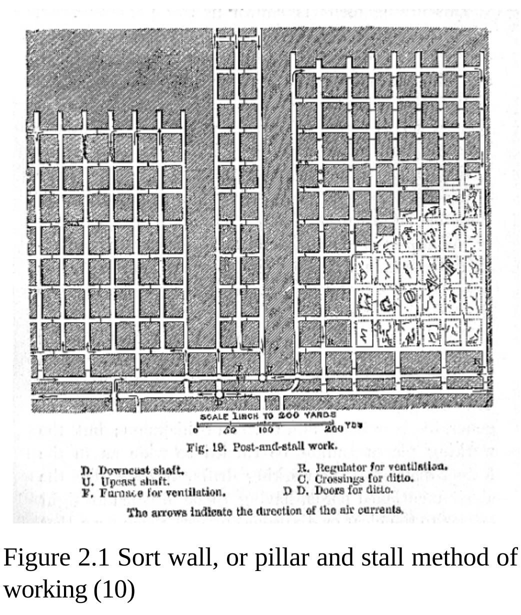

Figure 2.1 Sort wall, or pillar and stall method of working (10)

A diagram showing the short wall method of working is given as Figure 2.1. In this system the working area is criss-crossed with a network of intersecting roadways driven within the seam. This laves pillars supporting the roof. Historically these were up to twenty metres wide. Later the pillars are removed allowing the roof to collapse and form a 'goaf', or 'waste'.

The layout of a mine worked using the long wall system is given as Figure 2.2. When this monograph was first produced, in 1994, it was the most widely used method of working deep coal. In this system only two roads or 'gates' are driven into the area of coal to be extracted. Roughly parallel, they could be several hundred meters apart. The face is a straight tunnel linking their ends to form a 'U' shaped pattern. After the coal has been extracted, the roof supports on the face are moved forward, allowing the strata to collapse behind and form a waste.

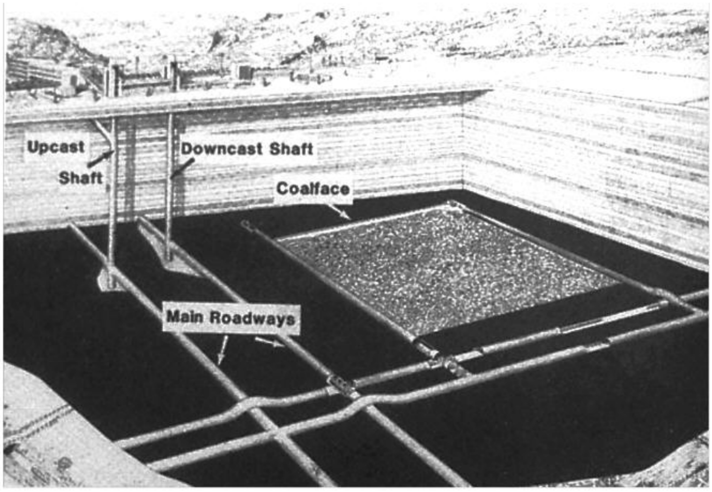

Figure 2.2 The long wall system of mining (copyright British Coal)

Prior to about 1960, the typical method of breaking coal from the solid on a face involved cutting a deep horizontal slot at floor level along its length. The unsupported mass was then broken down with wedges or explosives, as shown in Figure 2.3. Before about 1850, the 'undercut' was made using pick axes. Later, machines were used in increasing numbers.

Once broken down, in 'primitive' mines the coal was hand loaded on to sledges for removal from the face. Later tubs running on edge rails were introduced. Both were moved using muscle power be it human or animal. Between 1900 and about 1910 mechanised conveyor belts began to be installed on faces for coal clearance (8).

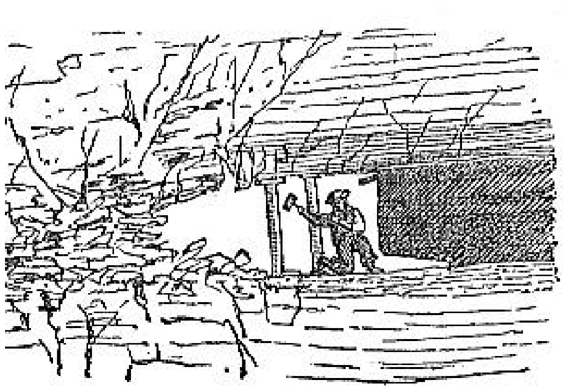

Figure 2.3 Breaking coal from the solid (10)

In 1913 only about 8% of the United Kingdom coal output was cut and hauled by machines. By 1935 it was still only 47% (7). During the post-nationalisation reconstruction of the coal industry the pace of change was accelerated with the result that by 1972 over 90% of the output from British coal mines was won by machines.

Factors that influenced the post-war pace of mechanisation were the introduction in 1952 of the Anderton shearer and the Anderson Boyes trepanner. Rather than undercutting the seam for later breaking down and loading by hand, in a single pass these two machines removed a face high strip of coal from the solid and loaded it onto a moving conveyor. Made from steel, this ran the whole length of the face and acted as a track along which the 'cutter-loader', an example of which is shown in Figure 2.4, travelled. Typically, early installations were rated at around 37 kW. Modern machines, principally developments of the Anderton shearer, are over ten times as powerful, an increase that is perhaps reflected in the improved productivity figures given earlier. Unfortunately such changes have not been without their environmental impact, notably from increases in the makes of firedamp, dust, heat and noise. The effects such pollutants can have on the safety and health of underground workers are considered in Chapters 5, 9, 11 and 13.

During the latter half of the 1950's the NCB began considering the possibility of introducing automatic coal mining systems underground. Two were subsequently developed, the Collins miner and the Remotely Operated Long Wall Face (ROLF). Neither proved successful, with trials being terminated in 1965 and 1971 respectively (8)(9). Despite their early demise, some of the environmental instruments developed for use with them found application in later monitoring systems, particularly in respect of firedamp.

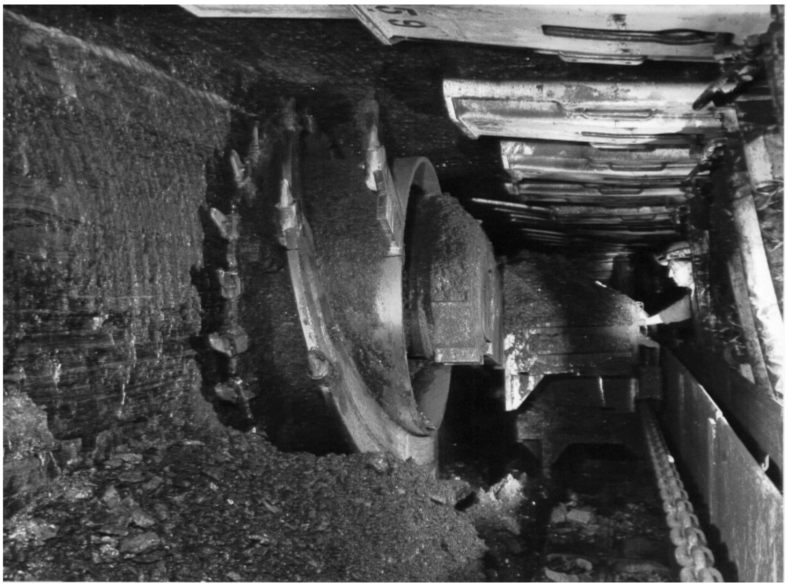

Figure 2.4 Cutter-loader (copyright National Coal Board)

2.4 Haulage and transport

Once cut, the coal must be transported from the face to the bottom of one of the shafts. Up to the early eighteenth century this was done using baskets, sledges, or wheel barrows. By 1790, railways made from cast iron had made an appearance. These made it easier to move the material about, thereby reducing the cost of haulage and making larger workings more economical. In the majority of cases muscle power was the prime-mover.

Rope haulages were introduced underground in coal mines for transport purposes in about 1870. Formed from strings of tubs clipped to a motor driven loop of wire rope, such systems were being used for coal clearance up to about the middle of this century. However, by this time they were considered antiquated and inefficient. As a result, one of the activities included in the post-nationalisation reconstruction of the coal industry was their replacement with more efficient alternatives. These included tracked diesel and battery locomotives and conveyor belts.

Tracked locomotives powered by diesel engines were first used underground in British coal mines in 1937. During the post-war reconstruction of the industry there was a rapid extension of their application. As an illustration, between 1945 and 1949 the number of underground diesels increased over four times. After 1965 the usage declined, due to a reduction in the number of mines and an increased use of conveyors to move coal from the face to pit bottom.

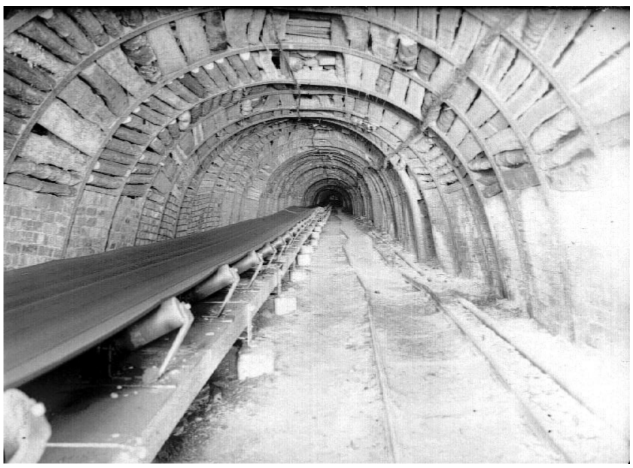

Figure 2.5 Underground conveyor belt (copyright National Coal Board)

During the late 1970's diesel powered free steered vehicles were introduced into British coal mines. By 1984 over fifty units were being used to move general supplies underground. A discussion of the impact their use can have on the working environment is included in Chapter 8.

In modern mines, coal is primarily moved on electrically driven conveyor belts, an example of which is shown in Figure 2.5. Such systems were first introduced underground at the beginning of this century. However, as with locomotives, their use expanded rapidly after nationalisation. For example, in 1948 there was 1356 km of conveyor belts in use. By 1953 this had increased to 2692 km. A single modern mine may have up to 30 km underground. Originally the belts were made from vulcanised rubber on a cotton carcass. However, a number of fires, some of which are mentioned in Chapter 6, led to the development and application of fire resistant PVC alternatives.

2.5 The use of electricity

For much of the nineteenth century mining machines were driven by compressed air. Electricity was introduced on an experimental basis in 1885. By the turn of this century it was powering a wide range of machinery types including coal cutters, pumps and haulage engines. These operated from 500 to 600 V ac supplies and were rated at less than 50 kW. Modern coal mining electric motors may be rated at over 500 kW and operate at 3.3 kV ac. A discussion of the impact the underground use of high powered machinery has had on the working environment is contained in Chapter 11.

During the nineteenth century electrical systems operating at low dc voltages were also introduced underground. Examples included fixed signalling apparatus, portable electric lanterns and environmental instruments, typically firedamp detectors. The latter tended to incorporate fine sensing wires, and to avoid any need for signal amplification, sensitive indicating meters. This made them fragile and thus not particularly suitable for underground use.

Where a system did require some form of signal processing, initial reliance had to be placed on thermionic valves. To operate, these needed a high voltage electrical supply. As will be seen below, because of this if the apparatus was to be used in a coal mine where potentially flammable atmospheres could occur it had to be placed in an explosion proof container. These tended to be heavy and thus only suitable for fixed systems.

Beginning in about 1960 there was an ‘electrical revolution’ with the development and introduction of an ever increasing range of versatile semiconductor electronic components. Operating 10 V dc or less and drawing mA currents, they enabled complex and yet compact signal processing circuits to be produced. Applied to coal mining, they were incorporated in a wide range of mains and battery powered environmental monitoring instruments as well as other systems for underground use. The impact these have had on the safety and health of coal miners will become apparent from the chapters that follow.

One of the dangers of using electricity in coal mines is that ‘incendive’ sparks can be generated that are capable of igniting flammable concentrations of firedamp. This fact was recognised during the nineteenth century and led to the introduction of restrictions limiting the use of electricity underground. This included a program of equipment certification.

High voltage equipment for use in coal mines is generally certified ‘flame-proof’. With such apparatus it is accepted that incendive sparks will be produced during normal operation. However, should an internal explosion occur the equipment container is designed to prevent any flame from propagating into the general body mine atmosphere. This makes flame-proof enclosures very heavy and bulky. Thus they are not usually used to contain equipment intended to be portable.

Although considered safe initially, even low voltage systems for use in coal mines now have to be certified. Classed as ‘intrinsically safe’ systems, they include electronic components that ensure no incendive sparks can be generated. Enclosures for intrinsically safe circuits can be made from, for example, thin metal or conductive plastic. This makes them light and thus suitable for portable instrumentation.

Some of the factors that led to the development of the concepts of flame-proofing and intrinsic safety are described in Chapter 5.

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Chapter 3 The ventilation of coal mines

During normal mining operations contaminants are released into mine atmosphere that are potentially dangerous to humans. These include: blackdamp (see Chapter 4), firedamp (see Chapter 5), carbon monoxide and oxides of nitrogen (see Chapters 6, 7 and 8), dust (see Chapter 9), radioactive particulates (see Chapter 10), heat and moisture (see Chapter 11). In each case the danger they represent to the safety and health of underground employees can be reduced by ventilating the affected workings, thereby diluting them. Consequently, it is appropriate that this monograph contain a brief discussion of practices employed. The associated monitoring instruments are described in (1).

3.1 The provision of ventilation

The Romans ventilated wells and other pits during sinking to rid them of noxious gases that prevented men from working (2). Whilst the reason for their appearance may not have been understood, it was appreciated that they could be removed with fresh air.

Precisely when British miners began to recognise the need to ventilate underground workings is not clear. Certainly by about 1700 fresh air currents were being used in some places as a means of avoiding explosions of firedamp. Despite this evidence of an early understanding of the benefits to safety that could accrue from the application of ventilation, even into the middle of the nineteenth century there were seemingly a significant number of unventilated mines working. Why managers could display such a low disregarded for the lives of their workers has not been discovered, but it may have been a desire to minimise coal production costs.

In response to a rising number of colliery explosions, Parliament was eventually forced to intervene in the operation of coal mines. This was done through the introduction of regulatory laws. Regarding the provision of ventilation, that passed in 1855 contained the important clause that: ‘an adequate amount of ventilation shall be constantly produced at all collieries to dilute and render harmless noxious gases to such an extent as that the working places of the pits and levels of such collieries shall under ordinary circumstances be in a fit state for working’.

Although the ventilation requirements of the 1855 Act lacked any real power through its failure to define ‘adequate’, it did promote a considerable amount of discussion in the courts and learned institutes. This led to a wider appreciation and awareness of the environmental hazards underground. Since ventilation was seen as the primary means of controlling conditions, this led in turn to the scope of the appropriate regulations being extended. One notably example was the 1911 Coal Mines Act. As described in Chapters 4 and 5, responding to a series of scientific investigations this was able to define ‘adequate’ in terms of limiting concentrations of carbon dioxide, oxygen and firedamp. Developments of these provisions are contained in the current mining regulations.

Another important aspect of the 1911 Act was an acceptance that new mining hazards may appear subsequent to its publication. Rather than require its complete revision, a clause was included that allowed for the introduction of ‘general rules’. These could be designed to covering a very specific aspect of mining safety and health.

3.2 The production of ventilation

To ventilate their pits the Romans made use of bellows to suck the foul air out (2). At other times they sank a second shaft close to the first. The two were linked underground to provide a circulatory path for a ventilating current.

It has been found that when a mine is created with two unequal depth shafts connected underground by the workings, under certain circumstances a current of air can flow spontaneously between the two. One of these is when a temperature difference exists between the ground and the surface air. For example, during the summer the latter is likely to be the hotter. This means that the column of air in the deeper shaft is cooler and hence heavier than that in the shallow one. It is the difference in pressure generated across the interconnecting workings as a consequence that produces the ventilating current. In the winter the ground will be the warmer and the air flow direction is reversed.

In practice, ‘natural’ air currents were found to be notoriously weak, disappearing altogether when the surface air and ground temperatures were the same. By the middle of the seventeenth century they were being augmented by artificially heating the air in one of the shafts. Initially this was achieved by the use of a suspended basket of burning coals. During the nineteenth century a need for ever greater flows of air to combat firedamp was leading to the construction of large furnaces at the bottom of what was now being called the ‘upcast shaft’. The other shaft became known as the ‘downcast’.

Recognition of the dangers represented by the presence of furnaces underground led to the development of alternative means of generating ventilating currents. Eventually the surface mounted fan became the main air flow generator for coal mines. First used with any success in Britain in 1827, the early installations were driven by steam engines. Modern fans are driven at high speeds by electric motors.

According to Lupton (3) furnaces could generate pressure differences between the upcast and downcast shafts of up to 500 Pa. Modern fans are capable of developing pressures over an order of magnitude above this. This has enabled ever increasing quantities of air to be passed through mine workings. Whilst this should make mines safer, it can lead to increased levels of air leakage through the fractured strata. As described in Chapter 6, this may result in the occurrence of ‘spontaneous combustion’. These fires emit the toxic gas carbon monoxide.

Along with a main ventilator on the surface, circumstances sometimes occur whereby it is necessary to install ‘booster’ and other ‘auxiliary’ fans underground. The former are generally fixed and used to provide local increases in the ventilation pressure. Auxiliary systems are temporary arrangements used to ventilate single entry tunnels. Since the end of the nineteenth century, they have incorporated electrically driven fans. These are joined to ducting that reaches the working face.

3.2.1 Ventilator monitoring

Mine ventilating machines convert thermal or electrical energy into a pressure difference between the ends of the tunnel system. For a given input, the air flow rate produced is dependent upon factors such as the pressure/flow characteristics of the ventilator and that of the system being ventilated. In the latter case this is characterised by an ‘aerodynamic resistance’, similar in its concept to electrical resistance.

In 1855 it became a legal requirement that a continuous current of fresh air be passed through the workings of a coal mine such as to render them safe. This immediately made it necessary for some form of ventilator monitoring system to be used, although some collieries already had the necessary instrumentation in place.

For naturally ventilated mines the variable determining the available power is the temperature difference between the surface and underground. Thus thermometers constituted the monitoring system applied under such circumstances. Typically, one was placed on the surface and another at the bottom of the downcast shaft. Variations in the difference between the two readings were used as an indicator of the changing strength of the air current being generated.

Furnaces were also monitored using thermometers, with one being placed at the bottom of the upcast shaft. If the indicated temperature fell, extra coal was added to the fire.

In 1843 the South Shields Committee noted how safety could be improved by recording changes in barometer reading. Rather than showing the power available for flow generation, a fall in barometer indicated when it should be increased to counteract a rise in the rate at which pollutants were being released from the wastes. These areas of broken ground were not usually ventilated. Consequently, after a time they became devoid of oxygen and filled with firedamp and other noxious gases. Under stable conditions their pressure was similar to that of the atmosphere and they diffused only slowly into the ventilating current. However, if the barometer fell rapidly the pressure in bulk of the waste became significantly higher than in the roadway. This caused the gas out-flow rate to increase. If the ventilation rate was low and the rate of change of barometer large, there was the potential for dangerous levels of pollutants to suddenly appear on the passing air current. In response too this understanding, by 1852 some mines had equipped themselves with the necessary instrumentation. To facilitate rapid remedial action in the event of a falling barometer, they were positioned at the underground furnace, or where a fan was installed, on the surface.

In recognition of the advantages to be gained from the use of barometers and thermometers, the Coal Mines Act of 1872 required that one of each be installed at the pit top of every mine. Although the current law requires the former, the latter is no longer considered necessary. This is because the performance of modern fans is not significantly influenced by changes in atmospheric temperatures as were natural and furnace ventilation.

When controlling pollutants by dilution the significant variable is the quantity of air flowing. This can not be determined from either the barometric pressure or temperature.

Sometime before 1849, water filled ‘U’ tube manometers, or ‘water gauges’, began to be used for assessing colliery ventilation systems. The two limbs were connected between the upcast and downcast pit bottoms. As to the significance of the reading provided, this was elucidated by Atkinson (5) in 1854. He showed that it was equal to the product of a constant, termed the mine’s ‘aerodynamic resistance’ and the square of the air quantity flow. The resistance was shown to be function of geometry, decreasing with roadway area and increasing with roadway length. Thus for fixed system, a falling water gauge would indicate a decreasing air flow. Alternatively, a rise in water gauge would indicate a rise in flow caused by a fall in resistance, that is a short circuit of the air. Both events meant that, potentially, part of the mine was being starved of ventilation, allowing airborne pollutant levels to rise.

Recognising the value of the water gauge as a ventilation state indicator, a set of general regulations were introduced in 1913, under the 1911 Act, that required one to be fitted at every ventilator, including fans. At those mines liable to firedamp, readings were to be taken every half an hour, whilst at the others it was every two hours. Similar requirements were included in the mining legislation in place in 1994.

The high reading frequency of water gauges meant that a man needed to be in constant attendance at each ventilator. When, during the 1950’s, the coal industry became increasingly conscious of its operating costs this was one of the areas it was felt that savings could be made through the application of remote monitoring. An illustration of how this worked out in practice is provided by Robson (6). At Mill Colliery near Newcastle upon Tyne the main fan was fitted with sensors for differential pressure, bearing temperature and drive belt breakage. The output from each was fed along a cable to indicators and alarms in the colliery office some three miles away. Following the system’s commissioning, the Mines Inspector relaxed the half hourly inspections and extended them to daily. This released three men for other duties. Later, five other similar systems were installed in the same NCB Area. The total installation cost was £6000. Between 1960 and 1967 the savings were nine times this.

Although economic considerations led to the introduction of the early remote fan monitoring systems, clearly mine safety was also improved. This was due to an increased speed with which management were informed of any failures, and an ability for adverse trends in system performance to be identified at an early stage. For example, if the continuous recording showed a gradually declining fan pressure, investigations could have been carried out to locate the source of the problem. Once this had been done, remedial measures could be instigated before catastrophic failure of the mine ventilation actually occurred.

The NCB’s MINOS system was applied to surface fan monitoring in 1982 at Shirebrook Colliery in Derbyshire (7). Included were transducers for bearing and oil temperatures, fan speed, electrical power consumption, barometric pressure, and fan water gauge. Following commissioning, the Mines Inspector granted an ‘8 hour exemption’ releasing the attendant for more productive duties.

Whilst the installation of booster and auxiliary fans underground is not specifically called for in the mining regulations, their use is often required to ensure that the manager fulfils his statutory obligation of providing adequate ventilation to all work places. Their supervision and monitoring tends to have been treated in a similar way to surface ventilators. Regulations introduced in 1956 required that each be fitted with a water gauge and an automatic recorder of either fan revolutions or ventilation pressure. Further, the system was to be inspected every thirty minutes, requiring the presence of an attendant.

The development of remote monitoring systems for booster fans was begun during the latter part of the 1950’s. One of the main problems encountered at the time was a lack of electronic indicators that were also approved for underground use. Consequently, use was made of switch type indicators such as those used in the ELSIE system described in Chapter 1. However, by the time MINOS was applied to booster fans the NCB and others had developed a range of intrinsically safe monitors for use underground. These included detectors of methane, pressure, air flow, bearing temperature and vibration.

Between 1959 and 1966 there were four reported ignitions of firedamp in headings ventilated by auxiliary systems. In the official report on that at Tower Colliery, in which nine men died, it was recommended (8) that arrangements be made for the electric power to be automatically cut-off in the event of the fan failing. In practice this was achieved by fitting air flow switches that changed their state when the incident wind speed fell below a predetermined level. Where ELSIE systems were installed, an additional level of safety would have been provided by the simultaneous activation of an alarm on the surface.

In June 1975 there was another explosion of firedamp in a heading, at Houghton Main Colliery Yorkshire. Five persons were killed. As a result of comments made by the Mines Inspector who investigated the accident, a working group was set up to review the way such workings were ventilated. In their report (9), it was noted that the two most important environmental variables to be considered were the quality and quantity of air being supplied at the face. Although it was considered adequate to provide monitors that simply provided high/low level alarms, the extra costs of installing more 'comprehensive' systems would be justified by a relaxation in the level of manpower required for inspection duties. By the time this suggestion was made the necessary intrinsically safe instruments for monitoring auxiliary fan systems had been produced. Further, their outputs could be connected into MINOS for analysis and display on the surface of the mine.

3.3 Distributing the air

Once generated, the current of air must be distributed to where it is needed to provide workers with oxygen to breathe and to dilute any noxious gases that may appear.

At those early eighteenth century pits where ventilation was provided, and this was far from all, the air was usually only directed to where coal was being cut. The problem with this approach was that it left large areas unventilated. These eventually became filled with pollutant gases, notably firedamp, that were released onto the mine ventilating current when the barometric pressure fell.

In an attempt to eliminate this problem, in about 1760 James Spedding introduced a system of colliery ventilation called 'coursing the air'. This involved passing a single current along a tortuous path through all the open workings. Whilst it may have proved effective when first introduced, by the early years of the nineteenth century mines were getting so extensive that the ventilating devices then available were unable to generate sufficient volumes of air to remove all the firedamp released. This was due to the large aerodynamic resistances such systems represented.

A solution to this new difficulty was introduced by John Buddle in about 1810. He divided the workings into a number of discreet 'districts'. The fresh air for each was split from a common intake. All discharged their foul air into a single return. Using the theory of Atkinson outlined above it can be shown that although the total road length may have been the same as with Spedding's system, the total resistance applied across the ventilator was considerably lower. So for a given generated pressure the total air quantity passing through the workings was higher.

Modern mine ventilation practice uses Buddle's basic approach, although there tend to be fewer districts and longer roadways than in the nineteenth century. Wherever possible, high voltage electrical machinery is installed in an intake roadway. This minimises the likelihood of it ever being exposed to firedamp, thereby reducing the risk of an explosion. Such a layout is called 'antitropal' ventilation. Under certain circumstances, notably where problems are being experienced with excessive heat on the coal face (see Chapter 11), it may be appropriate to put any conveyor belts in the return. Such an arrangement is called 'homotropal' ventilation.

3.3.1 Management of the systems

It is possible that recognition of the importance of maintaining a ventilating current of air through a mine resulted in attempts being made during the 1700's, or possibly earlier, to periodically monitor its speed. Any methods used would, however, have been extremely crude and probably based upon observations of the motion of feathers, smokes, or other light objects. Although the results provided are unlikely to have been very reliable, they would have highlighted those locations and times where the flows were lower than normal and, consequently, extra vigilance required if an explosion was to be avoided.

Although the introduction of Buddle's method of ventilation allowed more air to be passed through the workings than hitherto, it introduced a completely new system management problem. For the first time it was necessary to ensure that the total intake quantity was being properly apportioned between the individual districts. This could only be achieved by taking measurements in each and comparing the results. A comprehensive review of the methods used and their limitations are contained in (1).

Statutory rules governing the management of mine ventilation systems were included in the 1887 Coal Mines Act. These required that the quantity of air flowing in each split of the intake current be measured at least once per week. Similar requirements were contained in the regulations for coal mines in force in 1994. In addition to showing that the intake air is being correctly apportioned between the districts of a mine, such measurements can also, theoretically, be used to show the presence of leakage. This occurs through the broken ground separating two roadways between which there is a difference in pressure. Although such losses can have obvious financial implications, they can also lead to the development of spontaneous fires as considered in Chapter 6.

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Chapter 4 Blackdamp and chokedamp

Of all the hazards to be described in this monograph, a suffocating gas called 'blackdamp', or 'chokedamp', was probably the first to appear in underground workings. Although the given names describe the gas's more obvious characteristics, its appearance represents a fall in the level of oxygen below that normally found (20.95% by volume) and/or the appearance of appreciable concentrations of carbon dioxide. These atmospheric changes occur underground when oxidising processes, for example breathing humans, burning flames and the spontaneous combustion of coal (see Chapter 6), exist alongside a poor supply of fresh air.

This chapter discusses the impact blackdamp has had on the safety and health of coal miners and the steps that have been taken to mitigate its effects. The properties of its constituents are given in Appendix I.

4.1 Occurrence

An early reference to a blackdamp type gas in British coal mines is provided by Jessop (1). Writing in 1657, he describes how a heavier than air 'damp' (gas) could occur in unventilated workings, or where fires had been used to break rocks.

According to Galloway (2), the earliest recorded deaths attributed to blackdamp occurred at Dysart Colliery, Fife, in 1662. Eight men and one woman were suffocated when they walked into old workings. These were most likely unventilated.

In Chapter 3 it was noted how early coal mines contained large areas of unventilated workings. Thus it is possible that the above incident may not have been an isolated one. Despite this, it was the appearance of 'firedamp', and the devastation and loss of life its explosion could cause, that led to the development and introduction of improved and more planned ventilation systems for coal mines. A secondary effect was a reduction in the number of locations in which blackdamp could accumulate. This meant that by the beginning of this century blackdamp tended to be a problem in the shallower mines. These were often believed to be 'free' of firedamp and left unventilated as a consequence. As seen from Section 4.3, it was not until 1911 that regulations were introduced that removed this option by specifying statutory limits for the allowable underground concentrations of the blackdamp gases, namely oxygen and carbon dioxide.

Despite considerable improvements in the efficiency of colliery ventilation systems since 1911, blackdamp is still a hazard that can not be ignored. Evidence for this is provided by the fact that between 1971 and 1976 there were two recorded cases of injury through officials walking into old workings. Recognition of such a danger has led to the development of appropriate detection methodologies and instruments, as described in Section 4.4.

4.2 Physiological effects

Whilst early coal miners recognised the existence of a suffocating gas called blackdamp they did not know its precise constituents or the levels at which they became dangerous. Information on both was required if reliable detection methods were to be developed and realistic limiting regulations introduced. By 1852 the components of blackdamp had been identified as a deficiency of oxygen and enhanced levels of carbon dioxide.

For oxygen, by about 1870 it had been shown that the physiologically significant variable was partial pressure as opposed to volume concentration, with conversion between the two requires knowledge of the barometric pressure. Despite this, many scientists continued to use the latter units for their assessments. The reason for this has not been discovered. In 1894-5, Haldane and Atkinson showed (3) that humans began to experience breathing difficulties in blackdamp when the oxygen concentration had fallen to about 15% by volume. However, under presumably the same pressure conditions, marked signs of distress were not observed until about 10%. They also noted that a flame safety lamp, then the main provider of light in mine workings, was extinguished at a concentration of 17% oxygen. This was well above the danger point for humans.

Also in the 1890's, consideration was being given to the physiological effects of adding carbon dioxide to blackdamp. It subsequently became recognised that whilst this gas was toxic at high concentrations, at the levels expected to be found underground a sufficiently noticeable increase in the depth of breathing occurred in advance of any real danger.

Eventually it was accepted that the main danger from blackdamp came from oxygen deficiency rather than high levels of carbon dioxide. Whether this conclusion had any affect on the way the hazard was managed is open to debate. As will be seen from Section 4.4, although most attention has been given to the detection of oxygen it may have been due to difficulties in sensing carbon dioxide.

4.3 Regulations and recommendations

Before 1911 colliery operators tended only to pay scant attention to the danger from possible accumulations of blackdamp. Although this was known to the Mines Inspectorate, they had considerable difficulty in doing anything about it. This was because the then current legislation simply stated that a mine was to be adequately ventilated. It did not define what this represented in terms of pollutant gas concentrations.

The rectification of this perceived shortcoming in the law was one of the matters considered by the 1906 Royal Commission on Mines. In acceptance of the recommendations made, the 1911 Coal Mines Act subsequently included a statement to the effect that an atmosphere underground was deemed unfit to work in if it contained less than 19% (by volume) of oxygen and more than 1.25% (by volume) carbon dioxide. Legislation in force in 1994 included the same requirement. No precise details have been located as to why these particular limits were chosen. However, one of the Royal Commission's stated aims was to only suggest statutory rules that were practically enforceable. With gases this meant that a colliery operator had to be able to ensure his own compliance using equipment available to him, thereby minimising the potential for regulation avoidance.

Statutory underground oxygen assessments could be made by collecting samples of mine air in containers and analysing them in surface laboratories. However, this approach was slow and too laborious for more routine checks during a working shift. These were undertaken by underground officials and they only had a flame safety lamp for gas testing purposes. Consequently, it is possible that 19% oxygen was chosen because at this level the intensity of a lamp's output had fallen by noticeable amount from when it was in fresh air. To have set the statutory limit at the more easily determined concentration at which a flame was extinguished would have deprived workmen of the illumination required for them to escape from blackdamp. This was deemed unacceptable.

A number of reasons are suggested for the minimum allowed oxygen level being given in percent by volume rather than the physiologically significant partial pressure. The first is the probability that much of the data presented to the Royal Commission was expressed in these units. Secondly, the flame safety lamp had been shown to respond to volume concentration. Also, it may have been thought that the average colliery official would have difficulty in understanding the concept of partial pressure.

For carbon dioxide, the likely routine underground 'detector' was the human response. If this was the case, then 1.25% was possibly chosen because it was the lowest concentration at which an enhanced respiration rate became noticeable. However, since 1911 the understanding of the effects of carbon dioxide on humans has changed with the result that the current non-mining long term exposure limit for the gas is 0.5%. This is somewhat lower than that contained in the mining legislation. It is possible that this discrepancy has been allowed to continue due of an absence of suitable underground monitoring instrumentation that will accurately show such low concentrations of the gas.

4.4 Detection and monitoring

Underground blackdamp detection systems are typically required to fulfil two roles. One is to provide on-site warnings to underground personnel of developing irrespirable atmospheres. Such systems do not necessarily have to be very accurate, but they must have a fast response time and be reliable. The other is to provide the necessary quantitative measurements to ensure compliance with the regulations.

4.4.1 Oxygen deficiency

One of the earliest oxygen deficiency detectors to be used in British coal mines was the flame of a burning candle. When, from 1816, flame safety lamps began to be used to illuminate workings they fulfilled a similar role. Tests showed that their flames were extinguished at oxygen concentrations between about 16 and 18% by volume. Thus they could provide an automatic warning to a worker walking unbeknown into blackdamp. Unfortunately it had the disadvantage of removing the source of light required to affect his escape.

In an attempt to overcome this problem consideration was given to the use of birds and small animals. As described in Chapter 6, these were widely used in mines for showing the presence of the toxic gas carbon monoxide. Experiments showed, however, that a canary, for example, did not collapse until the oxygen level was 5.9% (4). This is well below that fatal to humans.

Eventually miners were provided with electric lamps. This resulted in the flame safety lamp being used exclusively for gas detection purposes and meant that the loss of its flame was less of a safety problem

Following the introduction of the 1911 Coal Mines Act with its limits on the blackdamp gases, a number of studies were undertaken into the use of the flame safety lamp as their detector. The results revealed that whilst the flame size and intensity output were seen to vary with oxygen concentration, the response was significantly affected by, for example, the level of flammable gas in the atmosphere and the design of the lamp. Thus it was concluded that the flame safety lamp was not capable of showing an oxygen concentration of 19% in accordance with the requirements of the law.

The only other way compliance with the law could be tested was to collect samples of mine air and analyse them in surface laboratories. Outlines of the techniques available are given in Appendix II. They were very slow, with it taking many hours or possibly days for the results to be returned. Attempts at developing faster underground versions of the systems used, for example the Haldane apparatus of 1901, met with only limited success. This was because they required skilled chemists to operate them. In the early half of this century few mines were thus staffed.

In response, the years around 1911 saw the invention of a number of devices that were intended to provide a quantitative indication of oxygen concentration and yet be simple enough for use by colliery officials. Examples include the ‘Haldane tube’ of 1912 (5), the ‘Briggs loop’ of about 1911 (6), and the ‘Briggs orifice’ of 1915 (7). Of these, the sensor used in Haldane’s device was a lighted taper, whilst the other two were based on flame safety lamps. Consequently it is reasonable to surmise that all suffered from similar uncertainties in performance as conventional flame safety lamps. Although the Briggs orifice was tested underground, no evidence has been located to suggest that it, or any of the others, found widespread use in coal mines.

The production of a portable and simple to use oxygen meter for coal mines, that would also raise the alarm at a predetermined concentration, came closer to being realised with the development of ‘polarographic cell’ gas sensors. Typically, they consisted of a small vessel, one wall of that was permeable to gas. In contact with a filling of electrolyte was a pair of electrodes. When a voltage was applied between them, dissolved gases such as oxygen and carbon monoxide were reduced at the cathode. The electrons required were provided by a balancing reaction at the anode. These flowed through the electrolyte. A plot of the current this represented versus the applied voltage revealed a characteristic formed from a series of flat plateau. The location of each ‘saturation region’ was related to the gas species being reduced. Its height was dependent upon the rate at which the gas was entering the cell. For the solid membrane this was related to gas partial pressure, the physiologically significant variable for oxygen.

Early polarographic oxygen cells became available in about 1956. However, they had associated with them a number of shortcomings. These included an unacceptably long response time to changes in oxygen partial pressure and a temperature sensitive output.

In about 1970 SMRE began developing an improved polarographic oxygen sensor, later known as the ‘Bergman cell’. This is shown in schematic form in Figure 4.1 (8). In it the cathode was formed directly on the back of the diffusion barrier. This eliminated the need for the sensed gas to diffuse through the electrolyte, producing response times as low as one second. As with other types of polarographic cell, the output from the Bergman drifted at an unacceptably high rate with changing ambient temperature, typically about 3% oxygen/^{o}C at constant atmospheric pressure. This arose from an exponentially varying gas diffusion rate through the membrane. To reduce its effects, thermistor based electronic temperature compensating networks were fitted to each cell (9)(10). One positive feature of the Bergman cell was that, unlike the flame based oxygen detectors, it did not respond to other gases commonly found in mines, such as firedamp.

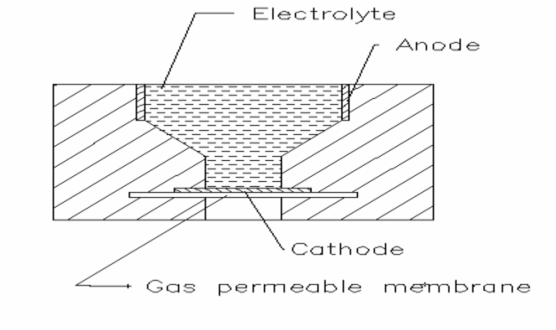

Figure 4.1 A schematic diagram of the Bergman cell

Having produced an oxygen cell, SMRE incorporated it in a pocket sized oxygen monitor (9). Later an apparently similar device was manufactured by Draeger Safety Limited. Designated the E10 Oxylarm it was intended to be worn in the breast pocket of overalls or hung on a belt. The unit was fitted with a meter calibrated in partial pressure and an audible alarm. This was activated when the indication fell below an internally pre-set level.

In about 1974 the NCB carried out an evaluation of a number of polarographic celled oxygen instruments, including the Draeger Oxylarm. The aim was to investigate their suitability as blackdamp detectors for coal mines. Whilst the detailed results of this study are not available for publication, it is known that problems were experienced with instabilities in output with changing temperature.

Partly as a result of this, in 1975 the NCB began funding development work on a new electrochemical oxygen sensor. This had been invented by the City University Electrochemical Technology Unit, later known as City Technology Limited. It is shown in schematic form in Figure 4.2. As with the Bergman cell, this sensor operated via the reduction of oxygen at a cathode. Unlike it, however, the reaction occurred spontaneously. This resulted in the generation of an open circuit voltage between the two electrodes. Connecting them through an external load allowed a current to flow. This was proportional to the rate at which oxygen was being reduced.

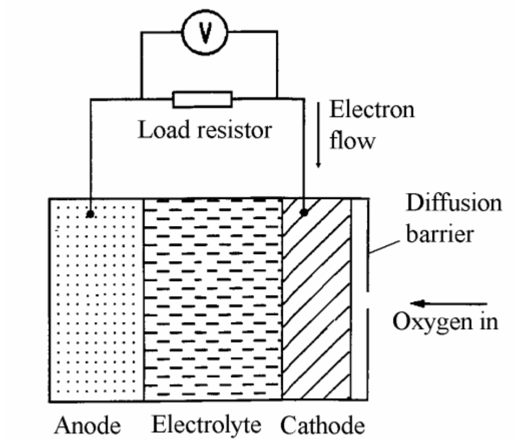

Figure 4.2 A schematic diagram of the City Technology oxygen cell

A novel feature of the City oxygen sensor was its use of a capillary tube as the diffusion barrier. This resulted in a relatively low temperature coefficient of output, typically in the region 0.1 to 0.3% signal/^{o}C (11)(12). Also, the choice of tube diameter allowed cells to be made with different response characteristics. For example, if this was very much smaller than the mean free path between collisions of the gas molecules the response was to oxygen partial pressure. However, if it was relatively large the response was to gas volume concentration. As seen above, in coal mining the latter was the preferred method of expressing oxygen levels. It seems this has also been the case with other cell users since between 1989 and 1993 City Technology apparently removed partial pressure cells from their catalogue.

In 1978, working under contract to MRDE, Sieger Limited began developing an oxygen monitor for use in coal mines. This incorporated a City Technology oxygen cell. Initially two versions of the instrument were produced, one showing volume concentration and the other partial pressure. The latter was subsequently abandoned, partly because the mining regulations specified oxygen levels in volume concentration units. Also, it is conceivable that the evaluation phase revealed that mine officials did have difficulty in understanding the concept of gas partial pressure, as suggested earlier.

Later Sieger Limited produced the improved ‘OXD-2M’ oxygen monitor shown in Figure 4.3 (13). Formed in a case small enough to be clipped to a belt or carried in a pocket, the sensed oxygen concentration was shown on a digital meter. In the event of this reading falling below a pre-set level, an audible alarm was activated. Incorporating low powered semiconductor components, it operated from an internal battery. Performance data for the instrument gave an accuracy of ± 0.5% oxygen over a range from 0 to 30% by volume. The response time was 10 s to 90% of a step change in gas concentration.

Taking a reading with the OXD-2M was simplicity in itself. A button was be pressed and five seconds later the sensed oxygen concentration was displayed and, if appropriate, the alarm raised. The unit could then be switched off again, or left on to provide continuous protection against oxygen deficiency. In this state the batteries lasted for up to 30 hours.

Figure 4.3 The Sieger OXD-2M oxygen monitor (copyright Sieger Limited)

In 1983 MRDE began developing an oxygen monitor for semi-permanent installation underground in coal mines. The intention was to produce a device that could provide continuous protection against blackdamp. Later, a similar instrument was developed commercially by Sieger Limited. Designated the BO1 it was similar in appearance to the BCO1 carbon monoxide monitor shown in Figure 6.2. The instrument was completely self contained, with a single enclosure containing the City Technology oxygen sensor, signal processing and display electronics and a rechargeable battery power supply. If the sensed oxygen level fell below a pre-set point the alarm was raised. Indication was in the form of pulsing relay contacts accessible via an external socket. Facilities were also provided allowing access to an analogue of the oxygen indication. Both this and the alarm indication could be used to operate local indicators or connected into a MINOS data transmission system described in Chapter 1.

4.4.2 Carbon dioxide

Although maximum level of carbon dioxide has been specified by mining law since 1911, the monitoring of this gas underground has received far less attention than has oxygen. This has possibly been due to a belief that most deaths due to blackdamp have resulted from oxygen starvation. In addition, even the presence of low levels of carbon dioxide can cause a noticeable increase in the depth of breathing, thereby providing warning of developing danger.

As with oxygen, the flame was one of the earliest carbon dioxide sensors used in coal mines. However, it seems that the indications provided were far from reliable.

In view of this, and with the requirements of the 1911 Coal Mines Act providing an impetus, a number of alternative carbon dioxide detection methods were subsequently developed using ‘colorimetric’ techniques. One example, ‘Smith’s apparatus’ (14), involved a reaction between calcium hydroxide (lime water) and the gas. The result was solid calcium carbonate in water. To perform the test, an ‘8 ounce’ glass bottle was filled with mine air. To this was added the contents of up to four ‘half ounce’ bottles of lime water coloured with an indicator. At each stage note was taken as to whether the solution had lost its colour, that is the calcium hydroxide had all turned into calcium carbonate and then settled out. If this occurred after the first bottle of solution had been added then the carbon dioxide concentration in the sample was over 0.25%, after the second and it was over 0.5%, and so on.

From this description it will be clear that the complexity of Smith’s test made it unsuitable for routine use by semi-skilled colliery officials. Taking this with an absence of any alternative meant that the only other approach that could be used was to collect mine air samples for analysis in a laboratory. The slowness of this process made it far from ideal.

A very much simpler colorimetric method of detecting carbon dioxide that could also be used in coal mines appeared in about 1965, or possibly earlier. This involved the use of small glass tubes filled with granules of an inert substance onto which was adsorbed a chemical reagent. For carbon dioxide this was hydrazine. Using a hand operated aspirator, air to be sampled was drawn through the apparatus. This resulted in a colour change that started at the inlet and extended along the tube. The length of the stain could be related to the volume concentration of the gas present in the sample. It was read directly off an engraved scale. Currently, carbon dioxide tubes are commercially available covering concentrations from 0.01 to 60%.

Despite their apparent convenience over anything else available, colorimetric detector tubes have a number of problems associated with them. One of these is related to the fact that it can take several minutes for a reading to be obtained. Also the uncertainty in the results provided by some detector tubes is high, possibly up to ±25% of reading.

In 1994, British Coal began an evaluation of a number of low powered infra-red sensors for carbon dioxide. Although it was recognised (15) that the gas is present in blackdamp, the motivation behind the project was in connection with the relatively high levels produced during a developing underground fire. None of the devices tested were immediately suitable for use in coal mines. The work seems to have been discontinued after privatisation.

4.5 Conclusions

There still seems to be no suitable instrument for the rapid measurement of low concentrations of carbon dioxide underground. Further, there is no evidence to suggest that such is being developed. Up to 1994, this was probably due in part to the lack of a suitable sensor.

Blackdamp will occur wherever unventilated workings exist. It may even occur in a modern mine, for example in the waste behind a coal face or a blind roadway where the ventilation has temporarily been disrupted. Thus blackdamp must be considered as a hazard that is under control rather than eliminated. Consequently there is no case for relaxing the measures taken to provide warning of its existence.

In view of the continued potential for blackdamp gases to appear in coal mines, it is concluded that there is a continuing need for an underground detector of carbon dioxide to be produced.

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Chapter 5 Firedamp

During the process of coal formation, hydrocarbon gases were produced. In some instances they leaked to atmosphere through fractures in the overlying strata. In others, notably in the deeper formations, they were adsorbed onto the coal or trapped under pressure within cracks and cavities. During mining any containment of the gases is removed, allowing them to be released onto the ventilating current. Under certain conditions the hydrocarbon and air mixture thus formed becomes flammable and capable of exploding violently. It has been given the name ‘firedamp’.

One of the earliest recorded deaths attributed to an explosion of firedamp in a coal mine occurred in 1621. Unfortunately this was not to be the last and by 1850 such incidents were killing well over 200 miners per year. The emergence of such data into the public domain resulted in pressure being put on the Government and coal operators to introduce measures that would lead to the control of firedamp in mines. This chapter outlines what these were. Their effectiveness is indicated by the fact that by 1900 the average annual death rate from explosions had fallen to 102.4 and by 1990 it was zero.

In Britain the main hydrocarbon component of firedamp is methane. For this reason the instruments used for quantitative indications of gas concentration are called ‘methanometers’. A device that automatically raises the alarm when a pre-set firedamp level is exceeded is called an ‘automatic firedamp detector’ or ‘AFD’.

5.1 Controlling firedamp

Methane based firedamp combusts when the flammable gas concentration is between 5 and 15% by volume in air. There must also be a source of ignition, for example a naked flame or incendive spark.

Long before the properties of firedamp had been fully identified it was recognised that the likelihood of it exploding in a coal mine could be reduced by ventilating the workings. However, a reliance on natural processes meant that a sufficiently high flow of fresh air could not always be maintained. The result was that flammable atmospheres often occurred. By the mid-seventeenth century, practical experience had shown miners that warning of developing danger could be obtained from observations of the candle flames used for illumination. This allowed the air flow to be increased or the workings evacuated. As an alternative, a ‘fireman’ could be sent underground in advance of the colliers. His job was to ignite any accumulations of gas found. Despite its obvious dangers, this practice persisted well into the nineteenth century.

As British coal mines got deeper and more extensive, rises in the gas content of the strata and the exposed surface area from which it was emitted led to increases in the minimum fresh air ventilation rates necessary to render workings safe from explosions. However, inadequacies in the technology available meant that these could not always be achieved. Also, by the latter half of the eighteenth century even the use of firemen could not keep some mines safe. To avoid the financially unacceptable alternative of abandoning the workings, attempts were made to remove the sources of gas ignition. Since these were primarily the candles and other naked flames used for illumination, the approach resulted in trials of a number of ‘flameless’ alternatives. Unfortunately they proved neither to be very safe or effective sources of light.

Chapter 12 shows that one of the more popular flameless illuminating devices was the ‘flint mill’. It was introduced around 1763. With this apparatus, light was radiated by a stream of sparks created when a flint was held against a rapidly revolving metal disc. As with candles, its use in so called ‘gassy’ mines led to the development of techniques by which rising flammable gas levels could be shown. These are described in Section 5.3.1.

In 1816 the Davy and Stephenson flame safety lamps became available to provide light in potentially flammable atmospheres. With both, safety was achieved by containing the flame in a gauze enclosure. In practice, neither lamp was found to be completely safe. For example, in high firedamp concentrations the illuminating flame could get so large that it made the gauze red hot and hence capable of igniting the gas. Further, both lamps could cause explosions in the general body if they were suspended in flammable currents flowing at speeds in excess of between 3 and 5.5 m/s. Despite an early recognition of these dangers, flame safety lamps became extremely popular sources of light underground. This was because, faced with inadequate ventilation technology, they were seen as the only way many mines could be worked with even the remotest chance of avoiding an explosion. Eventually improved flame safety lamps were developed. These remained in use in coal mines until the present day. However, latterly their role was not as providers of light but detectors of flammable and toxic gases. Such usage had apparently appeared almost simultaneous with their introduction in 1816. The methodologies used for firedamp detection are described in Section 5.3.2.

The 1860's saw the development of electric safety lamps for underground use. Although recognised as being brighter and possibly safer than their flame counterparts, an inability to show the presence of firedamp in the workings slowed up their general application in coal mines. Where they were used, regulations (see Section 5.2) were introduced to ensure a minimum number firedamp detectors at each work place. These could be flame safety lamps or other approved instruments. The latter are described in Section 5.3.

During the latter half of the nineteenth and early part of the twentieth centuries there were major advances in mine ventilating technology. Also, the attitudes of coal owners and legislators towards the safety of miners improved significantly. Taken together it meant that the means and will were in place for a more 'managed' approach to the problem of firedamp. This involved ensuring that sufficient air was being passed through the workings to render them safe under 'normal' conditions, whilst allowing for the flow to be increased in the event of abnormally high emissions of gas. To ensure the continued effectiveness of this firedamp control system mine officials ideally needed to be provided with reliable data on the gas concentrations present in the workings. Unfortunately, this was made difficult to achieve by the characteristics of the gas sensing methodologies and the behaviour of firedamp. The former were non-continuous and required skilled operators if reliable results were to be expected. Also, concentrations of firedamp could rise very rapidly. For example, it was not unknown for a 2% change, or nearly half the lower explosive limit, to occur over the period of a shift (1). Faced with such behaviour it was clear that the ideal firedamp monitoring system ideally needed to have a fast response time, be automatic, and continuously operating.

At the start of the twentieth century, the flame safety lamp was the main provider of underground flammable gas concentrations at work places. Also, samples of mine air could also be collected for subsequent analysis in a surface laboratory. Of these, the flame safety lamp provided results soonest after sampling, but required considerable skill to show gas concentrations much below the lower explosive limit of firedamp. The latter approach was more sensitive and accurate, but it could take several hours for the results to be returned. Recognition of these shortcomings led to numerous attempts at developing new firedamp detection methods. Most of the early ones proved largely unsuccessful and it was not until the 1920's that a 'pit worthy' underground methanometer became widely available. Called the 'McLuckie', it is described in Section 5.3.3. Here it will be seen that the apparatus was laborious to use and slow in its response. Further, it was neither automatic nor continuously operating.

In the absence of a continuously operating flammable gas detector, and knowing that the concentrations could vary significantly over the period of a shift, less scrupulous colliery managers ensured that any firedamp assessments were taken when they knew the results would be at their lowest (1). Although this may have minimised the ventilating costs it did little to lessen the danger of explosions. In an attempt to stop this practice, regulations were introduced requiring that any statutory measurements be taken when the results were expected to be at their highest, as determined by trial and error.

Even with this procedure in place no allowance was made for the appearance of unusually high firedamp concentrations due to unforeseen events. The potential consequences of this were clearly demonstrated when, on 17 May 1965, thirty-one men died in an explosion at Cambrian Colliery in Glamorgan. Prior to the incident, an accumulation of firedamp had formed undetected during a two and a half hour long interruption in the ventilation. The gas was ignited by unsafe electrical equipment. The official report on the incident (2) stated that the accident demonstrated a need for continuous monitors of firedamp in coal mines. These could be left underground all the times and used to raise the alarm and switch off electricity as and when there was a dangerous build-up of gas. As will be described in Section 5.3.4, such systems were subsequently developed by the NCB. By the time British Coal was privatised in 1995 they were in use in all large mines.

Tragically often, fatal accidents have revealed new aspects of the firedamp hazard in coal mines. These may be related to the gas's behaviour, or the introduction of a new source of ignition brought about by developing mining technology. Although there appears to be no particular thread linking them, some have influenced the development of firedamp detecting instrumentation. Consequently short discussions of those considered to be of most relevance to this monograph will follow.

5.1.1 Firedamp layering

Firedamp is less dense than the other general body mine air gases. This means it can accumulate in roof cavities, particularly those not swept by the ventilating current. Firedamp can also accumulate near the roof of tunnels in which the wind speed is low, typically below about 0.5 m/s. Here turbulent mixing effects are inadequate to prevent it from forming layers of high concentration gas, sometimes only a few centimetres thick.

Although it was suspected as long ago as 1845 that firedamp layers could occur (3), it was not until over a century later that the danger they represented received much attention. In a review of the circumstances surrounding thirteen colliery explosions that occurred between 1952 and 1957 (4) it was implied that firedamp layering had been influential in many of them.

In response it was recommended that high speed currents of air should be maintained at every location underground. This would prevent layers from forming and the gas from accumulating in roof cavities. As to the systems used to assess the continued effectiveness of these measures, doubts were expressed as to the suitability of the flame safety lamps then being used for general flammable gas detection purposes. In part this would have been due to difficulties in using them in inaccessible locations, but also because of their inability to sample gas from close to a roof. Eventually these problems were overcome by the use of aspirated sampling systems described in Section 5.3.2.1. Later, similar arrangements were produced for the electronic methanometers that replaced flame safety lamps as detectors of firedamp in coal mines.

5.1.2 Coal dust explosions

Following on from earlier speculations on the subject, between about 1850 and 1875 it was demonstrated that a mixture of finely divided coal dust and firedamp became violently explosive at concentrations well below the gas's normal lower ignition limit. Once initiated, the explosion quickly became self propagating by virtue of a shock wave that moved in advance of the flame. This scooped up previously settled dust to create a combustible cloud. By this mechanism many miles of mine roadway could be devastated in a single incident.

Initially the preventative measures applied involved sprinkling water along those roadways found to be dry. This was intended to hold the dust on the ground and prevent it from becoming dispersed on the air current. However, in hot mines this led to unacceptable increases in the humidity at the face, the significance of which is discussed in Chapter 11. Later it was found that laying incombustible stone dust on the ground arrested dust explosions. This is now the standard method applied.

Recognition that coal dust explosions could be initiated in the presence of very low concentrations of firedamp presented those officials with responsibilities for the safety of the underground workings with somewhat of the problem. This was because the levels that needed to be detected were well below the threshold for the flame safety lamps with which they were provided. In response, a large number of novel firedamp detectors were devised to show concentrations of 1% or less. Those considered to be the most significant are described in Section 5.3.

5.1.3 Electricity underground

Electrically generated sparks have been a major source of firedamp ignitions in coal mines. Early concerns over the problem related to machinery operating at high voltages. In 1895 regulations were introduced requiring that all such equipment be enclosed such that if an explosion did occur it would be contained and not allowed to propagate into the general body. Later, this approach was developed into the concept 'flame-proofing'. As noted in Chapter 2, flame-proof equipment tends to be bulky and heavy. Since it may produce incendive sparks during normal operation, regulations have been introduced limiting the maximum general body firedamp concentration in which it can be operated to 1.25%.

Amongst other attributes, continuously operating 'fixed' environmental instruments of the type suggested by the Tower Colliery accident report need to be transportable. This enables them to be easily relocated as a mine develops. Equipment used by officials to inspect individual work places must be lighter and capable of being carried in a pocket or clipped to a belt. To provide maximum protection for the longest possible time, both types of methanometer must be capable of operating in above 1.25% firedamp. Taken together, this all means that flame-proofing is not an appropriate form of electrical protection suitable for methanometers. Instead, transportable/portable environmental instruments for coal mine use are generally made intrinsically safe. Although this approach can lead to light systems, they must only contain low voltage and current circuits.

Some of the earliest low voltage electrical systems used in coal mines were for signalling. Typically operating at around 10 V dc, it was initially it was thought that any sparks produced would be incapable of igniting firedamp. The fallacy of this idea was tragically demonstrated on 14 October 1913 when 439 persons were killed in an explosion at Senghenydd Colliery, Glamorgan. It is now widely believed that the source of ignition was a spark from the bell of a 'safe' electrical signalling system.

After Senghenydd, investigations carried out by Wheeler showed that whilst low voltage supplies on their own may be incapable of producing incendive sparks, this was not the case when a bell was included in the circuit. Later, in association with Thornton, he showed how such problems could be overcome and incendive sparks prevented from occurring (5). Eventually the principles devised were developed into the subject of 'intrinsic safety' mentioned in Chapter 2.

In the early days the concept of intrinsic safety had little impact on the range of environmental and other instruments available to miners. This was mainly due to an absence of components that could be used in low voltage sensor signal processing circuits. Beginning in about 1960, this situation changed dramatically with the availability of an ever increasing range of semiconductor devices operating at low currents and voltages. These have since been used to produce a large number of intrinsically safe instruments, including methanometers, for coal mines. Many are described in the chapters that follow.

5.2 Firedamp regulations

In response to an ever increasing frequency of explosions in coal mines the nineteenth century saw the development of measures that if applied are likely to have reduced the number and severity of such incidents. Unfortunately the evidence suggests that not all colliery operators were prepared to make the necessary changes to their working practices voluntarily. The result was that the Government was forced to introduce a series of appropriate statutory safety codes.

The earliest 'anti-firedamp' rules were included in the Coal Mines Act of 1855. These required that an adequate amount of ventilation be constantly produced to ensure that all working places were 'safe'. No indication was given as to what this meant. As a result it is unlikely that the Act had much effect on the frequency of explosions.

Subsequent extensions to the scope of the regulations also contained equally ill-defined statements. For example, rules introduced in 1872 made it a requirement that officials equipped with flame safety lamps were to periodically carry out inspections of the underground workings. In the event of any being found 'dangerous' from the presence of flammable gas further access was prohibited, or any men already there withdrawn. No guidance was given as to what was meant by 'dangerous'.

The problems that arose as a consequence of the imprecise nature of the law were considered by the 1906 Royal Commission on Mines. They responded with a recommendation that 'dangerous' should refer to flammable gas concentrations above a specified minimum. To reduce the potential for regulation avoidance, compliance should ideally be determinable using a system available underground, namely the flame safety lamp. Against this, studies undertaken at the time revealed that the results typically returned by this approach were far from reliable. Although the reasons are considered further in Section 5.3.2, suffice it to say that they stemmed largely from a need to make a subjectively match between an observed flame and that expected in a known firedamp concentration. There was, however, one point at which the scope for errors was at a minimum. This was when a feint blue gas cap seen on top of a low luminosity 'testing flame' changed from being a truncated cone to one that was fully formed with a pointed apex. In view of the unambiguous nature of this point, it was chosen as corresponding to the concentration above which workings should be considered dangerous from the presence of firedamp.

This general view was accepted by the legislators who prepared the 1911 Coal Mines Act. By the time this was published, it had been adjudged that the flame shape changed occurred at 2.5% by volume of flammable gas, a figure that was included in the regulations. Thus although the background to the new law was the response of a flame safety lamp, the inclusion of a precise figure for the point at which the environment was deemed to become dangerous allowed for the later and rapid introduction of other types of flammable gas detector for statutory purposes.

Regulations in force in 1995 stated that the concentration of flammable gas present underground was to be deemed excessive if there was more than 2.0% present. No indication has been found as to why or when the change to this lower limit occurred.

Besides stating when a mine was deemed dangerous, the 1911 Act also allowed coal seams to be classified according to whether they could be entered with naked lights or only with locked safety lamps. The choice was based on the results to the laboratory analysis of six fortnightly samples of mine air collected in the return airways. Where the average exceeded 0.5% the safety lamp rule was applied, otherwise the workings were considered 'gas free' and naked lights allowed.

Unfortunately the naked light regulations seemed to work against any aim of limiting explosions in coal mines. This is demonstrated by the fact that between 1919 and 1939 nearly 80% of such incidents were caused by naked lights and mainly in those mines considered free from firedamp (6). One of the reasons for this can be related to the relative gas flow rate from the strata and that of the ventilating current. If the former is very low compared with the latter, the low concentrations measured as a consequence will make it appear as though the coal contains little or no flammable gas. However, any disruption in the supply of fresh air will allow accumulations to develop, notably in the high points of the workings. On restoration of the air supply these will be swept out of the mine as potentially explosive 'plugs' of gas, passing over any naked lights that may be present.

Another possible reason for the relatively high incidence of explosions in naked light mines was related to the fact that they were classified according to fortnightly mine air samples. These provided no information whatsoever about the firedamp concentrations in between times. Even had these been above the explosive limit the mine would still have been classed as 'gas free'.

Naked lights were banned from all underground coal mines with the introduction of the 1954 Mines and Quarries Act. This has led to a dramatic decline in the number of explosions they have caused; between 1970 and 1993 there was only one (7).

The problem of knowing what happened to the firedamp levels in between the fortnightly samples was addressed by the Coal Mines (Ventilation) General Regulations, 1947. These reduced the sampling period to weekly. If any of the results exceeded 0.8% then this was further reduced to daily. Recognising the dangers associated with temporal variations in firedamp level over a shift, all determinations were to be made when the concentrations were likely to be at their highest as determined b testing. Similar requirements were contained in more recent legislation, the Coal and Other Mines (Ventilation) Order, 1956.

Under the 1956 Ventilation Order, gas assessments could be made by the laboratory analysis of mine air samples. Alternatively an instrument approved by the Government's Mines Department could also be used. Precise details of the criteria initially used to grant this 'approval' have not been located. However, the reading accuracy was to be better than ±0.12% methane, or ±10% of indication. Such a performance specification would have precluded the flame safety lamp from being used as a flammable gas detector for statutory purposes.

In 1970 the Department of Trade and Industry issued Testing Memorandum No 7 (TM7). This classified flammable gas detectors for use in coal mines according to their mode of operation and range of indication. It also presented minimum performance specifications allowable under the mining regulations. For measurements made under the 1956 Ventilation Order only Class 1A methanometers could be used. These had scales up to 5% and an accuracy of better than ±0.1% methane from 0 to 1.25% methane and ±8% of true value above this (8).

TM7 was superseded first by a British Standard and then by a series of European Standards. All contain considerably more information on the tests detectors were subjected to before being approved under the appropriate mining legislation.

Included in TM7 and its successors has been a class of instruments called ‘methane alarms’. Rather than provide a quantitative indication of firedamp, as would a methanometer, these automatically raise the alarm when the sensed concentration increases above a pre-set level. As a general operating concept this type of device has been used in coal mines for as long as there has been the danger of explosions. Before the development of electronic devices described in Section 5.3, they were formed from the candles and safety lamp flames used to light the underground workings. With these, warning of danger was provided by a noticeable increase in the size and luminance of the flame.

From about 1860 electric safety lamps began to replace their flame counterparts as providers of light underground. Whilst this change improved the levels of illumination at the work place, it also removed any automatic protection against firedamp the latter provided. Recognising the effect this could have on the coal mine accident rate, in 1919 the Government set-up the Miners’ Safety Lamps Committee to study the problem. After five years of deliberation it had been concluded that regulations should be introduced whereby groups of underground workers were provided with at least some flame safety lamps for gas detection purposes (9).

The publication of this recommendation elicited no immediate response from the Government. Rather than necessarily being due to a disinterest in the safety of coal miners, it is believed that this lack of activity resulted from a recognised absence of any suitable device that would fulfil the perceived requirement. This was for a totally automatic firedamp alarm, rather than the traditional detectors that needed to be manipulated before showing a result.

By the mid-1930’s the situation had changed somewhat. In particular, the transition from flame to electric lighting had accelerated due to the introduction of increasingly stringent underground lighting regulations. Also, an automatic methane alarm called the ‘Ringrose’ (see Section 5.3.4) had become available. In response the Government issued the Coal Mines General Regulations (Firedamp Detectors), 1935. Amongst other things, they included the requirement that on longwall faces where safety lamps were required to be used one approved firedamp detector, not necessarily automatic, was to be provided for every eight men.

In 1938 the working of the 1935 regulations was reviewed (10). Whilst the aim of ensuring a minimum number of firedamp detectors underground was generally accepted, controversy existed over how best this could be achieved. The main concerns were centred on the compulsory use of the Ringrose instrument. Some commentators felt that such a move would be unjustified due to its unreliability. These objections were overruled, as evident from the fact that firedamp detector regulations introduced in 1939 were largely a continuation of the earlier ones. However, they did contain at least one major change. This was to the effect that where the average flammable gas content of air in a return airway was over 0.5% then the detectors used in the seam were to be of an approved automatic type. At the time this could only mean the Ringrose.

The provision of firedamp detectors underground was subsequently included in the Coal and Other Mines (Ventilation) Order, 1956. Whilst precise wording may have been different from the 1939 version, the requirements were broadly similar. Any uncertainties as to the merits of the compulsory use of automatic detectors were, however, removed by advances that took place in methane detection technology. These are outlined in Section 5.3.

Another location where more recent legislation has required that automatic firedamp be used is where flame proof electrical equipment is being operated. Rules to this effect can be traced back to 1905. Then, in recognition of the potential explosion hazard, it was made a requirement that a flame safety lamp be provided at each machine when working. If this showed any indication of firedamp the power was to be removed. At the time, no corresponding gas concentration was given, an omission that was removed by the 1911 Coal Mines Act. This stated that power to electrical machinery was to be removed when the level of flammable gas rose above 1.25%. It is suggested that this figure was derived from experimental studies that showed that the minimum detectable flammable gas concentration of most flame safety lamps was between 1 and 1.5%. The chosen figure of 1.25% is the mode of this range.

Through many revisions of the coal mining legislation, 1.25% remained the concentration of flammable gas at which the power to flame-proof electrical equipment was to be removed. Rather than flame safety lamps, this point has latterly been indicated by automatic firedamp detectors hung near the equipment being guarded.

5.3 The detection of firedamp underground

It seems possible that a basic desire for self preservation from explosions first led coal miners to develop methods of detecting flammable gas. With necessity being the mother of invention, they used of those resources they had around them, namely the lamps used to illuminate their workings. Initially this was the flame of a candle, then the sparks from a flint mill, and then the flame safety lamp.

5.3.1 Naked flames and sparks

Descriptions of the methodologies used to detect the presence of flammable gas using candles and the flint mill are provided by John Buddle (11), writing in 1814.

A possible accumulation of firedamp was tested for by slowly raising the candle towards the roof of the workings. Its presence was indicated by the appearance of a feint blue ‘cap’ on top of the otherwise yellow flame. This was seen to increase both in size and depth of colour as the lower explosive limit of the gas was approached. No indications have been located as to the minimum concentration of firedamp detectable by this method, although it was probably close to, if not over, 2.5%. Candles were still being used as gas detectors in coal mines as late as 1890.

With the flint mill, in increasing concentrations of flammable gas the luminosity of the sparks produced increased and their outlines became more diffuse. Near to the point at which firedamp exploded they tended to form concentric circles around the wheel rather than being emitted in a straight stream from its periphery. Also, their normally red colour attained a bluish tint.

Although the above approaches will have provided little more than a qualitative warning of a developing danger from explosion, they were better then nothing, and their development increased the safety of coal miners.

5.3.2 Flame safety lamps

A diagram showing the components of a ‘modern’ flame safety lamp is given as Figure 5.1. The glass tube allows light to be radiated from the flame. The gauze cylinders enable mine air to enter the lamp and the products of combustion to escape from it. At the same time they prevent the flame from igniting any explosive gases in the surrounding atmosphere. Most lamps have used mineral or vegetable oils as fuel.

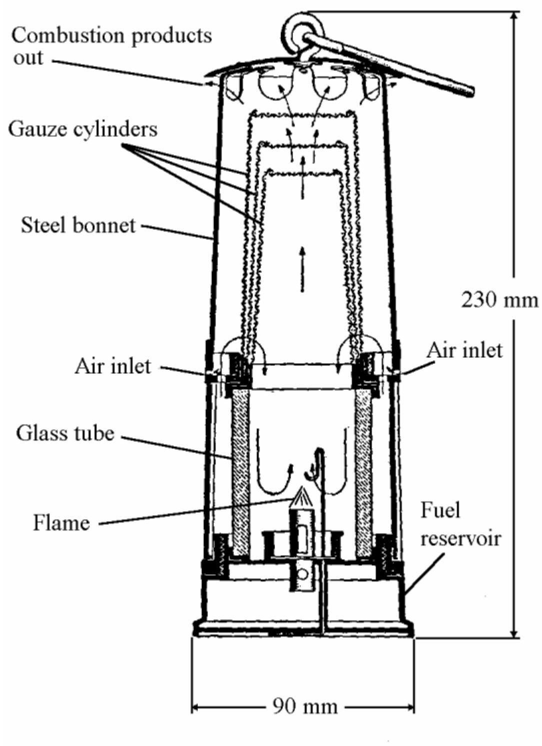


Figure 5.1 A flame safety lamp

Since their use as providers of light followed on from candles, it is not surprising that even the very first flame safety lamps were used for the detection of flammable gas in mines. Further, one of the methodologies used was the same. In this, the presence of gas was determined from observations of the height of the large yellow illuminating flame. With changes in the region of about 1.5 mm/% firedamp, even starting from fresh air it must have been very difficult to obtain anything approaching an accurate result by this method. More obvious changes in flame appearance were seen at between 2.5 and 5% (lower explosive limit for methane). In this region the flame gained a pointed top and began to smoke and flicker.

For a flame safety lamp to show concentrations of 1.25 and 2.5% flammable gas, namely the statutory limits for the use of flame-proof electrical equipment and withdrawal of men from a mine, a very much more laborious technique was developed. This involved lowering the wick to give a small, low intensity ‘testing flame’. Triangular in shape, it was about 3 mm high. Beginning at a threshold of about 1.25%, placing the lamp in ever increasing concentrations of flammable gas resulted in the growth of a feint blue cap on top of the flame. Initially this had the shape of a truncated cone, but by 2 to 2.5% it had become fully formed and more distinct.

Despite the availability of this relatively sensitive flammable gas detection methodology, studies by the 1906 Royal Commission revealed that concentrations of up to 4% were frequently going unnoticed by persons carrying out tests underground. One of the reasons stemmed from the common occurrence amongst miners of an eye disease called nystagmus (see Chapter 12). In many cases the eyesight of officials carrying out gas tests was so badly affected that they could not see the feint blue cap, or even the large yellow one for that matter.

Another problem with the flame lamp gas detector arose from the fact that away from 1.25%, where the cap first appeared, and 2.5%, where it became fully formed, the determination of firedamp concentration required the operator to judge how the appearance of the flame compared with that appertaining to a standard set of conditions. Thus, in addition to the skill of the operator the accuracy of the results provided were also strongly influenced by reliability of the lamp ‘calibrations’ used. The 1906 Royal Commission found that these were typically derived from the results of Davy in 1815. Despite the apparently unsatisfactory nature of this situation it was not easily rectified. In the absence of any means of taking the ideally required colour photographs reliance was initially placed hand tinted drawings. Later black and white photographs became available. A set of coloured pictures showing standard gas caps date from 1969.

Despite a recognition of the above difficulties associated with their use, flame safety lamps continued to be used for the detection of flammable gas in coal mines for well over a century and a half. This longevity of use can be attributed to the absence of an alternative that was believed to have been as good.

5.3.2.1 ‘Special’ flame lamps

The standard lamps considered above generally used oil as a fuel. As a consequence of its burning characteristics, the flammable gas detection threshold of such devices was around 1.25%. In some instances, notably in connection with the avoidance of coal dust explosions, this was considered to be much too high and attempts were made to reduce it.

In 1881 Mallard and LeChatelier found that trimming the size of a flame to reduce its luminosity also lowered its temperature and, as a consequence, its sensitivity to firedamp. Thus to produce observable gas caps at lower concentrations they believed it would be more appropriate to use a lamp fuel that burnt with a hotter, less luminous flame. Alcohol and hydrogen were suggested.

Although alcohol lamps were subsequently found to be more sensitive to low concentrations of flammable gas than their oil counterparts, in practice they could be dangerous to use. This was because of the relatively high volatility of the fuel. At elevated firedamp concentrations the lamps became so hot that it vaporised in the reservoir, causing a rapid increase in flame size. Attempts at solving this problem appear to have been largely unsuccessful.

Hydrogen fuelled lamps also produced a very sensitive flame based gas detector. However, none seem to have found wide use in the coal mines of this country. The reason for this has not been discovered.

As an alternative to developing a sensitive flame gas detector by changing its fuel, attempts were made at increasing the visibility of the feint gas caps on conventional lamps. Examples tried included coloured filters and the ‘Beard-Mackie indicator’ (12). None seem to have been used in coal mines.

Another problem with conventional flame safety lamps was an inability to detect the thin layers of firedamp discussed in Section 5.1.1. The effects of the convection currents around the hot bonnet meant that the sample drawn into the lamp originated from near its base. This left a region more than 200 mm thick untested.

One early attempt at removing this shortcoming, introduced by Gray in 1868, was to fit an inlet manifold at the top of the bonnet (13). Although lamps with similar arrangements were subsequently used by colliery officials, investigations carried out by SMRE during the 1950’s threw doubt on their effectiveness at detecting gas layers. Again this was due to the presence of convection currents.

A more successful solution to the problem, that also found wide application in the testing of relatively inaccessible locations such as wastes, involved moving the mine air from the sample collection point to a remote lamp. Faraday and Lyell had made use of such an approach during their investigation into the Haswell Colliery disaster in 1854 (3). They collected samples of mine air in bags. These were then emptied at the bottom of a glass tube containing a Davy lamp. Convection currents drew the gas into the flame, thereby allowing the presence of any firedamp to be seen.

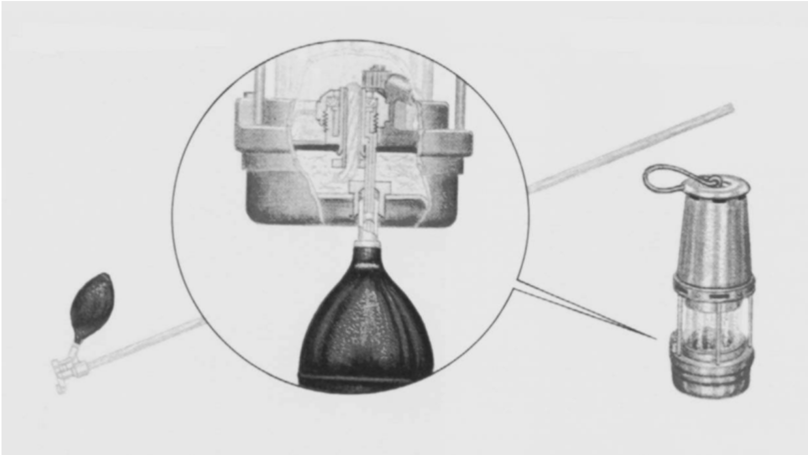


Figure 5.2 Garforths’s lamp (copyright National Coal Board)

In 1884 Garforth introduced a refinement to this process. As shown in Figure 5.2, he used small rubber aspirator bulbs to collect the gas. This was then injected directly into the base of the flame of a safety lamp. Samples could be collected from remote locations by mounting the aspirator bulb on the end of a long stick. Although it had obvious attractions, Garforth’s attachment did not become widely used in coal mines until the late 1960’s. This was probably in line with a developing understanding of the hazards associated with firedamp layers that occurred at around this time.

This later interest in the sampling of gas layers led to the development of another remote sampling attachment for use with flame safety lamps. Called a ‘probe lamp’ and shown in Figure 5.3, it was formed from a long sample tube connected by a flexible hose to an inlet port on the lamp. Gas was drawn through the apparatus by the operation of an aspirator bulb. Systems like this became available in the early 1960’s, although they never became as popular as the Garforth attachment. This was probably due to the cumbersome nature of the probe. However, a similar approach was widely used with electronic methanometers that were to follow.

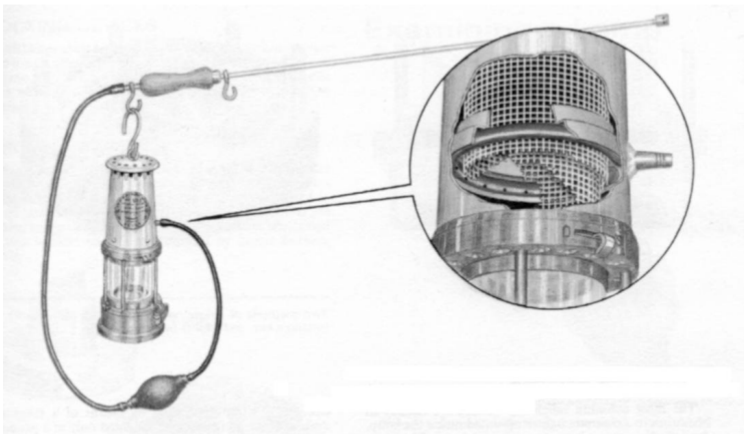
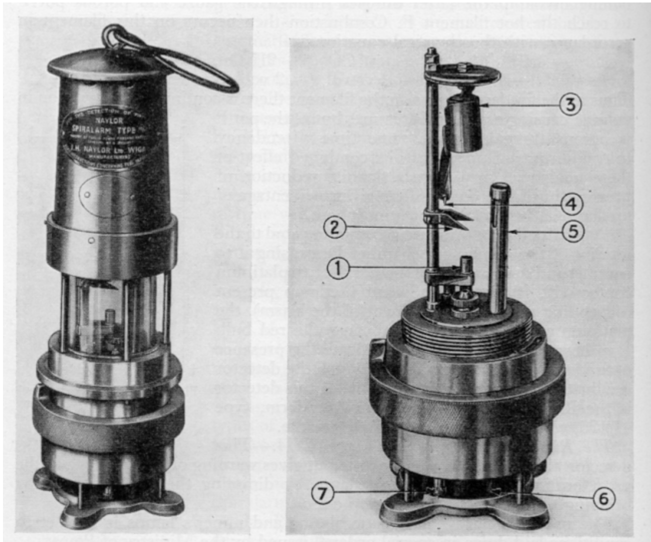


Figure 5.3 Probe lamp (Copyright National Coal Board)

As noted in Section 5.2, 1939 saw the introduction of regulations requiring the use of automatic firedamp detectors at specified locations underground in coal mines. Whilst conventional flame safety lamps were not approved for such an application, during the late 1940's a modified example was. Called the 'Naylor Spiralarm', it is shown in Figure 5.4 (a and b). A thermal relay in the form of a coiled bimetallic strip was mounted above the flame. This formed part of an electrical circuit that also included a battery and a red bulb. These were contained in an enclosure below the fuel reservoir. In the 'on guard' state the relay was open and the bulb unlit. If the concentration of firedamp increased, the flame temperature also increased. At a pre-set point the relay closed, causing the bulb to be illuminated and the alarm raised.



a) Exterior b) Workings

Figure 5.4 Naylor Spiralarm (Copyright Caxton Publishing)

Experience with the Spiralarm revealed that it was not particularly reliable, notably in respect of the gas concentration at which the alarm was triggered. This could vary unpredictably, mainly due to the effects of, for example, ambient temperature and pressure (14). Despite this, the device was used in British coal mines for many years. By the early 1970's, however, it was being superseded by the alternatives to be described later.

A similar approach to that of the Spiralarm was used by MRE in an early continuously operating flammable gas recorder. Designated the 'Sigma Type 208C', it is shown in Figure 5.5. Thermocouples were used to sense the temperature above a butane flame. By this means an indication of flammable gas concentration was provided. The voltage output from the device was either shown on a local clockwork recorder, or connected to external circuitry for remote data transmission and alarm generation. The device was approved for underground use in 1960 and by 1969 was in widespread use in this country (15). By 1971 more reliable methane monitoring systems were under development and its use was in decline.

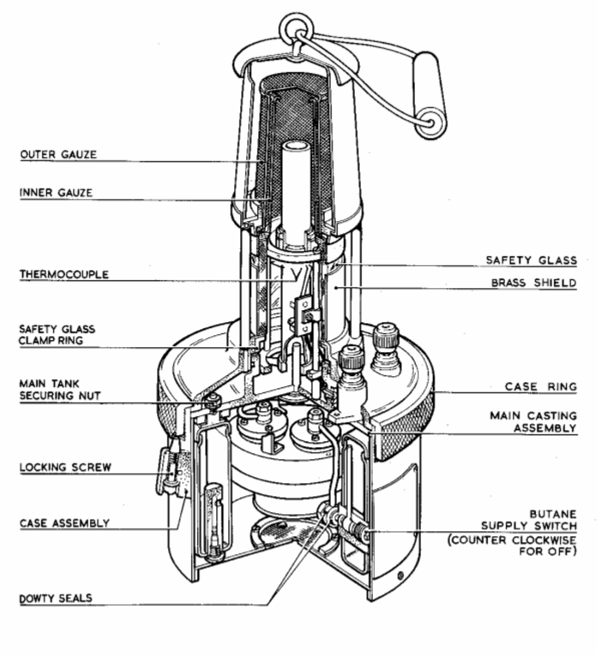


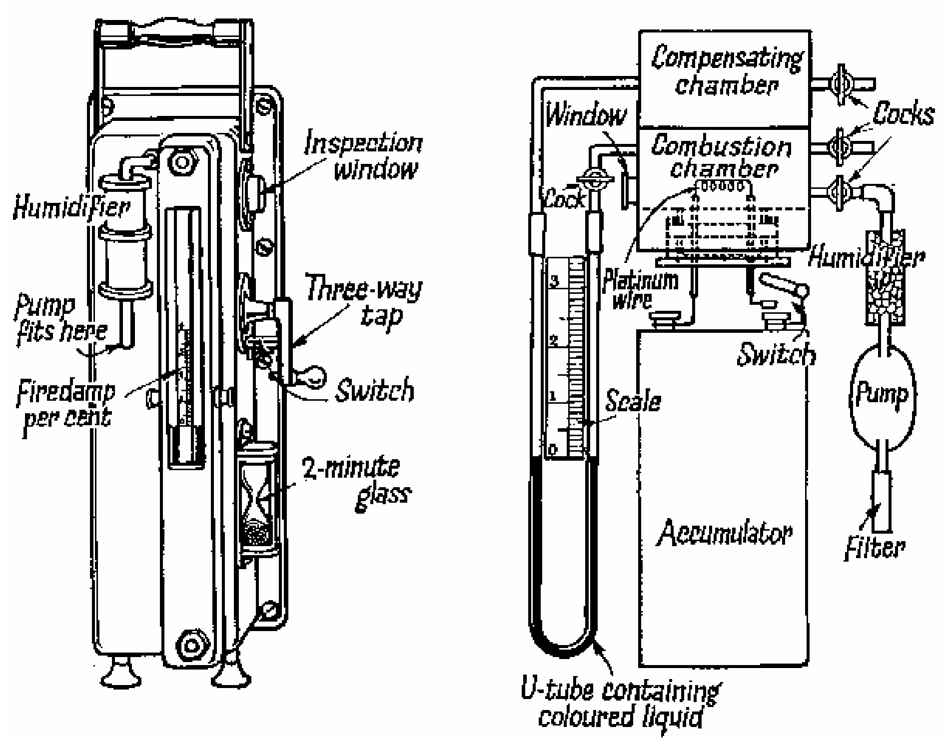
Figure 5.5 Sigma recording methanometer

5.3.3 Combustion methane detectors

The earliest attempts at producing non-flame firedamp detectors for coal mines involved the adaptation of techniques being used in the laboratory. One of these involved the determination of gas concentration from measurements of the contraction of a known volume of sample following combustion of the flammable component on a heated wire (see Appendix II).

In 1886-7 Joseph Swan used this approach to produce an electric safety lantern that would also show the presence of firedamp (16). It is not clear whether any were used underground, although the lamp without a gas detector attachment apparently was.

Seemingly motivated by the recognised insensitivity of the flame safety lamps to low concentrations of flammable gas, the next forty years saw the production of a large number of other firedamp detecting instruments operating on similar principles. However, none seem to have found widespread use in British coal mines. It is postulated that this was because, in part, they tended to be fragile in their construction



a) Exterior view b) Workings

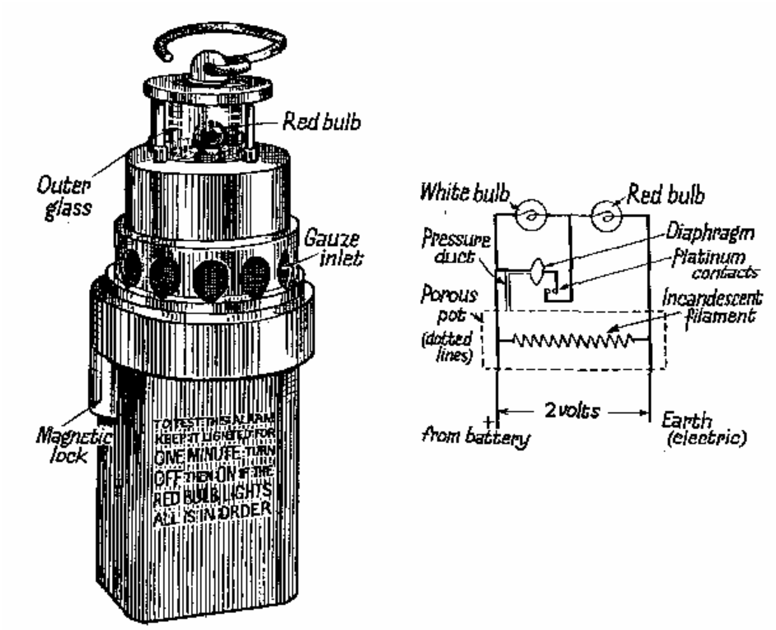
Figure 5.6 The McLuckie methanometer (copyright Virtue and Company Limited)

and complicated to use. During the later half of the 1920's this situation changed somewhat with the production of the apparently first 'pit-worthy' flammable gas detecting instrument. This was called the 'McLuckie' (17). At about the same time the 'Ringrose' non-flame automatic firedamp alarm was also produced.

The McLuckie methanometer and its workings are shown in Figure 5.6 (a and b). A measurement was taken by first filling the combustion and compensation chambers with mine air using the pump. With all cocks closed, the platinum wire was electrically heated to a temperature of about 370^{o}C. This burnt any flammable gases present leading to a decrease in the combustion chamber pressure. After a designated cooling period, the cock to the 'U' tube was opened. The methane concentration appropriate to the fall in pressure was read off the scale graduated from 0 to 3.5% in 0.1% steps. It took about eight minutes to complete a test.

Evaluation of the McLuckie (14)(17) showed that the readings obtained could be expected to be within ± 0.05% methane of the true value. Further, errors introduced by changes in atmospheric pressure and ambient temperature only became important in extremes. Despite the relatively long response time of the system, such performance characteristics were a considerable improvement over those of the flame safety lamp.

Before the end of 1930, the McLuckie methanometer had been approved for statutory measurements made under the 1911 Coal Mines Act. By 1950, after the flame safety lamp, it was the most widely used firedamp detector in British coal mines (14). This was despite its complexity of operation, but because of its relative sensitivity and robustness. However, from the early 1960's its popularity declined. This was due to the availability of smaller, simpler to use filament methanometers to be described later.



a) Exterior view b) Workings

Figure 5.7 The Ringrose automatic firedamp alarm (copyright Virtue and Company Limited)

Diagrams showing the Ringrose automatic firedamp detector and its workings are given as Figure 5.7 (a and b). It was 250 mm high and weighed 3.4 kg. Operating continuously, the relatively light firedamp from the surrounding atmosphere diffused into the porous pot faster than the other atmospheric gases. Their removal by combustion on the incandescent filament led to a reduction in the chamber pressure. The size was related to the flammable gas concentration. It was sensed by a diaphragm. In the event of the chamber pressure falling below an internally pre-set level, equivalent to either 1.25 or 2.5% methane, the red bulb was caused to glow brightly, indicating an alarm.

Although the Ringrose was simple to use and provided a considerably more obvious indication of the presence of firedamp than the gas cap on a flame, it was not without its faults. One concerned the fact that it was prone to giving false alarms. These were typically caused by rapid changes in atmospheric pressure, such as occurred during the descent of a shaft. Other problems included a slow response to changing firedamp levels and an uncertainty in the concentration at which the alarm was raised. Despite this, the Ringrose automatic firedamp detector was widely used in British coal mines, mainly because there were no alternatives. Its approval expired in 1975 by which time more reliable instruments had been produced. These are described below.

5.3.4 Catalytic filament methanometers and alarms

Although flame safety lamps, and the McLuckie and the Ringrose devices may have been considered successful flammable gas detectors in their day, ultimately all were replaced by instruments incorporating catalytic sensing elements.

5.3.4.1 General principles

A catalyst is a substance whose surface promotes chemical reactions without undergoing any changes itself. On the surface of such materials flammable gases can be oxidised, or combusted, at concentrations well below their normal limits of flammability. The amount of heat released in the process, and hence the temperature rise of the system, can be related to concentration. These principles have been used in the design of a wide range of methanometers and firedamp alarms. With these, the catalytic material has frequently been platinum. This was because its physical properties, for example luminance and electrical resistance, were known to change continuously with temperature. To promote the combustion of firedamp gases, namely methane, the catalyst must be pre-heated. As an example, in 1% gas a solid platinum wire must be between 800 and 1000°C.

An early catalytic methane detecting system was reportedly devised by a Aitken in about 1893 (19). He placed two thermometers side by side in a flow of sample air. This was pre-heated to the temperature of boiling water. The bulb of one, the 'detector', was coated with a layer of catalyst. That of the other, the 'compensator', was left uncovered. Any flammable gases present in the sample combusted on the detector causing its temperature to rise above that of the flow, shown by the compensator. The gas concentration was determined from the difference in thermometer readings. Although Aitken's device was not suitable for use in coal mines, as will be seen below, its use of two sensing elements, one for the heat of combustion and the other for the environmental temperature, later became a standard approach in methanometry.

5.3.4.2 Wire instruments

A more practical type of methanometer has been achieved using two platinum wire sensing elements. In its generalised form, one wire, the 'detector', is electrically heated so that combustion takes place on its surface whilst the other, the 'compensator', is maintained at close to ambient temperature. The concentration of flammable gas can be determined from a comparison of a temperature dependent parameter of the two elements.

Possibly the earliest portable underground firedamp detector to incorporate electrically heated catalytic wire elements was developed by Liveing in about 1883 (20). It is shown in Figure 5.8. If the mine air surrounding the detector wire contained any flammable gas, surface combustion caused it to glow brightly. The compensator was mounted in an enclosure containing fresh air. It formed a reference brightness against which that of the detector could be compared. From this an estimate of the ambient firedamp concentration could be made. The threshold of detection of the system was in the region of 0.25% flammable gas. This was well below that of the flame safety lamp.

Although the Liveing detector seems to have been extensively used in British coal mines (19), Lupton reports (21) that it was found practically useless. This view may have been prompted by, amongst other things, a high level of instability in the filament characteristics. This was such that the wires had to be replaced every few tests. It is now known that the cause of such behaviour is the evaporation of metal that occurs as a result of the high operating temperatures needed to combust methane on a solid surface. Another problem with the Liveing stemmed from the fact that whilst the brightness of the detector element increased with methane concentration up to about 9.5% it fell thereafter. This introduced the possibility of ambiguity in the measurements obtained. The behaviour is considered further in Section 5.3.4.3.

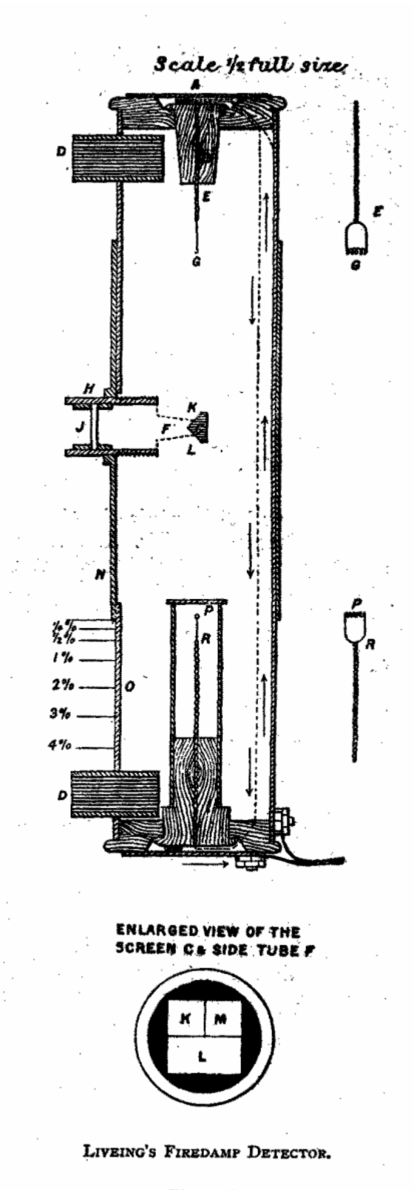


Figure 5.8 Liveing's gas detector

At some stage, thermocouples were placed in close proximity to the sensitive wires of the Liveing instrument (15). These were formed into a Wheatstone bridge circuit (see Appendix III) such that the output signal was dependent upon the sensed temperature difference. This was related to the flammable gas concentration in the sample with the result being displayed on a meter. Whilst it has not been possible to determine the extent to which this variant was used underground in British coal mines, it was an early attempt at producing a directly indicating flammable gas detector. Provided the meter is marked with appropriately sized graduations, it is very much easier to take readings with such instruments than where it is necessary to make a subjective judgement, such as comparing the relative brightness of two glowing wires.

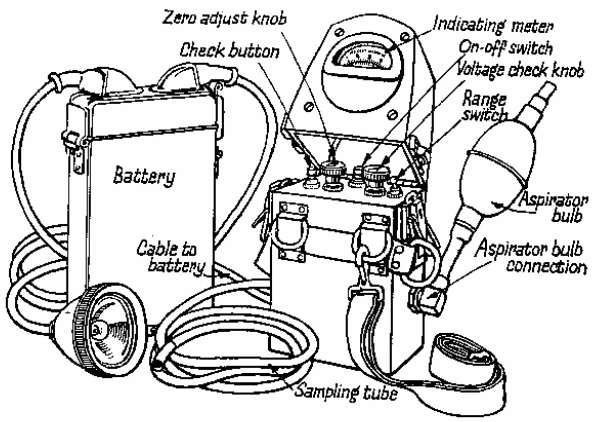
What eventually became a more widely used electrical arrangement of catalytic filaments was incorporated in the methanometer due to Léon in 1901 (22). Rather than relying on thermocouples for the sensing the heat of combustion, he used the platinum wire's own electrical resistance. This was known to vary predictably with temperature. Four wire filaments formed into a Wheatstone bridge were used. Two diametrically opposed elements were exposed to the environment under investigation whilst the others were kept in fresh air. Any bridge out of balance signal, indicating the presence of flammable gas, was shown on a galvanometer.

Whilst a device was made according to Léon's principles, it does not appear to have been widely used in British coal mines. However, the use of two active and two passive elements in a Wheatstone bridge circuit was an important advance in methanometer design. This is because the arrangement theoretically removed any dependence of the system's output on ambient conditions such as temperature, pressure and relative humidity. Should any effects have been present, all four arms of the bridge were influenced equally, leaving the galvanometer indication unchanged. In practice, however, this compensating system was not totally effective and it was necessary to allow the instrument to stabilise for about ten minutes when, for example, it was moved from a cold intake to warm return airway.

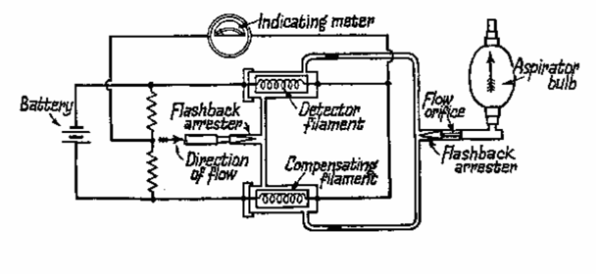
Léon's arrangement was simplified by Ralph in 1911-12 (23). Instead of using four wire sensors, he replaced two with fixed resistors. This resulted in the circuit shown in Figure AIII.1, where only Rd and Rc were the active elements. Although the instrument was not very successful, its electrical configuration subsequently became very popular.

A company that has had a major influence on the production of commercial flammable gas detectors for general underground use goes is the Mine Safety Appliance Company, or MSA. Set up in the USA during the 1930's, a British organisation had been formed by 1947.

One of the earliest MSA methanometers approved for use in coal mines was the 'W8' of 1936 (24). Diagrams showing the apparatus and its workings are given as Figure 5.9 (a and b)(18). This shows that Ralph's arrangement was used in that there were two platinum wire filaments and two fixed resistors formed into a Wheatstone bridge circuit. The detector element was 'sensitised' to promote combustion of methane at the relatively low temperature of 460°C. The compensator was 'deactivated' and operated at 340°C. Since no combustion took place on its surface, it was able to fulfil its role of maintaining the bridge balance during changes in



a) Exterior view



b) Workings

Figure 5.9 The MSA W8 methanometer (copyright Virtue and Company Limited) ambient conditions. Sample air was drawn through the apparatus using an aspirator bulb. The flammable gas content was shown on a meter calibrated directly in percentage methane. It covered two ranges, 0 to 2%, with an accuracy of ±0.05% methane, and 2 to 5%, with an accuracy of about ±0.1% methane. For collecting gas from remote locations a long sampling pipe could be connected to the gas inlet.

The MSA W8 was approved under the 1947 Ventilation Regulations and continued to be used for statutory measurements until the 1960's, By this time improved instruments had been produced. A reason for this longevity of use was its simplicity of operation. As an example, with the W8 it took less than a minute to obtain a reading of firedamp concentration compared with eight of the McLuckie.

As with other solid filament methanometers, the properties of the sensors in the W8 changed with time. This caused the meter to show the presence of firedamp even when the unit was sampling fresh air. To counteract this, a zero adjustment potentiometer was provided. Even so, the expected life of the filaments was about 1000 tests. This was considerably longer than with Liveing's device, a fact attributable in part to their relatively low operating temperature.

With the recognised problems associated with the Ringrose and the apparent success of the W8 and similar instruments, it is not surprising that consideration was given to the development of an automatic firedamp alarm incorporating catalytic wire sensing filaments. Apparatus of this kind was produced by MSA sometime before 1953. It did not seemingly find favour in British coal mines.

A more successful automatic instrument that also used solid catalytic filaments was made by the English Electric Company Limited from about 1969 on. Called an 'automatic firedamp detector' (AFD), significantly it was probably the first to combine the benefits of a quantitative methanometer with those of an alarm, hence the use of 'detector' in its title. Like the Ringrose, it was completely automatic. This enabled it to be used by unskilled workers and meant that protection from firedamp was maintained at the work place even in the absence of officials with their flame safety lamps.

A photograph of the English Electric AFD is reproduced as Figure 5.10. The unit was 306 mm tall and weighed 1.8 kg. Two sensing elements were used, each formed from a platinum heater coil wound around a small glass tube containing a thermocouple. The detector used wire coated with a 'specially prepared' catalyst. It is presumed the compensator used untreated wire. Increasing levels of firedamp resulted in a concentration dependent temperature difference between the two thermocouple outputs. This was amplified using a transistor based circuit, possibly one of the earliest to be incorporated in an underground methane detector. The result was displayed on a meter calibrated from 0 to 3% methane. If at any time the indication rose above an internally set alarm point, lights behind a translucent red screen were caused to flash, providing a readily apparent warning. An internal lead acid battery powered the AFD for up to nine hours continuous use. To facilitate the detection of thin roof layers of gas, the sensors were mounted on the top of the instrument. However, no remote sampling probe seems to have been available for use with the apparatus.

Approval for the English Electric AFD as a methane detector under the coal mining regulations was granted in 1965. It has not been possible to ascertain how many units were used underground.

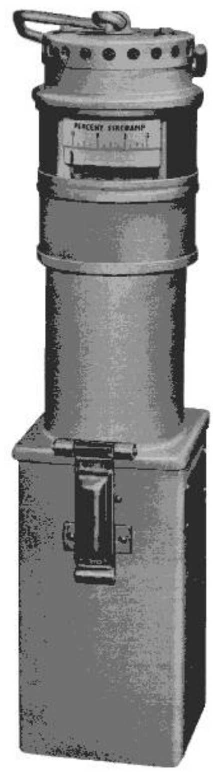


Figure 5.10 The English Electric automatic firedamp detector

5.3.4.3 Pellistor instruments

One of the problems with wire sensors was their change in sensitivity to flammable gas with time. This occurred as result of the high operating temperatures necessary for catalytic combustion to take place on a solid surface. Also, a need for electrical heating powered from portable power supplies meant that the filaments themselves needed to be very thin, typically 50 μm. This made them very fragile.

Working to overcome these problems, in about 1958 SMRE devised a new form of catalytic flammable gas sensor, later called the 'pellistor' (25). Shown in Figure 5.11, it was formed from a small porous ceramic bead upon whose surface was deposited a catalyst. This was often palladium, or an oxide of it. The assembly was heated electrically using a small platinum coil. The resistance of this element was used as an indicator of its temperature and hence the heat of combustion of any flammable gases present in the surroundings. This use of a catalyst other than platinum made the pellistors reactive to methane at relatively low temperatures, typically 500 to 600°C (26). Further, embedding the thin heater coil the bead gave the sensor good mechanical strength and stabilised its physical properties through the reduction of metal evaporation.

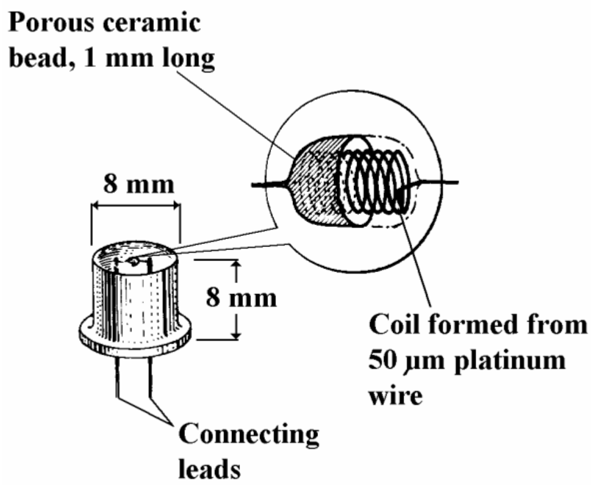


Figure 5.11 The pellistor

In methanometers, pellistors are usually formed into the Wheatstone bridge shown in Appendix III. In this, Rd would represent an active detector element and Rc a compensator. Fulfilling the functions previously described, the latter is virtually identical to the former, with the exception that its surface is made such that it can not oxidise flammable gases. Typical bridge supply requirements are 220 mA at 2V.

When exposed to increasing concentrations of methane between zero and about 3%, the output from a pellistor pair in circuit rises linearly. A sensitivity of 15 mV/% methane over this region seems typical for sensors used in mining applications. Above about 3% non-linearities begin to appear in the characteristic, with a peak in output occurring around of 8%. At higher concentrations there is inadequate oxygen to allow complete combustion and the output declines. Similar performance characteristics are seen with solid wire catalytic sensors. With a peaked response such as this there is clearly a potential for ambiguities in the readings provided by pellistor based methanometers, as there were with wire instruments. Few if any of the instruments developed for mining use appear to include provisions to overcome this problem. The reason for this has not been discovered.

Commercial exploitation of the pellistor was undertaken by the English Electric Valve Company Limited who began marketing a 'VQ1' type in about 1966. Working under contract to the NCB, some five years later the 'VQ2' was produced. This consumed considerably less power than its predecessor. Subsequently other manufacturers have developed their own catalytic flammable gas sensors that are similar in concept to the pellistor.

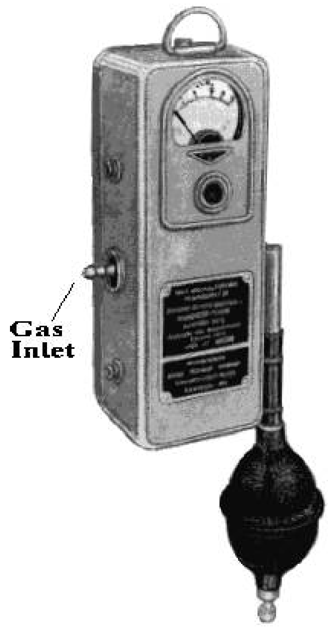


Figure 5.12 The MSA GP methanometer (copyright National Coal Board)

SMRE produced the first methanometer to incorporate pellistors in about 1959. Unfortunately no diagram of the device has been located, but it is believed to have been the direct forerunner of the MSA GP (General Purpose) methanometer shown in Figure 5.12 (27). With this device, sample gas was drawn over the sensors using the aspirator bulb shown. A reading of methane concentration was taken by depressing a button on the front of the unit. Within about seven seconds the result was shown on the meter. This was scaled from 0 to 5% methane in 0.2% divisions. Being only 206 by 94 by 50 mm in size and weighing less than 1.4 kg, the unit could be held in one hand whilst the other was used to operate the aspirator.

The MSA GP methanometer was approved for use in British coal mines in 1961 and was still being used over ten years later. However, the introduction of TM7 meant that it could not be used for statutory purposes due to an unacceptably poor reading accuracy of ±0.5% methane at 2.5% (28).

In 1967 MSA produced the C4(M) methanometer. Roughly similar in appearance to the GP instrument it had an improved reading accuracy of ±0.12% methane, or ±10% of the true value, whichever was the greater. It was approved for statutory methane measurements until 1975.

More recently the MSA D6 methanometer shown in Figure 5.13 has been developed. This is only 150 mm high and 65 mm wide, a compactness attributable to its inclusion of integrated electronic circuits. It is truly a single handed instrument. Rather than use an aspirated sampling system, gas diffuses to the sensors via a sintered disc dust filter and flame trap situated on the top of the instrument. The methane concentration is displayed on a meter, or liquid crystal display with the more recent versions. For sampling remote locations an aspirated probe assembly can be fitted.

Figure 5.13 The MSA D6 methanometer

The D6 was approved for use in statutory methane measurements in 1972. Since that time it has become very popular, aided no doubt by its smallness, simplicity of operation and robustness.

In addition to hand held sampling methanometers, pellistors have also been used in automatic methane detectors (AFDs). A specification for such was issued by the NCB in June 1972. Two devices were subsequently produced, one by Sieger Limited under contract to MRDE, and the other by MSA Limited as a private venture. Both became available for underground use in about 1974.

Figure 5.14 The Sieger automatic firedamp detector

A photograph of an early Sieger AFD is given as Figure 5.14. In this instrument the pellistor elements were mounted behind a downward facing sintered filter disc between two red alarm indicating lamps at the top of the unit. With gas diffusing to the sensors, the sampling of mine air was a completely automatic process. Indication of the sensed concentration was shown on a meter calibrated from 0 to 3% methane. In the event of this rising above an internally pre-set level, alarm lamps were caused to flash. The AFD was 225 mm tall and weighed 1.36 kg making it easy to carry around. A rechargeable battery could power the unit for up to 10 hours.

The Sieger AFD shown, and a later version incorporating a liquid crystal digital display, were both approved under TM7 and its successors and have been widely used for statutory purposes underground in British coal mines. The AFD made by MSA has likewise been approved to TM7 and also widely used underground in British coal mines.

In Chapter 2 it was noted how during the latter part of the 1950's the NCB began developing an automatic coal mining machine called the Collins miner with the aim of reducing the costs of production. Since the system was powered by high voltage electricity the law stated that provision must be made for the power supply to be switched off if the flammable gas concentration in the surroundings rose above 1.25%. With the operator remote from the coal cutter, locally indicating instruments such as those described above could not be used. Instead, MRE proposed the development of a transmitting methanometer fitted with SMRE pellistors. Initial trials revealed, however, that whilst the performance of these sensors may have been adequate for intermittent operation, when continuously powered their outputs showed unacceptably high levels of drift with time. Responding to these findings, SMRE and MRE embarked on a program of pellistor development and evaluation. This continued after work on the Collins miner had ceased.

Extra impetus was given to the development of a continuously operating firedamp monitor for coal mines with the publication of the official report into the Cambrian Colliery disaster in 1965 (2). This stated that the accident demonstrated a need for apparatus that could be left underground to raise the alarm and switch off electricity as and when there was a dangerous build-up of firedamp. Design work on such a system began at MRE in mid-1966.

A schematic diagram of the MRE Four Headed Methane Monitor Type 225 is given as Figure 5.15 (29).

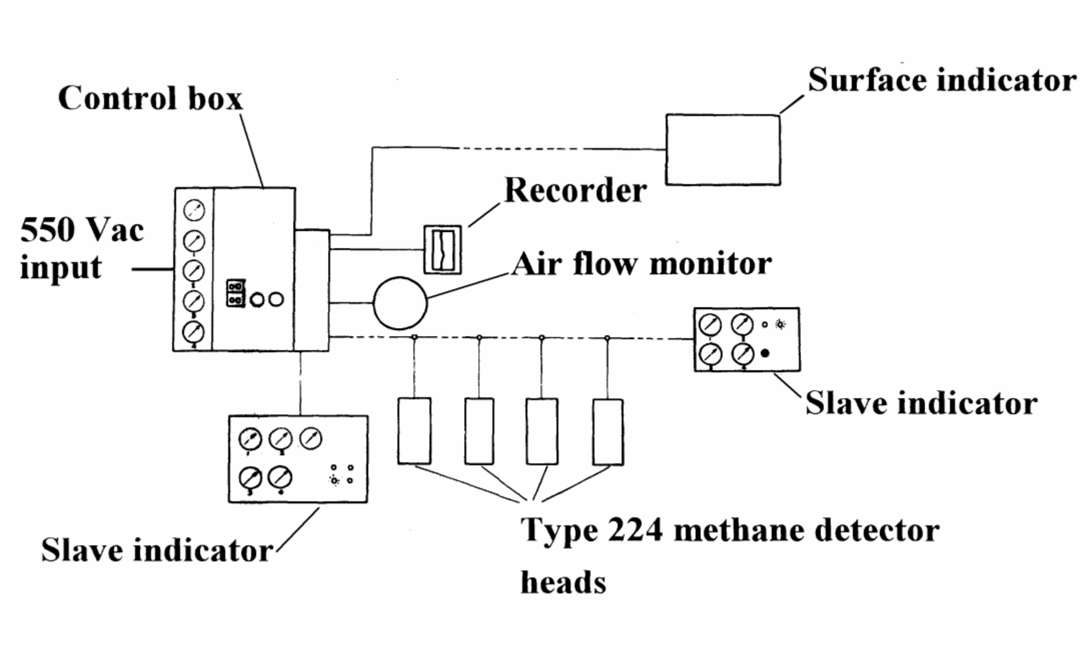


Figure 5.15 The MRE type 225 four headed methane monitoring system (copyright National Coal Board)

Each 224 methane sensing head was formed in a brass tube 113 mm long and 46 mm in diameter. A pair of VQ1 pellistors was mounted behind a sintered disk filter at one end of the assembly. With two fixed resistors, these were formed into a Wheatstone bridge circuit. Its output was amplified to produce a detector head signal in the range 0.4 to 2.0 V. This corresponded to input methane concentrations from 0 to 3%. Voltages outside this range were used as an indication of a fault condition. As with the AFDs, the environmental gases diffused up to the pellistors. This meant that sampling was completely automatic.

Intrinsically safe power for the detector heads was derived from 550 V ac mains in the flame-proof control box. This unit also processed the sensor output signals and initiated any alarm indications. These were shown locally and on any remote slave indicators.

Early 225 systems were installed underground in mid-1968. Experience revealed, however, that the bulky nature of the equipment and a consequence of the control unit being flame proof, and the need for a high voltage supply, limited the number of locations at which it could be used. As a result, in about 1970 the NCB suspended further development of this system. Instead MRDE was tasked with producing a single headed methane monitor. This was to be capable of being left installed at a site for an extended period of time and yet be small enough to permit easy relocation as and when required. To maximise its flexibility of use, it was to be formed from a number of modular components, bolted together and connected by cables. All electronic circuits were to be intrinsically safe.

A sketch of the subsequently designated BM1 methane monitor as it would appear installed underground is given as Figure 5.16 (30).

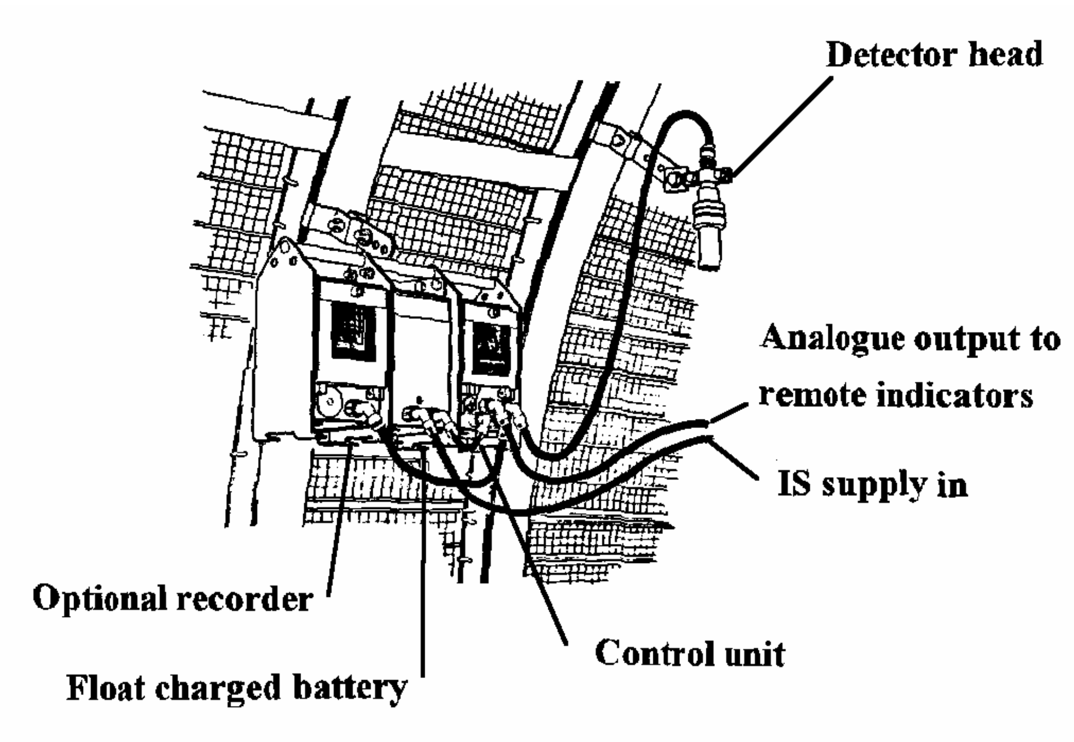


Figure 5.16 The BM1 methane monitor (copyright National Coal Board)

The detector head of the BM1 was similar to the Type 224, although it was formed in a metal coated plastic tube plastic and included the new VQ2 pellistors. These were mounted behind sintered bronze and activated charcoal filters through which the gas diffused. The response time to changing gas levels was about 12 seconds.

Mounted near the roof of a roadway, the detector head was power by the control unit. This also processed the output signal and displayed the sensed methane concentration on a meter scaled from 0 to 3%. An electrical analogue, in the range 0.4 to 2.0 Vdc, of the value shown was available at externally accessible sockets for connection into a local recorder, as seen in the diagram, and/or a data transmission system such as MINOS. Also contained in the control unit were alarm circuits that could activate pairs of internal relay contacts. These were accessible to external devices via sockets. In the on guard state the 'alarm' indicators pulsed every 15 seconds to show that the monitoring system was functioning. Should the methane concentration rise above a pre-set level this flash rate increased to once per second.

Power to the system was typically provided by the battery shown. This was float charged from a flame-proof transformer. It could continue supplying the BM1 in the event of the mains being switched off.

Manufactured by Sieger Limited, the BM1 was certified for use as a methanometer for statutory purposes in January 1973. By December 1975 there were over one hundred units in use. Some twenty years after its introduction the BM1 was still in widespread use in the coal mines of this country and abroad. A contributory factor to this popularity has been the reliability of modern pellistors; a detector head assembly was typically only removed from the mine for re-calibration every two months.

The need for underground methane monitoring equipment that was able to switch off electricity, a requirement identified by (2), was reiterated in the report (31) of a non-fatal explosion at Cardowan Colliery, Strathclyde in January 1982. Whilst this requirement could be met by the BM1 the necessary ancillary equipment was expensive and very bulky. Consequently, MRDE began work on a new methanometer. Designated the BM3, it was basically a modernised BM1 that also included most of the components needed to isolate mains power automatically. The apparatus was certified for underground use as a methanometer in 1986 and was in widespread use in British coal mines at the time of privatisation.

5.3.5 Optical methanometry, the past and the future

Despite the advantages of pellistor based methanometers over most of their predecessors, they are not without their operating problems. These include the possibility of an ambiguous reading. Also they can suffer a permanent loss of sensitivity when exposed to commonly found substances such as silicones. In response, during 1980's HQTD and others began developing underground methane monitoring systems that incorporated optical gas sensors, notably those using infrared radiation.

The detection of methane in coal mines using optical techniques was not new to the 1980's. For example, work was being done on apparatus of this type in Germany in 1912. By 1950, or possibly earlier, a number of companies had produced so called 'interferometer' type mining methanometers. In their general form, shown schematically in Figure 5.17, a beam of light was split in two. One part was directed through a cell containing a reference gas and the other through a cell containing the air sample under investigation. When the two beams were recombined at an eyepiece a pattern of straight lines, or fringes, was seen. This consisted of a single dark line with a number of lighter ones on either side. Increasing concentrations of methane in the sample caused the fringes to shift relative to a scale calibrated directly in percentage methane (32).

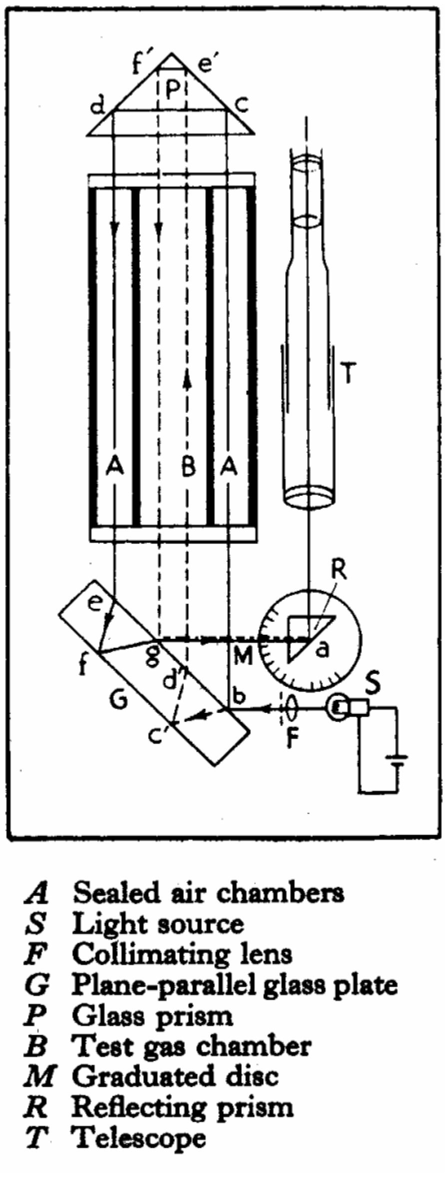


Figure 5.17 Interferometer gas detector (copyright Cleaver-Hume Press)

In 1957, SMRE reported the results to an evaluation of an interferometer type methanometer (32). This revealed that changes in 'normal' environmental variables could combine to give flammable gas readings more than 50% higher than a laboratory analysis of the same sample. Despite behaviour of this kind such instruments were used in 'substantial' numbers in British coal mines, certainly up to the late 1960's (26). This usage subsequently declined with the introduction of the simpler pellistor based systems described above.

The more modern application of optical methanometry makes use of the absorption of infrared radiation by the gas. Two basic layouts have been considered (33). In the first of these, a sample is introduced into a small chamber traversed by a beam of radiation. In the second the beam propagates through several meters of open air. In both cases, the concentration present is determined by the relative intensity of adjacent spectral lines, one of which is affected by methane and the other that is not. At the time of writing (1995), neither of these ideas have been converted into a practical instrument for use underground in coal mines.

5.4 Conclusions

All efforts to remove every possible source of ignition of firedamp from coal mines have proved unsuccessful. Thus it is concluded that the only way of ensuring that underground workings are safe from explosion is to ensure that adequate quantities of fresh air are always being provided to dilute the gas below its lower explosive limit. The efficacy such measures can only be ensured by the continued use of firedamp monitors.

Firedamp occurs in most, if not all, coal seams. Thus the hazard it represents to miners is under control rather than removed. Consequently it is concluded that there is no case for relaxing the firedamp safety measures and monitoring procedures that are being applied underground.

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Chapter 6 The hazard posed by the gaseous products of explosions and fires

Chapter 5 outlined the hazard associated with firedamp. During its combustion, oxygen is removed from the atmosphere and a group of gases collectively called 'products of combustion', or 'POC', added. Similar gases are also produced by fires. This chapter discusses their occurrence in coal mines from both sources and the steps that have been taken to protect workers from their effects.

6.1 Explosions

In 1814 John Buddle suggested (1) that only about twenty-five percent of an explosion's victims died during the initial combustion phase. He believed the remainder were suffocated by irrespirable gases left as a consequence of the ventilation being disrupted. By 1843 these were being called 'afterdamp'.

This belief that afterdamp resulted from poor ventilation, that is a similar source to blackdamp, led to the view that their constituents were also similar, namely a deficiency of oxygen and/or elevated levels of carbon dioxide. Consequently rescue workers entering a mine after an explosion assumed warning of personal danger would be provided if they used the same detection methodologies. From Chapter 4 it will be seen that these were the flame safety lamp and observations of their depth of breathing.

In 1896, observations of the blood of victims of colliery explosions led Haldane to the conclusion that most had died from carbon monoxide poisoning rather than the effects of the blackdamp gases. This toxic gas was produced during the combustion of carbon rich materials, notably coal, in the presence of an inadequate supply of oxygen.

Unfortunately, fatal concentrations of carbon monoxide have no visible effect on the flame of a safety lamp, nor do its physical sensations provide much warning that a human is about to be overcome. Thus the discovery of this gas in afterdamp showed that the safety precautions being applied by rescue workers were not providing them with any protection from one of its major hazards. This finding led directly to the development and application in coal mines of gas detection methodologies that would respond to carbon monoxide. These are described in Section 6.3.1. Here it will be seen that one of the approaches adopted has been to use small birds.

Legislation covering the provision of safety apparatus for use in colliery recovery operations was first introduced in 1928. Under the Mines General Regulations (Rescue) it was made a requirement that every colliery was to be affiliated to a local rescue station. Amongst other things, this was to be equipped with cages for the containment of small birds. With the advent of the more reliable electronic detectors for carbon monoxide described in Section 6.3, the statutory use of birds was phased out. However, this was not done completely until 1995.

6.2 Fires

Underground coal mine fires either occur as a result of the low temperature oxidation of coal, called 'spontaneous combustion', or the thermal decomposition of material by naked flames or on hot machinery. For the purpose of this monograph these will be termed 'open' fires. In both cases toxic gases can be released into the atmosphere.

Precise details of the number of coal mine fires that occurred during the nineteenth century have not been located. Reasons for this include the fact that unlike accidents to the person regulations requiring the reporting of such events were not introduced until 1906. Collating the data that is available shows that between 1889 and 1953 underground fires killed over 650 coal miners (2). The associated economic costs through lost production were also severe. For example, between 1907 and 1913 at one colliery alone there were about 36 fires per year leading to an annual loss of 144 working days (3).

Concerning the causes of mine fires, data from around 1930 reveals that about 70% were spontaneous combustion with most of the remainder being open fires initiated by matches. By the 1950's an increase in the use of machinery underground had led to a change in the situation. For example, by then only about half were spontaneous combustion. Causing increasing concern at this time was the number and severity of the incidents associated with conveyor belts. Although they only accounted for about one fifth of the total they caused over 90% of the fatalities, a matter considered in Section 6.2.2.

Recent data (4) reveals that even at the end of the twentieth century fires were still a real problem in coal mining. As an example, in 1989/90 there were nearly fifty reported incidents. Of these nearly half were caused by catastrophic mechanical failures and friction associated with conveyor belts. Fewer than 20% were spontaneous combustion.

Before describing how underground fires have been detected, it is considered appropriate to provide more specific information as to their nature and the influence this has had on the methodologies devised for their detection.

6.2.1 Spontaneous combustion

When some types of coal are exposed to air at room temperature, spontaneous oxidation takes place at the surface. This reaction is exothermic and occurs at a rate that increases with temperature. Thus if the heat produced is not removed the oxidising mass gets hotter. Eventually a point may be reached where flame appears. The whole process is known as ‘spontaneous combustion’.

An early record of spontaneous fires is due to Dud Dudley in 1665. He described how they occurred in mines when air passed over coal dust.

As to understanding the causes, in 1686 Dr Plott of Oxford suggested that the heat was produced by the oxidation of pyrites contained within the coal, a theory accepted for many years. However, by the turn of the this century it was being recognised that although this material did play a part in the processes taking place, the main mechanism was a surface reaction between atmospheric oxygen and carbon.

By the early 1920’s there was a sufficient understanding of the variables associated with spontaneous combustion to facilitate the identification of those locations at which it is most likely to occur. Generally, these contain carbonaceous material and through which a current of air passes. The air flow rate has to be high enough to provide sufficient oxygen for the chemical reaction to take place yet low enough so as not to remove too much heat. Typical sites liable to spontaneous combustion have been identified as including the waste behind a coal face and other areas of fractured ground. Here the required air flow is associated with leakage between bounding airways brought about by pressure differences between different points on the ventilation network. The likelihood of a fire developing can thus be reduced by increasing the size of the airways (to reduce the ventilation pressures) and applying sealant materials to the walls. Such precautionary measures are applied in modern coal mines liable to spontaneous combustion.

Between initiation and bursting into open flame, a spontaneous fire emits a range of ‘contaminants’. These eventually find their way on to the colliery’s ventilating current. Recognising how their patterns of release are related to the state of a fire has proved crucial in the development of the detection methodologies described in Section 6.3.

Smoke is an obvious and visible product of spontaneous combustion. It tends to occur when there are inadequate amounts of oxygen to produce carbon dioxide and carbon monoxide. Thus it is generally associated with the later stages of a developing fire when reaction rates are high.

The heat produced by the oxidation process causes localised warming of the strata and of the passing air current. If the latter gets hot enough the temperature of any other air with which it mixes may also rise detectably. In Section 6.3.2 it will be seen how air warming and abnormal ground temperatures have both been used to provide early warning of developing spontaneous fires.

Water is produced during the combustion of coal. As with heat, if sufficient quantities are released they may lead to a detectable increase the relative humidity of the mine ventilating current. Further, if this is relatively cool, condensation will occur at the mixing point. The result is either a visible haze or the appearance that the road walls are sweating. Both these phenomena have been used as indicators of spontaneous fires.

From a detection point of view an important emission from a fire is a characteristic smell. Given the name ‘gob stink’, it has been described as being initially like that of decaying vegetation with a taint of onions. Later, as the source temperature rises, it tends towards paraffin or petrol. Tests (5) revealed that detectable smells might occur many hours before the appearance of some of the other fire indicators.

In 1898-9, Haldane and Meachem reported (6) the detection of enhanced levels of carbon dioxide plus relatively small amounts of carbon monoxide in return mine air> Further, they were present even under normal conditions. Whilst carbon dioxide could have been produced in significant quantities by innocuous processes such as breathing humans or burning lamps, a primary source of carbon monoxide was spontaneous combustion. Responding to this, rises in the latter's concentration above a so called 'district norm' have since been used to indicate the possible presence of a developing fire, as described in Section 6.3.2.

Whilst spontaneous combustion is one source of carbon monoxide, the reliability of this gas as an indicator of fire underground is reduced by the fact that it is not the only one. For example, normal mining events such as the firing of explosives and the operation of diesel locomotives also produce the gas. Also, changes in ventilation flow rate and barometric pressure can lead to elevated levels return airways. However, their 'masking' effect can be minimised by the use of a discovery due to Graham in 1914. He found (7) that the ratio of the volume of carbon monoxide produced to that of oxygen consumed, subsequently called 'Graham's ratio', was dependent upon the temperature of the oxidising coal and hence it closeness to bursting into flame. Later it was also shown that non-fire events only cause the numerator in the ratio to rise, making it easier to differentiate between them and real fires. The latter causes the denominator to fall.

Investigations into Graham's ratio during a developing fire have enabled the following interpretations to be put on the values obtained (8):

- 0.4 or less: normal.
- 0.5: recommended that a thorough check be made of the district.
- 1.0: spontaneous heating almost certain.
- 2.0: spontaneous heating is serious.
- 3.0: active fire.

Since Haldane, Graham and others described the emission of carbon dioxide and carbon monoxide by spontaneously combusting coal, the availability of increasingly sophisticated analysis techniques has enabled a more comprehensive list of fire gases to be produced. A relatively recent review (8) shows that:

- At room temperature: carbon dioxide and carbon monoxide are produced, oxygen is depleted.
- At 100^{o}C: traces of hydrogen are produced and coal looses moisture normally contained within it.
- At 140 to 150^{o}C: traces of the higher hydrocarbons, such as ethylene and propylene, appear.
- At 400^{o}C: traces of distillation products appear, including methane and increasing levels of hydrogen.
- At 600 to 700^{o}C: the distillation products are burnt in the fire zone producing carbon dioxide, carbon monoxide, and water.

This list is far from complete and other products of combustion have been identified. Also, factors such as the type of coal, its exposed surface area, the oxygen concentration present, the temperature, and the thermal conductivity of the surrounding strata can lead to significant variations in the release patterns between locations. For example, some fires may progress from their initial stages into uncontrolled conflagrations within a few hours whilst others may take weeks. This apparent unpredictability in the behaviour of spontaneous fires has made their reliable detection difficult to achieve.

6.2.2 Open fires

Open fires typically occur when combustible material is brought into contact with a hot body or flame. Further, they often develop into major conflagrations with a few minutes of being initiated. In the presence of a ventilating current the mine workings down stream of the incident can thus be rapidly contaminated with high levels of potentially toxic products of combustion. For this reason it is important that a very early and widespread warning of such a fire be provided.

Up to about the middle of the twentieth century the majority of non-spontaneous fires were initiated by naked lights. The materials involved were almost exclusively hydrocarbon based, namely coal and wood. Consequently, the products of combustion were primarily a deficiency in oxygen, carbon dioxide, carbon monoxide, and water. Despite the recognised toxicity of some of these gases little attention seems to have been directed at the study of open fires. This was probably because, being caused by naked lights, they had an obvious remedy. They also occurred when somebody was present to raise the alarm.

Beginning in the mid-1940's, pressure to increase the productivity of coal mines saw an acceleration in the application of conveyor belts underground. Commenting on this in 1947, Bryan noted (9) that over the previous seven years such systems had been responsible for sixty-three fires. Of these about one third had developed after the belts had ceased running and the attendant withdrawn. With the burning materials being mainly natural rubber and organic fibres the POCs would have been similar to those of other open fires of the time. What made belt fires potentially more dangerous was the fact that many occurred when there was no one present to raise the alarm. This led to the possibility that miners down wind of the incident could be exposed to toxic gases without being aware of the danger they were in. Clearly, such situations could only be avoided by the provision of automatic fire detection systems for use with conveyor belts. For some undiscovered reason no action was taken along these lines at the time.

Before the end of 1948 a conveyor belt fire had claimed its first lives. This happened at Whitfield Colliery in Staffordshire (10). The cause was the frictional heating between a stalled belt and a still rotating drive roller. The machinery was unattended at the time. One of the three victims was almost a mile away from the fire. Despite a similarity between the circumstances of this death and those outlined by Bryan, for some undiscovered reason the provision of automatic underground fire detection systems was still seemingly not considered at the time.

On 26 September 1950 a disastrous belt fire occurred at Creswell Colliery. Eighty men died from carbon monoxide poisoning. The cause was later identified as having been a torn section of conveyor, heated by friction as it rubbed against a gear head. The fire eventually travelled 555 m downwind from its source. A combination of factors, including the location of the conveyor belt in the intake and the presence of the ventilating current, led to the toxic products of combustion being transported to the return side of the mine where many of the fatalities occurred.

Following this disaster serious attempts were made to improve the safety of underground conveyors. Ultimately these included the introduction of belting made from fire resistant PVC, the initiation of regular patrols throughout their lengths and the fitting of instruments such as belt slip indicators. However, for some unaccountable reason automatic fire alarms sensitive to POCs carried on the ventilating current were not introduced until some eight years later. These are described in Section 6.3.3.

Despite the above precautions, in the 1990's conveyor belts still represent a major fire hazard in coal mines; during 1989/90 they caused 47% of all the reported incidents of this kind with the trend being upwards (11). Although PVC belts do not burst into flames as their predecessors had done, they do give off toxic fumes, including hydrochloric acid. For these reasons the need for effective automatic fire detection systems was as great as it ever was.

6.2.3 Fighting fires

To extinguish a fire the temperature of the burning mass must be reduced, the fuel supply removed, or oxygen excluded. This section briefly considers the application of each of these approaches to the control of coal mine fires.

On the surface the temperature of fires is traditionally reduced by the application of large amounts of water. Underground, restricted access to the seat of a fire may mean that insufficient quantities reach the burning mass to achieve its rapid cooling. Under these circumstances, water gas may be formed. This is a mixture of carbon monoxide and hydrogen, or hydrogen on its own. It is highly flammable and if not diluted with a current of fresh air may represent a considerable explosion hazard. Whilst warning of such a danger would be reduced by the provision of underground hydrogen detectors at fire sites, it is not known whether consideration was given to this matter within the British coal mining industry up to privatisation.

Fuel is removed from a fire by digging out the burning material. This practice can, however, only be applied to small incidents. For this reason early detection is vital.

Once a fire has been allowed to develop into a large conflagration, or can not be accessed, the only other approach is to starve it of oxygen. This is done by constructing impervious and explosion proof walls, or stoppings, across all approaching airways. If these are efficient all the oxygen in the enclosed space will eventually be consumed and combustion cease. In addition, conduction of the heat through the surrounding strata will cool the once burning materials to below their ignition temperature. Once this has occurred the affected area can be reclaimed. However, a major problem is knowing when this can be done without risk of the fire recovering. To some extent, the information required to make this judgement can be gained from observations of the temporal behaviour of, for example, the oxygen, carbon dioxide and carbon monoxide concentrations behind a stopping. The necessary samples are drawn off through pipes. Due to the relative slowness with which the conditions change, the delays associated with their being analysed in surface laboratories appear acceptable.

This slow response time of laboratory analysis is not satisfactory when attempting to ensure toxic gases are not leaking from around the stoppings. For this, and also when the reclaimed area is being entered, portable toxic gas detectors are used. These are described in Section 6.3.

The process of oxygen depletion within a sealed off area can be accelerated by the injection of inert gases, an approach investigated as long ago as 1858. By 1915, carbon dioxide had become a recognised fire extinguishing agent for surface installations. However, its application underground was less successful (12). One reason stemmed from difficulties in constructing gas tight stoppings. More recently it has been realised that carbon dioxide decomposes in fires to release oxygen and carbon monoxide. This is not an ideal situation since the former will fuel the fire and the latter then becomes unavailable as an indicator of the state of the fire.

Since 1962, nitrogen has been widely used to extinguish fires underground. This gas does not decompose to toxic components, is not flammable, and is not used as an indicator of the state of the fire. There is, however, the danger of creating localised areas of blackdamp at the injection site. Protection against such an eventuality can be provided by the use of the oxygen deficiency monitors described in Chapter 4.

6.2.4 Regulations covering underground fires

In Chapter 1 it was noted how one of the hazard management principles requires knowledge of the system state. Possibly with this in mind, the earliest mining regulations specific to fires were concerned with data collection. Under the Notice of Accidents Act, 1906, it was made a requirement that all cases of fire below ground were to be reported.

It has not been discovered why the statutory reporting of fires was omitted from the earlier mining regulations. From comments made after 1906 it seems possible that it may have been because most mine fires were spontaneous combustion. These tended to develop only slowly with the result that the legislators experienced difficulties in formulating rules that defined precisely when an incident became so active and dangerous as to justify it being reported. What caused attitudes to change in 1906 is not clear, but by this time it was accepted that the moment of existence should be when gob stink, smoke or some other clear sign of combustion was detected or observed. Included in the latter was a 20^{o}F (11.1^{o}C) rise in the air temperature above ‘normal’, or the attainment of 110^{o}F (43.3^{o}C) (3). As will be seen from Section 6.3.2 this led to the placing of thermometers at strategic locations underground. From the results of Haldane and Graham, another recognised sign of combustion would have been increases in the concentration of carbon monoxide gas. However, during the period under consideration no reliable underground measurement method for this gas was available.

On discovery of a fire underground both the 1911 Coal Mines Act and the later Mines and Quarries Act, 1954 required men to be withdrawn from the affected parts of a mine. Those engaged in inspection or recovery work were, however, allowed to remain. Clearly these needed to be protected against the presence of toxic gases. Details as to how this was to be done were contained in the Coal Mines General Regulations (Rescue) and its successors. Until very recently, these required that small birds be provided for gas detection purposes.

Along with a thermometer, the 1911 Act required that hygrometers be placed in the intake and return airways. It is postulated that the differences in readings were intended to show abnormal rises in the moisture content of the air current associated with developing spontaneous fires. This requirement was later abandoned, possibly indicating that the approach had not proved successful.

Responding to the Creswell disaster of 1950 the NCB introduced its own regulations and codes of practice designed to limit the effects of fire underground, particularly those associated with conveyor belts. One example required that such systems be examined between one and three hours after they had stopped running. Clearly for mines with long belts this could represent a considerable cost in manpower. However, a relaxation in the rules was allowed in those places where automatic monitors of heat or products of combustion were installed. Examples of the latter are described in Section 6.3.3.

6.3 Afterdamp and fire detection

6.3.1 Afterdamp

Until the 1890's, the detecting methodologies used for afterdamp were similar to those adopted for blackdamp. They are described in Chapter 4.

Once carbon monoxide had been identified in afterdamp detection methodologies appropriate to this gas began to be applied. Possibly one of the most widely known was to use small animals and birds. As Haldane showed, having relatively high pulse and respiration rates their blood accumulates toxic concentrations of carboxyhaemoglobin (see Appendix I) faster than a human would under identical conditions. Thus by observing how the animal behaved an early warning of danger from carbon monoxide could be obtained.

It is believed that small birds were first used as an 'alarm' for carbon monoxide at Talk-o'-th'-Hill Colliery, Staffordshire, possibly following an explosion on 27 May 1901. From then on, and in the absence of any alternative, the approach quickly became the standard. Regulations introduced in 1928 made it a requirement that all mines rescue stations and the larger collieries maintain a supply of small birds for the detection of toxic gases. This provision was not removed until 1995 by which time the legislators had recognised the availability of reliable electronic carbon monoxide detectors. These are described below.

Many different animals and birds were considered for use as detectors of carbon monoxide, including mice, guinea pigs, rabbits, dogs, canaries, pigeons, and chickens. Of these the most widely popular was the canary, due to a combination of its small size and great activity. Taken together, they made it very sensitive to the toxic gas. Also a clear sign of being poisoned was provide when it fell off its perch.

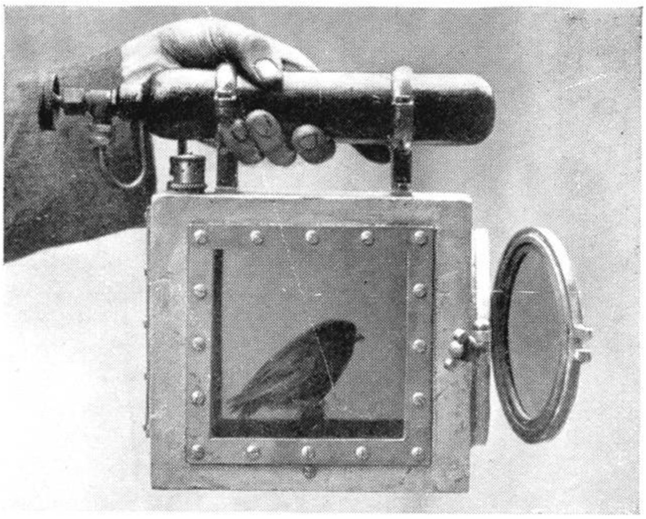

Figure 6.1 The Haldane cage (copyright The Saint Catherine Press)

Once a canary had succumbed to gas the protection provided was removed. To overcome this problem, by 1914 'Haldane cages' were being used to transport birds underground. Shown in Figure 6.1, they consisted of a box fitted with a small oxygen cylinder. On entering a mine the cage was sealed. When the presence of carbon monoxide was suspected it was opened to atmosphere and the behaviour of the bird observed. If it fell off its perch the cage was re-sealed and reviving oxygen administered.

Photographs of mines rescue brigades equipped with Haldane cages suggest that the apparatus was widely used in British coal mines.

A relatively recent study (13) into the performance of the canary as a detector of carbon monoxide revealed that whilst it could often be expected to show symptoms of distress well before a human, there were circumstances when it would not. Typically these occured at the lower gas concentrations. Here a working man could be overcome whilst the bird was not. Such performance tended to enhance the danger of a situation rather than reduce it as intended. This was because of the false sense of security generated. Problems such as this, and also the fact that the bird was incapable of providing a quantitative indication of gas concentration, led to the development of alternative forms of carbon monoxide detector for use in coal mines. These will be discussed in the sections that follow.

6.3.2 Spontaneous combustion

Although smoke is one of the more obvious emissions from spontaneous combustion, significant amounts are not necessarily produced in the early stages. Thus its detection is not always a reliable means of obtaining an early warning of a developing incident, such as is required to minimise the danger to underground workers. Although sensitive electronic smoke detectors have been produced, as described in Section 6.3.3, experience has shown that they are unlikely to respond to the POC from spontaneous combustion.

One detection methodology being given serious consideration by 1900 involved sensing the associated heating of the mine ventilation current. This was done using thermometers placed at strategic locations underground. In practice other detection methods proved faster and more reliable (14). More recently, modern sensitive temperature sensors have been used to show the presence of open fires as described in Section 6.3.3.

Whilst warming of the air current has not proved a particularly reliable indicator of developing spontaneous combustion this is not necessarily the case with the strata heating. Heat conducted through rocks adjacent to the fire seat has been shown to lead to localised warming of roadway walls. However, to locate these ‘hot spots’ using contact thermometers requires the taking of a large number of closely spaced measurements. This tended to render the approach impractical until recently.

In 1937 Bryan suggested (15) that the heated strata associated with spontaneous combustion could be detected by measuring the emitted infra-red radiation with a globe thermometer. Whilst it is not clear whether the idea was ever tested in coal mines, the general approach was revived in about 1975 by MRDE. They used newly developed thermal imaging devices and non-contacting surface thermometers. With these instruments radiation from the body under investigation is focused onto an array of solid state sensors. In thermal imagers their outputs are processed to produce an image on a screen, the colours of which correspond to the range of temperatures sensed. By this means unusually hot areas can be easily differentiated from their surroundings. With non-contacting thermometers, the sensor outputs are converted into an equivalent temperature for display on a meter. In both cases the units are extremely portable and provide results in real time. This means large areas of roadway can be quickly surveyed.

The non-contacting thermometers and thermal imaging instruments used for the initial trials carried out by MRDE were not specifically designed for underground use. However, by 1984 the NCB had financed the development of intrinsically safe systems. Since then such devices have been widely used for the location of roadway heat associated with spontaneous combustion. In addition, they have also proved useful in the identification of overheating electrical and mechanical systems before they have had a chance to cause a dangerous fire.

In the period leading up to privatisation, reconsideration was given to the detection of spontaneous combustion by contact temperature measurements along roadways. In the so called ‘Distributed Optical Fibre Temperature Sensing’, or DOFTS, system a pulse of laser light was launched into a fibre fixed to the strata’s surface. Temperature variations along its length led to changes in the material’s optical properties. These discontinuities scattered some of the light back to a receiver mounted at the input. Here the time varying intensity signal detected was processed by a computer to provide a plot of the temperature distribution along the fibre. For a 4 km long sensor updating its data every 10 seconds, the temperature resolution was typically 1^{o}C and accuracy of its location ±1 m (16). British Coal installed an experimental DOFTS system at Asfordby Mine, Leicestershire in about 1991. No details of the system's subsequent performance are available for publication.

Despite consideration being given to alternatives, alongside the visual detection of smoke, the presence of gob stink was considered a very important indicator of developing spontaneous combustion for a very long time. As late as the 1930's, some collieries employed men specially trained as 'sniffers'. Even in the modern coal industry with its sophisticated environmental sensing systems the human detection of the subtle changes in the smell of an air current is a valuable means by which major incidents can be avoided.

Detection methodologies based on smoke, heat and smell did not prove particularly reliable at providing early warning of spontaneous combustion. Eventually the problem was avoided by the use of techniques based on the detection of gaseous POCs. Until relatively recently, these primarily involved the analysis in surface laboratories of mine air samples collected underground. The techniques available are described in Appendix II. Here it will be seen that an analysis methodology considered suitable for the determination of carbon monoxide in mine fire gases did not become available until 1919. As a result, before this date the existence of fires had by necessity to be determined from oxygen deficiency and carbon dioxide measurements. Despite the fact that both are produced by non-fire events it is reported (17) that the ratio of carbon dioxide concentration to oxygen deficiency could be use to show a developing fire in its early stages.

Even with analytical techniques for the fire gases, the need for discrete samples to be removed from underground to the surface was far from an ideal situation. The laborious nature of the processes and long time delays that could occur before the results were returned were at best inconvenient. At worst they had the potential for being dangerous, for example where the location of a fire site was being sought, or data on a rapidly developing incident required. In Britain these problems have been reduced by equipping officials with portable indicating instruments and installing continuously operating fire gas monitors underground. In the case of the former these have been almost exclusively for carbon monoxide, probably because of the relatively high danger associated with it. For fixed systems, oxygen monitoring has also been included.

From their use as detectors of afterdamp, it is not surprising that small animals and birds were considered for use in the location of spontaneous combustion. According to Haldane and Douglas (18) a number of small animals were suspended in the mine air around the suspected site of a fire for about 15 minutes. Each was then drowned and the colour of their blood examined. The inhalation of any carbon monoxide caused this to take on a reddish appearance. No evidence has been located to suggest that this approach was widely used. Reasons may have included its cruelty and the potentially large number of animals that would have to die before a fire was precisely located.

Some of the earliest non-animal detectors developed for carbon monoxide incorporated chemical reagents discovered by late nineteenth century chemists. These changed colour in the presence of the gas. Methodologies that subsequently made use of this approach have been called 'colorimetric'.

What became one of the more successful colorimetric gas detection systems was patented by Hoover and Lamb in the USA in 1919 (19). Shown in Figure 6.2, it was formed from a small sealed glass tube (a) filled with a mixture of iodine pentoxide and fuming sulphuric acid. These were held on a pumice carrier. In the un-reacted state the mixture, called Hoolamite after its inventors, was greyish white in colour. To use the apparatus, the ends of the tube were broken off and, using the aspirator bulb (c), a known volume of sample gas, filtered and dried by (b), drawn through. The presence of any carbon monoxide caused the Hoolamite to turn green, beginning at the inlet end and progressing along the tube. At a fixed volume throughput the stain length was dependent upon the gas

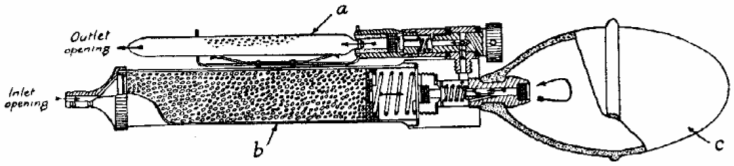

Figure 6.2 Hoolamite gas detector (original copyright Methuen & Co)

concentration present. This was determined immediately after the cessation of pumping using a set of pre-calibrated standards.

Over the years, companies including MSA in the United States, Siebe Gorman in Britain and Draeger in Germany have produced colorimetric tube type carbon monoxide detectors. Although different reagents were used, the operating principles were generally similar to those above, although they do not seem to require separate gas dryers and filters. In the case of Draeger tubes, they are available to detect gas concentrations from 2 to 3000 ppm. To obtain a reading it is necessary to operate the aspirator anything between one and ten times, depending on the range covered. This process can take several minutes to complete.

Following their use by air-crew during the Second World War, the late 1940's saw the evaluation of tube type carbon monoxide detectors in coal mines. At the time it was concluded (20) that they were suitable for use by colliery personnel during emergencies. From (21) it appears as though they were being supplied to officials for use in the hunting of fires, particularly spontaneous combustion, at least until the 1980's.

Although carbon monoxide detector tubes were undoubtedly better than animals, they suffered from a number of shortcomings. Not the least of these was the fact that it could take several minutes to obtain a reading. In the presence of a gas as toxic as carbon monoxide this could lead to an observer being exposed to a lethal dose before conditions had been assessed. Responding to this, the NCB undertook its own research into the development of improved carbon monoxide detectors. The aim was to produce an electronic instrument that could provide a readily apparent indication of gas concentration on a meter. A target performance included a full range of at least 500 ppm, a resolution of 1 ppm, and a low sensitivity to hydrogen, a gas known to be produced in spontaneous fires (22).

An early underground electronic carbon monoxide detector was produced by the North Western Division of the NCB in 1962 (23). Called the 'electronic canary', it used a small electric pump to draw sample air over a 'Hopcalite' catalyst. This oxidised any carbon monoxide to carbon dioxide and released heat. A series of thermocouples sensed the consequential rise in temperature and their outputs were processed for display on a meter. Facilities were included whereby an alarm could be activated should the indication rise above a pre-set level.

The electronic canary was used in several areas of the NCB. By 1975, however, it had been redesigned and designated 'CORA'. Little is known about this instrument, but it was not believed to be in use by the mid-1990's.

Other types of carbon monoxide sensor considered for use at about the same time as the above were a development of the Bergman polarographic oxygen cell described in Chapter 4 and an American gas cell.

The Bergman carbon monoxide cell dates from about 1974. Operating on similar principles to its oxygen counterpart it seems to have suffered from similar problems. These included a drift in output with temperature and a response to partial pressure. Whilst the former could be allowed for by the use of a thermistor, the latter was more unfortunate. This was because the exposure limits for carbon monoxide were expressed in concentration units, necessitating the application of a pressure correction to the cell's output. Tests of an instrument incorporating a Bergman carbon monoxide cell were carried out by MRDE in 1977. It was found that the sensitivity of the cell fell at an unacceptably high rate with time.

MRDE also evaluated an American electrochemical carbon monoxide instrument called the 'Ecolyser'. Although it was found unsuitable for underground use, during the 1980's the South Midlands Area of the NCB used its gas sensing cell in a portable monitor called 'Pitco'. Initial impressions of the new instrument were favourable. However, after a few months use its performance became erratic (24). Despite undergoing at least three redesigns the unit was never without its problems (25). Notable amongst these was an unacceptably short cell life of typically six months. It is understood that the Pitco was no longer available by the mid-1990's.

Faced with problems over the existing carbon monoxide sensors, in about 1977 the NCB contracted City Technology Limited to develop a new device. This was to be based on ideas from the NCB's Yorkshire Regional Laboratory and incorporate some of the features included in City Technology's oxygen cell (see Chapter 4). Notable amongst these was the capillary diffusion barrier that made the cell's response proportional to gas concentration. Production of a '2T' carbon monoxide sensor began in 1981.

A schematic diagram of the City Technology cell is given as Figure 6.3. It was formed in a moulded plastic case approximately 43 mm in diameter and 18 mm thick. Having diffused through the inlet capillary the carbon monoxide underwent spontaneous oxidation at the catalytic sensing electrode. With a balancing reaction taking place at the counter, the connection of the load resistor allowed a current to flow. This was proportional to the sensed gas concentration at a sensitivity of typically 0.1µA/ppm up to a maximum of 200 ppm. In varying temperatures, problems with drift in the cell characteristics were not encountered below 30^{o}C (26).

On its debit side, the 2T cell showed a significant sensitivity to hydrogen; 5 ppm of the gas present led to about 1 ppm carbon monoxide being registered (26). Also, it showed poor zero recovery following exposure to transient concentrations above about 200 ppm carbon monoxide. Partly because of the undesirability of such behaviour, the NCB continued to finance carbon monoxide cell development at City Technology. One of the results was a new device designated the '2E'. This operated in up to 1000 ppm whilst at the same time maintaining the good temperature characteristics of the earlier 2T. However, it also showed a response to hydrogen. Further work led to other cells being produced. One of these, the '2.3E' reportedly had a much lower hydrogen sensitivity than its predecessors' (27).

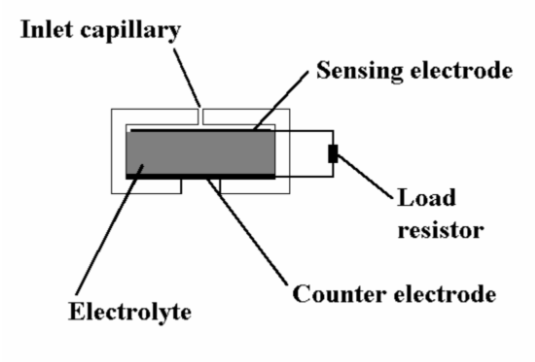

Figure 6.3 The City Technology 2T carbon monoxide cell

Even during their development it was clear that the City carbon monoxide cells had a number of characteristics that made them more suitable for underground use than the sensors hitherto available. These included a long operating life. According to Gibson (27) some cells were still responding to gas some 4 years after being made. Also the City cells had fast response times to changes in concentration, typically less than 35 seconds to 90% of a step change. In addition, their small size and low operating power requirements made them ideal for inclusion in portable battery powered instruments for coal mining use. Such was produced in 1982 by the Yorkshire Regional Laboratory of the NCB. Initially designated 'Digico', commercial development was undertaken by Sieger Limited who renamed it the 'SCO1'. This instrument was very similar in its appearance and basic mode of operation to the Sieger OXD-2M shown in Figure 4.3. Unlike it, however, once a reading had been taken the unit automatically switched itself off. The full range output was 200 ppm carbon monoxide.

Subsequently Sieger Limited produced the SCO2 and SCO2-M that were similar to the SCO1. The former was intended for continuous operation and had an audible alarm, whilst the latter is believed to have incorporated an improved City cell. All seem to have been widely used underground, for example in the location of spontaneous combustion. They were also suitable as replacements for the canary in rescue and recovery operations and their availability may have led to the relaxation in the law that required that birds be kept at mines. Experience showed however that the gaseous products emitted alongside carbon monoxide during the combustion of coal, notably sulphur dioxide, hydrogen, and hydrogen sulphide, could cause the instruments to over-read. Whilst the errors thus introduced may have been significant, up to 70% in some instances, they did err on the side of safety rather than danger and their presence was thus seemingly considered acceptable.

In March 1958 a spontaneous combustion incident occurred at an unspecified Warwickshire coal mine that necessitated the introduction of a daily underground air sampling regime for fire gases. Although the protection thus afforded was deemed adequate, at the time it was felt that safety would be improved if collection was undertaken three times per day. Consideration of the high costs involved in doing this manually led to the development of automatic apparatus (28). This became known as the 'tube bundle', a schematic diagram of which is given as Figure 6.4. It was available by the beginning of the 1970's and was still in use in coal mines during the mid-1990's. Each installation was formed from a multiplicity of pipes, between 3 and 13 mm in diameter, linking sampling locations underground to a central point on the surface. Here pumps drew mine air through the system and motorised valves sequentially applied it to the inputs of automatic, laboratory type analysis instruments. For carbon dioxide and carbon monoxide non-dispersive infra red gas analysers were typically used, whilst for oxygen they were paramagnetic (see Appendix II).

In one early tube bundle installation at Daw Mill Colliery near Coventry twelve underground sampling tubes were used. On the surface, the gases flowing through each were analysed once every twenty-four minutes. A combination of the length of the sample pipes and the maximum obtainable gas flow meant that there was a delay between collection and analysis of up to 40 minutes (28). For other installations the number of sampling points and reading delay time varied. In view of the widespread use of tube bundle systems any problems with its use were clearly considered acceptable. This was possibly because of the flexibility in the type of analyser that could be used and because any reading delays were short when compared with those associated with manually sampling.

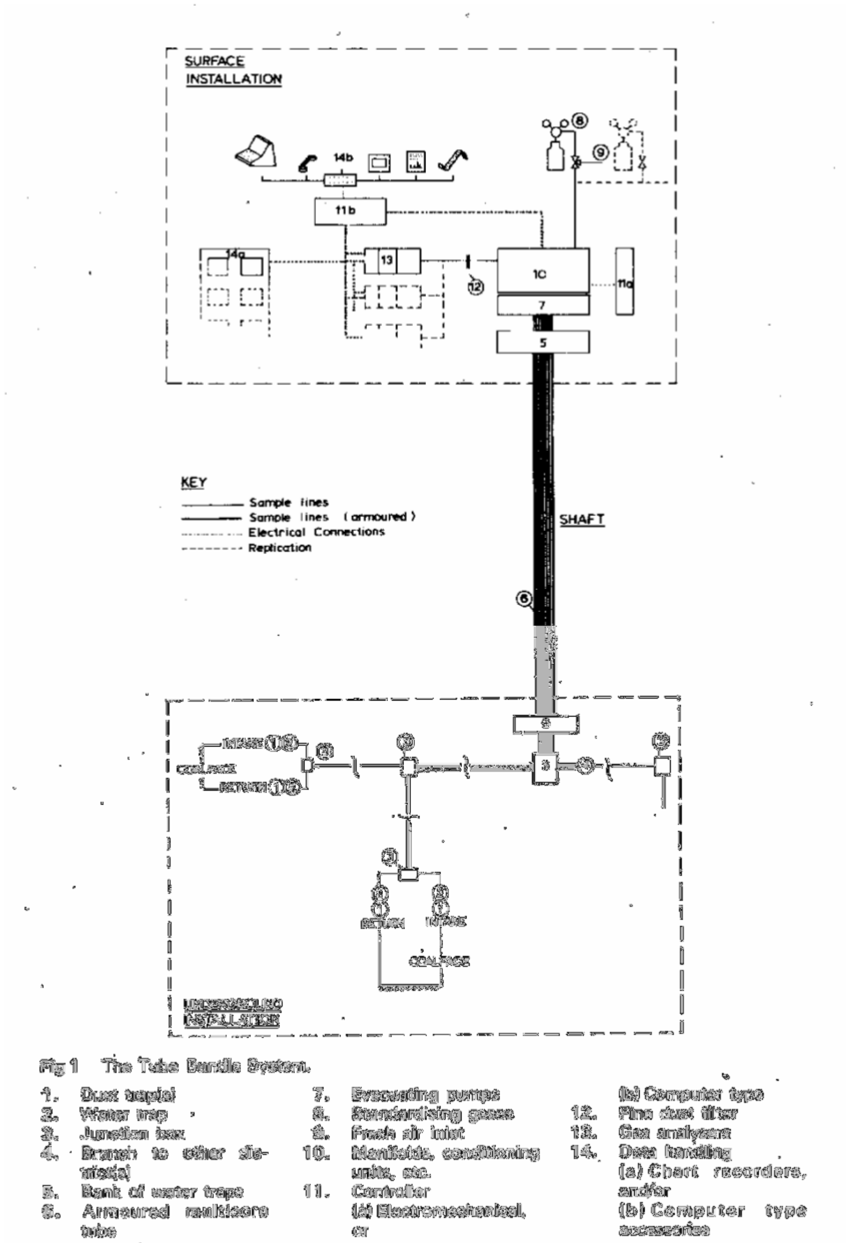

Figure 6.4 The tube bundle system (copyright National Coal Board)

With the earlier tube bundle systems the outputs from the gas analysers were displayed on recorders. These were interpreted periodically by an attendant who then had to make a subjective judgement as to whether or not the observed behaviour constituted a developing spontaneous fire. Assistance was provided by the presence of automatic alarms normally activated by the detected level of carbon monoxide. However, the fact that this gas is produced by normal mining operations led to problems associated with false warnings. Although the use of Graham's ratio may have reduced their occurrence, it is postulated that before the advent of electronic calculators it would have been impractical for colliery staff to undertake the necessary calculations on a routine basis.

By 1981, microcomputers were being applied to tube bundle systems. Not only were they controlling the sampling process, but also evaluating the analyser outputs and presenting the results. Regarding the latter function, the processing power available enabled new alarm generating routines to be implemented that reduced the number of false fire alarms. One of these, developed between 1981 and 1984, was called the ‘Multi-Discriminating Alarm’ or MDA (29). This was intended to ignore situations such as the firing of shots and the operation of diesel locomotives and to raise the alarm only after a series of low probability events had been detected. As an example, these may have involved the detected carbon monoxide concentration remaining above a number of discrete threshold values for specified periods of time.

Up to 1988 sixteen collieries in Britain were using MDA. Experience showed that it caused the fire alarm to be raised considerably earlier than would have been possible using the conventional single level approach. This was because the latter need to be set relatively high to avoid too many false warnings.

Even when coupled to MDA there were aspects of the tube bundle that made it a far from ideal fire detection system. One of these concerned its long response time. Although at Daw Mill it was less than 40 minutes at other mines it was to 4 hours. Also, it proved difficult in some circumstances to add new sample points to existing installations to meet rapidly changing circumstances. Whilst these drawbacks were not always serious, on occasions there could be, notably where the location of a very slowly developing fire was being sought. Here a likely requirement was for the number of sample points in a district to be increased at short notice. Another situation was where men were working to bring a known fire under control. In this case an extremely rapid indication of rising fire gas levels was required.

An early attempt at producing a more flexible POC detection system involved the use of an underground infra-red carbon monoxide analyser that became available in Germany in 1962. Called ‘Unor’, it operated on similar principles to laboratory instruments described in Appendix II. The range of operation of the unit was from 0 to 300 ppm carbon monoxide, with the measured result being shown on a meter. A corresponding voltage output was available for data transmission purposes. Power required by the system was either 240 or 110 Vac necessitating it be certified flameproof. It was, therefore, very heavy. It was also expensive.

Unor was first used underground in Britain in about 1970 (30). Here it was incorporated into an underground tube bundle system. This led to much shorter response times and an increased flexibility. The Unor was still being used underground in 1982, although by this time it was being replaced by low powered instruments incorporating electrochemical cells. These were smaller, lighter and easier to use and install.

Electronic carbon monoxide monitors for semi-permanent underground installation were developed by the NCB at MRDE, and its East Midlands Regional and Scottish Area laboratories. All were produced between about 1980 and 1982 and incorporated the City Technology electrochemical cells.

The MRDE system, developed in association with Sieger Limited, was designated the ‘BCO1’ and is shown in Figure 6.5. It was built to the then standard environmental monitor format. The sensor was mounted behind a gauze dust filter in the centre of the front panel. The sensed gas concentration, up to a maximum of 200 ppm, was shown on a digital display above it. An electrical analogue of this indication was available at one of the sockets shown for connection to either a local recorder or a data transmission system for surface display. Should the sensed gas concentration rise above a pre-set level, the alarm was raised. Indication of such an event was provided via a small flashing indicator fitted to the unit and a pair pulsing relay contacts. Power to the BCO1 was provided by an internal battery float charged from an external ac supply.

The BCO1 system was certified intrinsically safe. With external dimensions of 283 by 198 by 172 mm and a weight of just over 9 kg it was relatively portable. This made it easy to move underground should the monitoring requirements change. The fact it also contained a battery power supply, meant that it became operable immediately on installation. By 1986 there were some two hundred BCO1 units in use in British coal mines (31).

Figure 6.5 The BCO1 carbon monoxide monitor (copyright National Coal Board)

The East Midlands carbon monoxide monitor was designated the 'Emcor'. It was manufactured by MSA (Britain) Limited and is shown in Figure 6.6. Units were widely used in British coal mines up to privatisation.

Rather than being a self contained underground monitor for carbon monoxide, the instrument produced by the Scottish Area Laboratory of the NCB, called the 'Multigas', was intended as support for existing tube bundle systems. The aim was that it would be installed underground to provide more immediate indication of the concentrations of a number of mine air gases present, not just carbon monoxide. Formed from a 'BM1 methanometer style' enclosure (see Figure 5.16) the system contained City Technology carbon monoxide and oxygen cells and a pellistor methane detector. Sample gas was drawn over these by an internal electric pump. The sensed gas concentrations were shown on individual digital displays. No facilities were provided for remote transmission of data or a local recorder or alarms. It has been reported (32) that by 1986 some ten units had been used underground in British coal mines on a trial basis. No information has been located as to any subsequent usage.

Compared with the tube bundle system, the instruments that included the City carbon monoxide cells represented a considerable advance in the reduction of the hazard associated with spontaneous combustion in coal mines. This was probably largely due to their portability. However, they did not completely replace the tube bundle system for a number of reasons. One of these was the fact that the electrochemical cells tended to over-read during a developing fire, due to a cross sensitivity to other POCs. Whilst these effects could be reduced by fitting chemical filters they could not be eliminated altogether.

6.3.3 Open fires

Early warning of developing spontaneous fires can be obtained from observations of the carbon monoxide concentration in return air ways. The approach is not suitable for the detection of open fires for a number of reasons. Firstly, they tend to develop relatively quickly, meaning that the long response time typically associated with tube bundle systems is unacceptable. Next, unless the fire involves coal, and this is by no means a certainty in a modern coal mine, significant quantities of carbon monoxide may not be produced in the early stages. With machinery an early POC will most likely be dense smoke and in the case of PVC conveyor belting hydrochloric acid vapour.

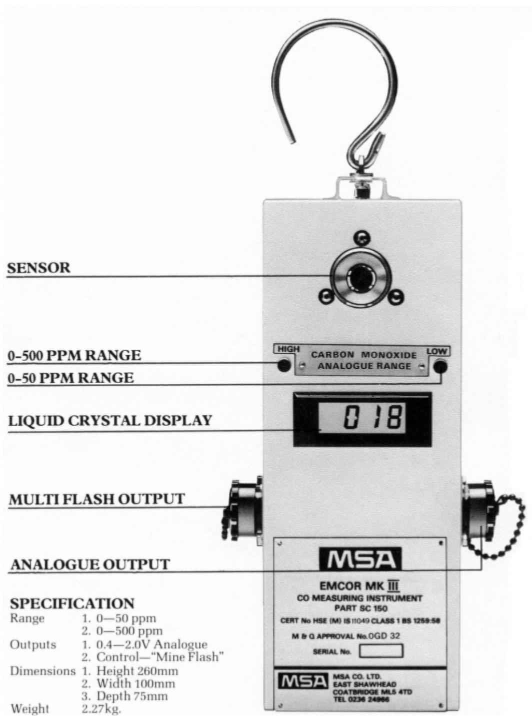

Figure 6.6 Emcor (copyright MSA (Britain) Limited)

Automatic fire indicating systems began to be installed on underground machinery during the 1950's. These typically consisted of thermostatic devices fitted to the outside of enclosures. If the sensed temperature rose above a pre-set trigger level, alarms and fire extinguishing systems were activated. For the purposes of this monograph such devices are not considered to be 'environmental monitors'. Consequently they will not be considered further, other than to note that by the late 1970's there were several thousand installations. A more modern implementation of this approach would be to make use of the DOFTS system described in Section 6.3.2. It is not known if this idea was tested in coal mines.

Whilst contact temperature sensors may be suitable for use on compact plant such as electric motors, some underground equipment is extremely spread out. For example, a conveyor belt may be several kilometres long and include a pair of support rollers every 1 to 2 m. A bearing failure at any one of these could lead to frictional heating and a consequential fire. It was to provide protection against such eventualities that the NCB instigated conveyor patrols, later using thermal imaging devices. By this means, overheating bearings could be quickly identified. Such an inspection regime did not, however, provide continuous protection against fire, or warn any workers downwind of a need to protect themselves against the effects of the toxic POCs. It was this danger that was a feature of the incidents at Whitfield and Creswell collieries. Eventually automatic fire detection systems appropriate for the protection of underground plant and machinery, rather then spontaneous combustion, were produced. Their basic operating requirements included an ability to react to a range of POC, not just carbon monoxide, a fast response to maximise the time available for the evacuation of areas liable to contamination, and local and remote alarm indications. In addition, the reliability of the system needed to be high. If there were too many false alarms the real ones would be ignored. However, if fires were not detected men would be lulled into a false sense of security with a lower level of vigilance than they may otherwise have had.

Figure 6.7 The Minerva T86 smoke detector (copyright National Coal Board)

Responding to such a requirement, in 1958 the East Midlands Division of the NCB approached a company called Minerva and invited them to produce a suitable fire detector. By the early 1960's they had developed an intrinsically safe instrument called the 'Minerva T86'. It incorporated an ionisation type smoke sensor then being widely used to protect buildings. A photograph of the complete system, including its dry battery power supply, is reproduced as Figure 6.7. Installed underground, the detector was suspended such that the wire mesh grill pointed downwards, exposing the smoke sensor to the ventilating current and any products of combustion it was supporting. The output was in the form of a pair of relay contacts that could be connected to local or remote warning systems. In the 'on guard' state they were held closed, whilst in the presence of smoke (for the T86B variant) they pulsed. A system fault or the removal of the power supply was indicated by the relay contacts remaining open.

Laboratory evaluation of the Minerva smoke detector showed that it would respond to smoke carried on a ventilating current. However, false alarms tended to occur if the air flow speed was above 6.4 m/s (33). Also, the detector head needed to be kept clear of accumulations of dust and moisture. Again this was to avoid false alarms.

Eventually the Minerva T86 became a very popular system, with many hundreds being installed underground (34). This was despite the fact that operational experience revealed a high ratio of false to true fire alarms, as may have been predictable from the laboratory tests. It is postulated that this performance was tolerated because there was nothing better available.

Development of an improved mining smoke detector was undertaken by Trolex Limited in association with MRDE. A photograph of the resulting 'Trolex P3270' is shown installed underground at Rawdon Colliery, Leicestershire in Figure 6.8. It is being tested by the Author. Operating on similar principles to the Minerva T86B, it incorporated a new sensor that was believed to be less sensitive to dust and moisture. This was confirmed by extensive laboratory and underground evaluations. These also showed that the Trolex P3270 could be made to respond to a standard fire in wind speeds up to 7 m/s, the maximum achievable in the tests (35).

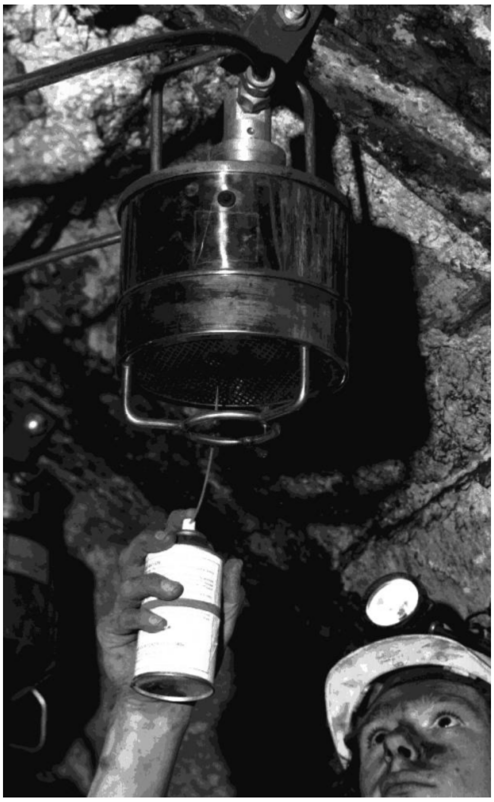

Figure 6.8 The Trolex P3270 smoke detector (copyright National Coal Board)

By March 1986 there were about 5000 Trolex smoke detectors in use in British coal mines (31). Typically they were used for the general monitoring of conveyor roadways. In this application one instrument would be placed at the drive with others separated by a distance equivalent to that moved by the air current in one minute (34). It is believed that this figure was derived from the MRDE test results.

Ionisation type fire detectors can not be considered to be 'universal' fire detectors. Firstly, laboratory tests revealed that they are unlikely to respond to POC from slowly developing fires such as spontaneous combustion. Also their sensitivity to smoke falls with distance from the source. This characteristic has been attributed to a coagulation of the smaller carbon particles, that the sensor will respond to, into larger ones that it will not. It also means that the instrument may not respond to such an obvious indicator of a fire as a cloud of dense black smoke. A combination of these shortcomings, and their potentially serious consequences, led the NCB to consider alternative solutions to the fire detection problem. These included the use of semiconductor gas sensors and a reconsideration of air temperature measurements.

During the 1950's it was found that the adsorption of gases such as carbon monoxide onto the surface of a semiconductor led to changes in its conductivity. Later, during the 1970's, this was used by Taguchi in Japan to produce a range of commercial gas sensors. Tests at the Yorkshire Regional Laboratory of the NCB revealed that when these were exposed to the fumes from heated coal their response was over five times greater than that attributable to the simultaneously measured carbon monoxide concentration. Further, detectable changes in sensor conductivity were observed when the latter was less than 1 ppm (36)(27).

In about 1978 an instrument called 'Fides', incorporating a Taguchi sensor, was installed in the return airway of a colliery. Analysis of the results provided showed that whilst it responded to the products of combustion from fires, the fumes from events such as shot firing also caused the output to change.

However, it was found that with the former event the ratio of the Fides output to carbon monoxide concentration rose whilst with the latter it remained constant.

From this, an instrument called ‘Fidesco’ was produced. This included a semiconductor POC sensor and a City Technology carbon monoxide cell. Both were contained in an instrument similar to the BCO1 shown in Figure 6.5. A single meter displayed either the semiconductor indication or the carbon monoxide reading. An alarm could be activated by a pre-set rise in either one or the other.

Even with their carbon monoxide cell, Fidesco units have been generally installed in the intake airways of mines in an attempt to minimise the likelihood of false alarms being initiated (37). Here their primary role has been to protect conveyor belt systems. Despite this restricted range of application the advantages to be gained from their use were considerable. For example, at one colliery the installation of Fidesco allowed four overtime shifts per week to be saved through a reduction in the number of belt patrols.

Reconsideration of air temperature measurements as a means of providing warning of underground fires was undertaken during the latter half of the 1970’s. What made this approach new was its use of a randomly varying ‘thermal noise’ found to be associated with mine air flows. Containing frequencies up to a few tens of Hertz, it was seen to be superimposed upon the relatively constant ambient temperature. Under normal conditions the amplitude of the noise was about 0.1^{o}C, but in the presence of a fire it rose by detectable amounts. Using this discovery, the Scottish Area Laboratory of the NCB developed a patented fire detection system called ‘Firant’. This was subsequently produced by Sieger Limited. It is shown in Figure 6.8. In Firant a low mass thermistor, contained in the cage on the left of the photograph, sensed the air temperature. The output signal was then filtered to produce a standard dc voltage representative of the amplitude of the thermal noise. This was available at sockets for transmission to the surface or to activate alarms should a pre-set level be exceeded. No local indication of the heat fluctuations was provided.

Figure 6.9 Firant (copyright Sieger Limited)

It is understood that Firant found widespread use underground in British coal mines. Here it protected items of plant such pumps and motors. It was not suitable for use in association with spontaneous combustion or systems distributed over a wide area. This is because the temperature fluctuations decay with distance from their source. Despite these limitations, Firant provided a number of early warnings of overheating components before a visible fire developed (32).

The purpose of using the instruments described above is to detect fires. However, in (4) it is revealed that between 1987 and 1989 only in 11% of incidents was the alarm first raised by the automatic monitoring systems. Perhaps of more concern is the fact that in twenty-five of a sample of forty-four fires studied the installed automatic monitoring systems failed to respond at all. This is clearly unacceptable. Factors known to have contributed towards this situation include the use of an inappropriate system for the danger being guarded against and the location of the sensor such that the POCs failed reach it. To minimise the likelihood of these problems occurring, British Coal produced a standardised procedure for the installation, use and maintenance of fire detectors (38). No discussions of the effect this had on the efficiency of the system response underground have been located. Also, it is not known whether British Coal’s procedures were carried over into the privatised coal industry.

From the above it will be apparent that the problem of developing a reliable fire detection system for coal mines had not been solved by the early 1990’s. More recent studies into the matter are addressed by (39). This describes an ‘intelligent’ detection system in which the concurrent outputs from a multiplicity of different sensors were fed into a neural network. This is a processing system that can be ‘trained’ to ignore ‘unwanted’ signals not directly related to the variable being measured. As an example, a fire signal could be automatically separated from those associated with normal mining operations. For laboratory tests a number of different semiconductor sensors were used along with a thermistor and a City Technology carbon monoxide cell. It was demonstrated that the system could be trained as predicted. At the time (39) was published a validation exercise was being planned for a coal mine. Results to this have not been located.

Even should the neural network approach prove successful at identifying real fires, the problem of locating the sensors such that they all intersect the flow of any POCs remains. This difficulty is enhanced by the fact that in a fire the roadway air flow patters may be severely altered from normal, making any predictions as to the best positions potentially unreliable.

6.4 Conclusions

Up to the mid 1990’s when the research for this monograph was completed, fire was still a major danger to underground workers. Further, a detection system had yet to be produced that would reliably indicate all types. Based on this, it must be concluded that there is a potential need for continuing studies into coal mine fires. Work areas identified include the development of an improved and more versatile sensor and signal processing system, consideration of the behaviour of fires in tunnels and where best to site a detector such that it will intersect the POC.

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Chapter 7 The environmental impact of shot firing

Chapter 6 noted how the development of a reliable fire detection system for use in coal mines has been complicated by the presence of fire like pollutants produced by the firing of explosives. These have been used to break solid ground. This chapter considers the impact this practice had on the working environment underground in coal mines, particularly in respect of the toxic gases produced. Whilst the potential danger for firedamp to be ignited in the process will be considered briefly, the gas detection techniques used to minimise the hazard are those described in Chapter 5.

7.1 Explosives used underground

Gunpowder was first used in British coal mines in about 1760. It is a mixture of powdered charcoal, sulphur and potassium nitrate. When ignited, toxic carbon dioxide, carbon monoxide and hydrogen sulphide are released. The amounts vary with the conditions under which combustion takes place.

In 1879 Sir Alfred Nobel invented a group of explosives formed from nitro-glycerine and an oxidising agent such as ammonium nitrate. Being more powerful, they subsequently replaced gunpowder in coal mines. During combustion carbon monoxide, carbon dioxide, nitrogen, oxides of nitrogen (nitric oxide and nitrogen dioxide) and water are produced. From Appendix I it will be seen that some of these are toxic to humans.

In use, explosives are formed into shots. These are loaded into holes drilled in the strata. Allowing for the passage of some means of initiating the charge, the hole is sealed using clay like stemming materials.

7.2 The firedamp ignition hazard

Principally, there are two ways in which the firing of explosives can lead to an explosion in the mine general body. The first is when the shot is initiated and the second if the explosive's hot products of combustion are allowed to emerge at speed from the containing hole.

When gunpowder was first used, initiation was by a naked flame. In 1856 a safer electrical method was devised. Subsequently intrinsically safe exploders were produced for coal mines thereby reducing the likelihood of firedamp being ignited during this phase.

During the combustion of explosives high gas pressures are generated. If a shot is not firmly stemmed in its hole, hot gases and solid particles can be ejected into the general body as a consequence. These have the potential for igniting any explosive concentrations of flammable gas that may be present. A danger of explosion in the general body also exists if the site is dry and dusty. This is because the ejected material can stir up a cloud of coal dust. As described in Chapter 5, this will be flammable even in the presence of very low concentrations of firedamp. In view of this, attempts at reducing the likelihood of shot firing causing an explosion in the general body have centred on cooling the products of combustion. Initially the charges were surrounded by water jackets. In about 1890 'flameless explosives' were produced. These were formed from ammonium nitrate to which was added an incombustible salt. This was intended to act as a flame coolant.

Shortly after their introduction, a study revealed (1) that flameless explosives simply lessened the danger of firedamp ignition rather than removing it altogether. This meant that their use did not eliminate the need for firedamp tests to be carried out, or that conditions be made such that a flammable cloud of coal dust could not be created. The latter involved the application of water or stone dust to the area surrounding the shot hole.

That checks for firedamp should be made prior to shot firing had been officially recognised before the introduction of flameless explosives. This is indicated by the fact that regulations to this effect had been included in the Coal Mines Act of 1872. These stated that at any place where gunpowder was to be used a competent person was to examine the shot hole and the atmosphere around it for firedamp. The apparatus to be used was the flame safety lamp. If the conditions were found to be unsafe then no shots were to be fired. There must be some doubt as to the effectiveness of these measures. For example, between 1850 and 1872, that is before the introduction of the regulations, there were eighteen recorded explosions of firedamp initiated by shot firing. After the Act was brought in, from 1873 to 1895, there were twenty (2). Over 950 men were killed. It is postulated part of the reason was the unreliability of the flame safety lamp as an indicator of firedamp.

No mention was made of the coal dust hazard in the 1872 Act largely because mining engineers were unaware that it existed. This situation had changed by 1887. Contained within an Act of this date was a requirement that water be applied if the area around a shot hole was dry and dusty. Also, it was made a requirement that water jacketed explosives, or similar, be used. Later, in 1896, recognising a fallibility of some of the flameless explosives available, this regulation was altered to introduce the concept of a 'permitted list' of explosives. Only those included were allowed to be used in dry and gassy coal mines.

More recent regulations covering the use of explosives underground were issued in 1993 (3). Briefly they specified the tests to be made for flammable gas and prohibited the firing of shots where the measured concentration exceeded 1.25%. By this time, hand held gas detectors had been developed. These were easy to use and sensitive to very low concentrations of gas.

Modern shot firing control measures do appear to have led to a reduction in the number of consequential explosions of firedamp. From (2) it has been calculated that between 1896 and 1963 there was, on average, such an incident every 2.5 years. This compares with every 1.2 years for 1850 to 1872 and every 1.1 years for 1873 to 1895. More recently Browning and Warwick (4) state that between 1981 and 1993 there were none. Other factors that must be considered as aiding this decline in accidents due to explosives include a reduction in the number of shots being fired, an improvement in the control of firedamp through the application of ventilation, and the introduction of sensitive methane detectors.

7.3 The toxic gas hazard

In 1888 it was reported (5) how at least six men had died after being exposed to the fumes from shot firing. Other comments from around the same time suggest that this was not an isolated incident and that it was well appreciated that harmful gases were produced during the combustion process.

Shortly after this incident the Durham Coal Owners' Association began a study into the gases produced by the mining explosives Roburite and Tonite, and whether they represented any danger to human health (6). The former was ammonium nitrate based and the other nitro-cellulose, or guncotton. By making use of air sampling and analysis procedures outlined in Section 7.3.1 it was found that the fumes produced by both contained carbon monoxide. Further, the concentrations close to the shot hole could be as high as 600 ppm. From Appendix I it will be seen that levels such as these are dangerous to humans. Although oxides of nitrogen were expected to be produced, none were detected. It is postulated that this may have been due to an insensitivity of the analysis techniques used rather than their absence.

Despite the presence of carbon monoxide, the Durham group concluded that the fumes from Roburite and Tonite were no more harmful than those from gunpowder. However, it was recommended that a minimum of five minutes be allowed to elapse before men returned to the working place after a shot had been fired to allow them to disperse.

The hitherto suspected existence of oxides of nitrogen in shot firing fumes was confirmed by Mann in 1906. He claimed to have detected up to 260 ppm of nitrogen dioxide. From Appendix I it will be seen that such concentrations would have represented a considerable toxic hazard to humans.

Thus by the early years of this century it had been shown that the fumes produced during the combustion of coal mining explosives could contain significant quantities of carbon monoxide and oxides of nitrogen. Added to this, the combustion process also consumed oxygen and generated carbon dioxide. As to which of these components was the more dangerous, in 1916 Irvine showed that it was likely to be carbon monoxide and oxides of nitrogen, the effects of which were exacerbated by the presence of carbon dioxide through its tendency to enhance the rate of respiration (7). From considerations of safety, this was a rather unfortunate conclusion because it was the least dangerous gases, notably oxygen deficiency and carbon dioxide, that were the most easily detected underground environment and the most dangerous, that is carbon monoxide and oxides of nitrogen, that were the hardest.

Possibly in recognition of the shortcomings of the available detectors for shot firing fumes, the more modern mining regulations have required that ten minutes be allowed to elapse after a round has been fired before the site is approached. Although this is to give the fumes time to disperse, according to Nicholas and Wall (8) the concentrations of carbon monoxide and nitrogen dioxide can still be expected to be above 100 and 30 ppm respectively. Whilst not immediately life threatening, a study (9) of the health of a group of one hundred coal miners with a history of exposure to these gases suggests that they may be dangerous in the longer term; over a ten year period five had died from lung related diseases that were not dust related (see Chapter 9) and four showed evidence of advanced emphysema. The believed cause in each case was prolonged exposure to shot firing fumes.

7.3.1 Assessment

Since there was no alternative, the Durham Coal Owners' Association had to rely on surface analysis of mine air samples for their investigations into the composition of shot firing fumes (6). One collection methodology, called 'snap' sampling, involved the use of evacuated brass cylinders. Once a shot had been fired an operator rushed up to the hole and momentarily opened the container, allowing it to fill with the fumes. It was probably anticipated that by this means any transient peaks in the gas concentrations could be detected. No information is provided in (6) as to the analysis techniques subsequently used.

Personal experience of working with oxides of nitrogen has shown that the two main components, notably nitric oxide and nitrogen dioxide, are difficult to handle. In the presence of oxygen the former rapidly converts into the latter. This is extremely reactive, readily adsorbing on to most metal surfaces. With their use of brass sample containers it is not considered surprising that the Durham group failed to detect such gases in their fumes. They were probably adsorbed.

By the 1920's shot firing fumes were being collected in evacuated glass vessels. This would have reduced the likely errors associated with the adsorption of nitrogen dioxide. A further refinement, introduced in about 1943, involved the inclusion of a small amount of oxidising agent (hydrogen peroxide and sulphuric acid) in the glass vials before they were sealed. This stabilised the oxides of nitrogen in solution. According to a relatively recent NCB publication (10). This is believed to have been the sampling approach used up to privatisation for use in connection with shot firing fumes.

For longer term sampling the Durham group used glass bottles aspirated by connecting them to the inlet of a water filled box. This was allowed to empty over a period of about an hour, drawing sample air into the collection container as it did so.

Shift average carbon monoxide concentrations were determined using live mice (6). These were taken underground at the start of the observation period, left to inhale the shot firing fumes and then killed on return to the surface. The colour of their blood was examined using a spectroscope, with the intensity of the red colour providing an indication of the integrated carbon monoxide dose.

None of these methodologies were capable of protecting underground workers from the immediate effects of the toxic gases found in shot firing fumes. This required fast response portable gas monitors. For carbon monoxide small animals and birds were commonly used. For oxides of nitrogen, as late as 1956 it was being suggested (11) that detection should involve looking for a characteristic brown coloration in the atmosphere.

Since the late 1940's, portable carbon monoxide indicators in the form of colorimetric detector tubes have been used in coal mines. These are described Chapter 6. Similar devices have also been produced for oxides of nitrogen. Coupling the need to use a different tube for each gaseous component being investigated with the fact that it can take several minutes to conduct a single test, leads to the major disadvantage with this approach that a worker could be overcome by the fumes before having completed an environmental assessment.

Very much better systems began to appear from the 1970's onwards with the development of reliable electrochemical cells. The original developments were mainly targeted at the detection of carbon monoxide and resulted in the introduction of a number of commercial instruments that have since been widely used in coal mines, mainly in fire incidents. However, within the last ten years cells have been produced for nitric oxide and nitrogen dioxide. From the available data, the former can expected to have a response time of less than thirty seconds. This is considerably faster than a detector tube.

A portable dual nitric oxide and nitrogen dioxide instrument called ‘Mentor’ has been manufactured by Status Scientific. British Coal evaluated this instrument in the early 1990’s in connection with the assessment of diesel exhaust emissions (12). The results revealed considerable uncertainty in the instrument’s response both with changing gas concentrations and environmental temperature. Subject to these apparent problems being overcome it should be possible to use a similar instrument to provide protection from the effects of shot firing fumes. It is not known whether such has been done within British Coal or its successors.

7.4 Conclusions

So long as explosives are fired in coal mines, the firedamp ignition and toxic gas hazards will remain. Consequently, it is concluded that there is a case for the continue use of methanometers and fast response carbon monoxide detectors at shot firing points. Also, since significant quantities of oxides of nitrogen have been shown to be produced, a similar detector for these gases should also be provided. Since such does not appear to be currently available the necessary development work should be undertaken.

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Chapter 8 Diesel engines underground

Another ‘normal mining operation’ that some automatic fire detection systems described in Chapter 6 have confused with ‘real’ incidents is the operation of diesel engines. These have powered tracked locomotives since the late 1930’s. More recently they have also been used to produce ‘free steered’ mine vehicles.

As with shot firing, the diesel engine represents firedamp ignition and toxic gas hazards. In the case of the former, from the earliest date appropriate precautions have been taken to minimise the risk. These include the measurement of firedamp concentrations where engines were operating. The instruments used are as described in Chapter 5 and so will not be considered further. The main subject of this chapter is the danger to the health of coal miners posed by the exhaust fumes.

8.1 The hazard and its alleviation

A review of the major constituents of undiluted diesel exhaust fumes is contained in Table 8.1. Also shown are the quoted emission levels, although in practice these will depend upon, for example, the age, condition, and speed of the operating unit.

The possibility that the exhaust fumes from diesel engines may be of danger to humans was recognised from the earliest days of their use underground. This meant that when the number of units underground began to increase during the late 1940’s SMRE undertook an investigation into, amongst other things, how the hazard could be controlled. For carbon dioxide, nitrogen dioxide and sulphur dioxide it was found (1)(2) that the concentrations could be reduced considerably by bubbling the exhaust gases through a water bath, or ‘wet conditioner box’, before discharging them into the atmosphere. Carbon monoxide and nitric oxide emissions, however, could only be rendered safe by diluting them with the mine ventilating air current.

Recent studies (3)(4) have confirmed the reliability of dilution as a means of rendering certain components of the exhaust emissions safe. For example, in roadways in which diesels were operating measurements revealed general body concentrations of carbon monoxide and nitric oxide of 15 ppm and 3.8 ppm respectively. Both are well below the accepted exposure values given in Appendix I. Likewise with the aldehydes (formaldehyde) where a level of 0.5 ppm was measured against an occupational exposure limit of 2 ppm.

Substance	Quoted emission levels
Aldehydes	less than 100 ppm
Carbon monoxide	1500 ppm
Carbon dioxide	2 to 13%
Total oxides of nitrogen	1000 ppm
Nitric oxide	400 to 1000 ppm
Nitrogen dioxide	1 to 30 ppm
Oxygen	0.5 to 1%
Sulphur dioxide	100 ppm
Hydrocarbons	760 to 25000 ppm
Particulates	up to 200 mg/m^3

Table 8.1 The constituents of undiluted diesel exhaust fumes

Also included in diesel exhaust emissions are particulates. These appear as smoke. With sizes ranging from less than 0.1 µm to 1.0 µm, it will be seen from Chapter 9 that they can be considered as being ‘respirable’ and are thus capable of being transported deep in to the lungs. It has been found (5) that with an engine on idle the particles are largely carbon. However, at higher speeds they include an increasing proportion of adsorbed chemical compounds derived from the unburned and partially burnt fuel.

Concern that the inhalation of diesel particulates may be injurious to health via the toxicity of the adsorbed substances was expressed to Parliament as long ago as 1938 (6). However, it subsequently became the accepted view that they simply had an irritating effect. Consequently, the regulations governing the use of such engines underground, as described in Section 8.2, make no reference to this subject.

A resurgence of interest in particulate emissions occurred during the 1970's, particularly in the USA. Here the concern was that they could form a means by which known carcinogens were transported deep into the lungs. Subsequent attempts at quantifying the consequential risk of developing cancer met with only limited success. However, recent studies, for example (7) show that it is potentially significant.

Responding to the likely danger represented by particulates and an increased usage of free steered vehicles in coal mines, around 1990 the Institute of Occupational Medicine (IOM) in Edinburgh, British Coal and the Health and Safety Executive (HSE) began programs of work to consider matters further.

A report on the first phase of the IOM study (8) concluded that exposure to the particulates in diesel exhaust emissions probably did increase the risk of a human developing cancer. However, the relationship between exposure and incidence could not be established due to insufficient data. The collection of such would require the development of exposure assessment methodologies. No results to any second phase of work have been located.

The measurement of worker exposures to diesel particulates was one of the subjects considered by British Coal and the HSE, and will be briefly considered in Section 8.3.2. In addition, efforts were directed at reducing the emissions. According to Currie (5) this can be done by passing the exhaust through 'water scrubbers' and ceramic filters. The work may have been carried on by a contractor after British Coal was privatised. However, no results have been located.

8.2 Regulations

Although diesel locomotives were not used in coal mines until 1937, the need for statutory provisions aimed at limiting the hazard they represented had been anticipated by the 1911 Coal Mines Act. This stated that internal combustion engines could only be used underground with the permission of the Secretary of State. Further, for each installation a set of special rules had to be formulated. According to Crook (2) these specified a maximum level of 5000 ppm carbon monoxide in the undiluted exhaust. No mention is made of oxides of nitrogen. This was probably due to difficulties in routinely detecting the gases in the coal mine environment, or possibly a failure to realise they were actually present.

With the post war rise in diesel engine usage in coal mines came the introduction of a more 'formal' set of statutory regulations. Introduced in 1949, they specified maximum allowable concentrations of carbon monoxide and oxides of nitrogen in the undiluted exhaust fumes of 2000 and 1000 ppm respectively. Measurements were to be taken at three monthly intervals. By this time a phenoldisulphonic acid test (see Appendix II) allowed for the laboratory analysis of high levels of oxides of nitrogen.

Also, the 1949 regulations stated that the ventilation past a locomotive was to be sufficient so as to render the gases from its exhaust 'harmless'. This was considered to have been achieved when the general body carbon monoxide concentration was less than 50 ppm. The absence of a corresponding figure for general body oxides of nitrogen probably reflects a difficulty in detecting them at low levels (below about 25 ppm) at this time.

The regulations covering the use of diesel locomotives underground were revised in 1956. For the general body carbon monoxide and exhaust gas composition there were no significant differences between the new regulations and those published in 1949.

Later, the 1956 regulations were also applied to the operation of free steered vehicles. However, additional requirements were laid down when, for instance, they were used in blind tunnels. The extra constraints included a need to provide means of monitoring the levels of carbon monoxide and oxides of nitrogen in the general body (8). In the later case, sanctions were applied if the concentration of nitrogen dioxide exceeded 3 ppm. The systems and methodologies available to ensure compliance with these requirements are described in the next section.

8.3 Hazard assessment

8.3.1 Toxic gases

Before the introduction of the 1949 Locomotive Regulations, diesel emission sampling would only have been undertaken in conjunction with the investigations that led to the awareness of their toxicity. Since the components of interest were carbon monoxide and oxides of nitrogen it is suggested that the methods used would have been similar to those described in Chapters 6 and 7.

Since 1949 it has been a statutory requirement that regular determinations be made of the concentrations of carbon monoxide and oxides of nitrogen in the undiluted emissions and the general body mine atmosphere (oxides of nitrogen only since 1956). Undiluted exhaust samples have been collected in glass containers. The method involved pushing one end of a flexible pipe into the engine's exhaust outlet and placing the other in the bottle. After allowing a sufficient time for the system to purge, the bottle was sealed with a stopper and sent to a laboratory for analysis. The statutory general body assessments have also involved collecting samples in containers for later analysis on the surface. Typically a rubber bladder or the NCB air pump (see Appendix II) would be used for carbon monoxide and glass bottles for oxides of nitrogen.

One of the problems with the statutory samples is that they are only taken monthly whereas diesels could be operating almost continuously. Consequently, to ensure workers are not exposed to unacceptably high concentrations of toxic gases continuously operating instruments are required. Ideally these should also provide automatic warnings in the event of the designated safety limits being exceeded. As with shot firing fumes described in Chapter 7, a part solution to this requirement came with the introduction of colorimetric detector tubes. Examples have been made available that will respond down to 2 ppm carbon monoxide and 0.5 ppm oxides of nitrogen. Although sensitive, they are incapable of providing a quick and automatic warning of the presence of a developing toxic gas hazard.

A detailed discussion of the monitoring instrumentation available for carbon monoxide in the general body is provided in Chapter 6. Here it will be seen that both fixed and portable systems have been developed that are capable of providing the required assessments of the hazard present.

The provision of instrument systems for the measurement of oxides of nitrogen underground is not so well advanced. In the period immediately before privatisation, British Coal did evaluate a number of electrochemical cells for nitric oxide and nitrogen dioxide, the two primary gaseous components. However, it was found that their characteristics were such that any instrument in which they were used would require frequent re-calibration (10). Such performance is not likely to be considered ideal.

In 1994 TSRE began investigating the possibility of using a combined nitric oxide and nitrogen dioxide monitor to provide a rapid indication of the total oxides of nitrogen in undiluted diesel exhausts. Such would be of considerable value during the servicing of the engines. For this work, use was made of a hand held instrument called 'Mentor' manufactured by Status Scientific Controls Limited. Certified as intrinsically safe for use in coal mines, the sensed gas concentrations were shown on a digital display. Initial tests involved exposing it to known mixtures of nitric oxide, nitrogen dioxide and air. These revealed that the sum of the indications provided was unlikely to represent the total oxides of nitrogen concentration in a sample. This was confirmed by the results to tests with fumes from an operating engine. These returned reading errors of between +150 and -30% of the expected value (11). However, no attempt was made to made to validate the analysis procedures on which these findings were based.

After the investigation of the Mentor was completed no further action was taken by TSRE in respect of the assessment of oxides of nitrogen in the underground environment. It is not known whether the work was continued by any other agency following privatisation of the British coal industry.

8.3.2 Particulates

The Americans became interested in the health effects of inhaling diesel particulate emissions during the 1970's. This led to consideration being given to the assessment of the levels in undiluted exhausts and at the work place. One of the problems associated with mining related to distinguishing between diesel carbon and coal dust suspended on ventilation currents. Studies showed, however, that whilst the peak in diesel particulate size distribution occurred at around 2 μm, for mine dust it was at 0.15 μm. Also, there was a clear separation between the two curves over the range from 0.7 to 1.0 μm, with a minimum at 0.8 μm. Using this data the University of Minnesota and the United States Bureau of Mines (USBM) developed a personal sampler for diesel particulates. The apparatus was a three stage device with the first removing those particles that would not normally enter the lungs (see Chapter 9), the second collecting the coal particles with sizes greater than 0.8 μm, and the third the diesel particulates with sizes from 0.001 to 0.8 μm (11)(12). Over this range only about 10% of the collected material was expected to be coal (5).

Consideration of the applicability of the USBM approach to Britain has shown it to have serious limitations (13). These are based on the fact that differences in the way British mines are worked can lead to considerably higher concentrations of sub-micron coal particles. In some locations underground these can be up to 35% of the collected diesel material, compared with 10% in the USA. Further, German studies have shown that the exhaust particles can attach themselves to larger dust particles. This results in a measurement of the sub-micrometer fraction underestimating the real emission levels (5).

Faced with these uncertainties, British Coal was forced to search for an alternative approach. No results to this work have been located, nor is it known whether it was continued after privatisation.

8.4 Conclusions

At present there are no means by which a rapid and automatic warning can be provided of potentially dangerous concentrations of oxides of nitrogen appearing in the general body atmosphere in which diesel engines are operating. In view of the toxicity of nitrogen dioxide in particular it is concluded that it would be appropriate for the work begun at TSRE on the sensing of this gas be continued.

It is believed that the inhalation of diesel particulates can lead to cancer of the lungs. Progress in fully assessing the danger in coal mines is being inhibited by a lack of suitable instrumentation that enables diesel carbon to be differentiated from coal dust. Thus if such engines continue to be used underground, the serious nature of the disease means that it is important that research work on this aspect of the health effects of exhaust emissions be continued.

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Chapter 9 Respirable dust

During the mining and transport of coal and other minerals, dust is created. Some of this settles on the ground around its point of production. However, some will be light and small enough to become airborne. By this means it becomes available for inhalation by miners. As described below, it has been found that the retention of some mineral compounds in the lungs can cause irreversible damage through the development of fibrosis. In the severest of cases the consequential loss respiratory function results in severe disablement or death.

Two dust induced respiratory diseases associated with coal mining are 'silicosis' and 'pneumoconiosis'. With the former, silica is the single 'toxic' component whilst with the latter coal, shale and other dusts are included. This chapter traces the incidence of these diseases amongst miners, including the control measures introduced and the instrument systems used in associated scientific investigations and routine airborne dust assessments.

9.1 Silicosis and pneumoconiosis

Agricola noted (1) that the inhalation of airborne mineral dust may be harmful to humans as long ago as 1556. According to him, its penetration into the windpipe and lungs of miners led to difficulties in breathing and the development of asthma.

Evidence of a similar respiratory condition amongst British coal miners began to appear during the early nineteenth century. Called 'black spit', or 'miner's asthma', studies carried out in 1820 revealed that in life the victims experienced symptoms of breathlessness and excessive expectoration. After death their lungs were found to contain accumulations of black pigment believed to be coal (2). This would have entered the body by the inhalation of airborne material.

As the British coal industry subsequently expanded so did the incidence of lung disease within it. As an example, statistics covering 1849 to 1853 revealed that amongst miners over fifty-five years of age the death rate from this cause was more than 70% above the national average for all occupational groups (3). Although post-mortem studies would have revealed what seemed to be coal in the lungs of at least some of these victims, proving a link between its presence and death was complicated by the existence of bacterial respiratory diseases such as tuberculosis. These had symptoms that were, at the time, difficult to distinguish from those now associated with the damage caused by the retention of rock and coal dust. They were also relatively common amongst the British working classes during the nineteenth and early twentieth centuries.

During the latter half of the nineteenth century a need to combat firedamp (see Chapter 5) led to improvements in the quality of underground ventilation. At the same time there was a fall in the death rate from lung dis ease amongst coal miners of all ages. The improvements were so great that Haldane felt able to claim (4) that there was no evidence from the mortality statistics to show that the inhalation of dust represented any danger to life in British coal mines. One author (5) even went so far as to remark that coal mine dust may help 'preserve' lungs. This idea stemmed from the view that the need to expell inhaled material exercised their dust removal mechanisms, reducing the susceptibility to other respiratory diseases, such as tuberculosis. In reality, increased ventilation rates had resulted in generally lower airborne dust concentrations due to increased levels of dilution.

Whilst it may have been believed around the turn of this century that the airborne dust in coal mines was harmless to lungs, at the same time there was a suggestion that this was not necessarily the case in metal mines, notably the gold mines of South Africa and tin mines of Cornwall. An indication of the size of the health problems being faced in these locations is provided by Haldane (4). In 1917-18 he noted that in both industries almost every man who operated a mechanical rock drill had died of lung disease before the age of forty. Further, the cause was believed to be the inhalation of airborne silica containing dust produced during the breaking of quartz bearing strata. Consequently it had been called 'silicosis'.

Recognising the existence of a health problem associated with the inhalation of airborne silica dust in metal mines, the 1909 Royal Commission on Mines took steps to try and ensure that a similar situation did not develop in coal mines. To this end they recommended the adoption of dust prevention measures where siliceous rocks were being drilled. As will be seen from Section 9.3, appropriate requirements were included in the 1911 Coal Mines Act.

Unfortunately these measures do not seem to have been particularly effective for within ten years cases of silicosis were being diagnosed amongst rock drill operators in the Somerset coal field. An investigation carried out in 1925 revealed that at one mine in a sample of twelve such men, eleven had the disease. At about the same time similar problems were being noted in the South Wales coal field (6)(7). Faced with this serious situation, the Government's Mines Department began an urgent investigation to ascertain the actual risk of British coal miners contracting silicosis (6). This included worker medical examinations and the collection of samples of rock dust for chemical analysis. In addition, the efficiency of the dust collection systems used in compliance with the 1911 Coal Mines Act were examined.

By the time the Mines Department began its investigations studies had shown that the outward sign of silicosis, that is an increasing degree of breathlessness, was caused by the formation of fibrous material in the lungs. Representing damage to their operating efficiency, its development was irreversible. However, rather than having to rely on post-mortem examinations for diagnosis, sensitive X-ray techniques had been developed that could show the fibrosis as shadows on a photographic plate. This allowed the Department investigators to identify silicosis amongst living patients. It also allowed those with this disease to be differentiated from those suffering from tuberculosis.

Descriptions of the dust sampling devices available to the Mines Department in 1925 are given in Section 9.4. For short period 'snap' samples a konimeter could be used. This enabled the number of particles per unit volume of mine air to be counted. For shift average dust concentrations, or for material be collected for chemical analysis an aspirated filter system was available.

From this initial study it was confirmed that silicosis was a problem in British coal mines and that it appeared to be worst in the anthracite region of South Wales. Also, the inhalation of rock dust was the recognised cause. However, it was felt that there was insufficient data to fix a justifiable maximum dust concentration that would ultimately lead to its control. Faced with this unsatisfactory and serious situation, in 1927 the Government appointed the first Medical Inspector for the mining industry, a Dr Fisher. One of his tasks was to 'sort out' the silicosis problem (8).

An indication of the task faced by Dr Fisher was provided by the introduction of the Various Industries (Silicosis) Scheme in 1929. This required that every death due to silicosis be recorded. The data collected shows that over the first five year period, 81 men died from the disease and 257 were permanently disabled. About 90% of these cases occurred in South Wales. Over the next twelve months, 37 more men had died and 160 been disabled (7). This suggests that the silicosis problem amongst coal miners was worsening, a fact later attributed to an increase in the mechanisation of underground mining operations and an inability of the ventilation systems to adequately remove the extra dust created as a consequence. Fast operating ground breaking and cutting machines create much greater volumes of fine, potentially respirable, dust than do slower, hand powered tools.

Within ten years the situation began to be complicated by the appearance of another respiratory disease amongst coal workers. This had symptoms similar to silicosis but occurred even though the victims had not been exposed to siliceous rocks. Studies carried out by the Medical Research Council (MRC) amongst coal handlers at docks in South Wales subsequently led to the suggestion that coal dust was not harmless as hitherto believed. Follow-up research, again by the MRC, into the health of coal miners in the same region, which also included measurements of the airborne dust levels underground, confirmed that a disabling dust induced lung disease different from 'classic' silicosis did exist (9). It was recommended that it be called 'pneumoconiosis of coal workers'. Whilst this disease was found to be present in the whole of the South Wales coal field, its prevalence seemed to vary widely between locations within that area.

From Section 9.3 it will be seen that in 1931 certified sufferers of silicosis became eligible for compensation payments. In 1943 this was extended to those suffering from pneumoconiosis. Men in both groups were suspended from work in mines. In response to an unacceptably high level of unemployment this caused, 1948 saw the introduction of a revised set of regulations. These allowed sufferers of pneumoconiosis, a term that now included silicosis, to continue working in mines, but only in 'approved' conditions. These were determined on the basis of the concentrations of airborne dust present at their work places. Rather than being based on medical data as to what levels would give rise to the development of fibrosis, such not being available at the time, the set limits were determined by what was realistically attainable using the then available dust control technology.

Responding to this lack of pathological justification behind the setting of the approved conditions of dustiness for underground work places, the newly created National Coal Board was invited to carry out its own study of respiratory diseases amongst coal miners. Set up in 1952 the project was called the Pneumoconiosis Field Research. Its primary aims were to determine the kinds of dust that caused pneumoconiosis and the environmental conditions that need to be maintained if mineworkers were not to become disabled by it. Twenty-five mines were included in the study, chosen such that they covered the whole range of conditions expected to be found underground in Britain. At each, every worker was subjected to a chest X-ray every five years. Concurrently, records were kept of each individual's dust exposure. Since it was considered impractical to take measurements specific for each worker all the time he was underground, thermal precipitator dust sampling instruments, described in Section 9.4.3, were used to determine the airborne respirable dust concentrations expected to be present at each underground work place. Using deployment records, the cumulative dosage for each individual was then calculated from the length of time spent at each location. The aim was to correlate any evidence of developing pneumoconiosis seen on the periodic X-rays to the exposure data obtained.

At its inception, the Pneumoconiosis Field Research Scheme continued the hitherto generally adopted practice of expressing airborne dust concentrations as the number of particles per unit volume of air. However, rather than include all sizes, only those between 1 and 5 μm were counted. For the reason why this was done it is necessary to consider what happens to dusty air as it is inhaled and how environments had hitherto been assessed.

Air, and any dust it is supporting, enters the body at the nose or mouth. Before reaching the lung cavities, or alveoli, across whose walls gaseous exchange with the blood takes place, it is passed through a labyrinth of tubes. This contains many changes in cross section and direction, forming an elaborate aerodynamic filtering system designed to remove any suspended particulates. It is not, however, completely effective as some material, classed as respirable' dust, will reach the alveoli.

When dust assessments were first made in about 1916 it was assumed that the danger of silicosis developing depended on the number of particles in the inhaled air. Consequently, the instruments used were particle counters, an example being the konimeter described in Section 9.4.1. However, rather than count all the material collected, only that smaller than 5 μm in size was considered. It is postulated that this cut-off point was chosen because post-mortem studies, or an understanding of the physiology of inhalation, had led to the realisation that only the smaller particles reached the alveoli.

In about 1939, doubts began to be expressed as to the pathological significance of the dust particle count. Instead it was felt that the mass of dust collected may be a more appropriate indicator of the potential health hazard. Whilst accepting this idea in principle the Medical Research Council noted in 1943 (9) that the problem with changing to a 'gravimetric' standard (one involving determination of the mass of respirable material per unit volume of air) was a lack of suitable measuring instrumentation. Against this, a 'short running thermal precipitator' (see Section 9.4.3) could reliably provide counts of airborne particles on a routine basis. To some extent these difficulties were reduced by a finding which showed that if the count range was restricted to a size range of 1 to 5 μm the results obtained correlated well with the mass concentration of dust below 5 μm.

The conflict between the accepted pathologically significant variable for airborne dust and what could be measured was still present when the Pneumoconiosis Field Research began its work. Consequently they adopted the restricted range assessment methodology devised by the MRC, as note above.

A feature of the MRC count based assessment methodology was that it assumed that all inhaled particles below the 5 μm limit were retained in the lungs and none above it. By the 1950's, studies of the dust removal processes of the respiratory tract had indicated that a non-linear retention curve may be more appropriate. One proposal gave a 1.6 μm dust particle a 100% chance of settling in the lungs, whereas at 5 μm it was 41% and at 7 μm 30%.

As will be described in Section 9.4.4, by the end of the 1950's an automatic ærodynamic particle sizing system called the 'horizontal elutriator' had been developed. This mimicked the removal processes taking place in the human respiratory system. A standardised form, endorsed by an international conference on pneumoconiosis at Johannesburg in 1959, transmitted all the infinitely small particles, 50% of the incident 5 μm, and none above 7.1 μm. The dust size selection curves for the standard elutriator and the human respiratory tract are shown in Figure 9.1.

By 1963 MRE had made use of the standard horizontal elutriator to produce an instrument suitable for the routine gravimetric assessment of underground respirable dust over the period of a working shift. Designated the MRE Type 113A, it is described in Section 9.4.6.

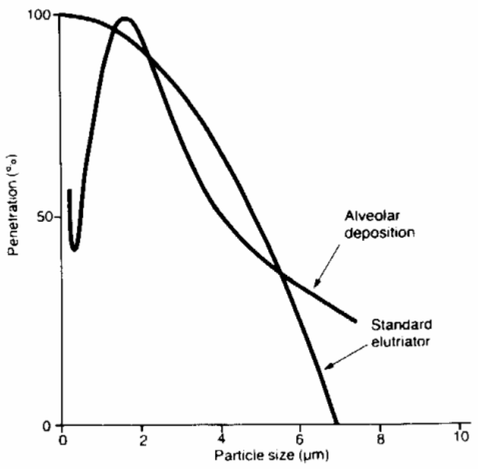


Figure 9.1 Dust size selection curves (copyright National Coal Board)

Provided with MRE gravimetric dust samplers, the Pneumoconiosis Field Research Scheme proceeded to install them alongside the hitherto used thermal precipitator counting instruments. From simultaneous measurements they were able to make a number of very important discoveries. Firstly, contrary to the MRC belief, no simple relationship appeared to exist between the number of 1 to 5 μm particles per unit volume of air and the measured mass concentration. Further, the correlation between the integrated worker dust exposure expressed in particle counts and the development of pneumoconiosis was poor (10).

The Pneumoconiosis Field Research Scheme did however find a significant correlation between the development of pneumoconiosis and worker time weighted respirable dust mass exposures (11). With the pathological significance of gravimetric dust sampling thus confirmed, since 1970 the limiting dust exposures for coal mines have been expressed in mass of particles per unit volume of sampled air averaged over a working shift. This matter is discussed further in Section 9.3.

To look for a correlation between the development of pneumoconiosis and dust exposure it was necessary for the Pneumoconiosis Field Research Scheme to be provided with the means of charting the progression of the disease. This was achieved using the shadows cast by the fibrosis on chest X-rays. In the early stages of the disease, when few outward physical signs may be apparent, these appear on the exposed films as small spots 2 to 5 mm in diameter. Later they merge to form large dense patches. Between 1940 and 1950 it was realised that progression through such changes was characterised by two distinct stages. These became known as 'simple pneumoconiosis' and 'progressive massive fibrosis', or 'PMF'.

Post-mortem studies have revealed that simple pneumoconiosis is characterised by small agglomerations of dust and fibrous tissue in the lungs. Depending on the number and size seen on an X-ray, a subject's condition is assigned to one of four categories. Only those placed in the upper two are certified as having pneumoconiosis. In its early stages the disease can be expected to have little effect on the expectation of life. Further, the likelihood of it developing to anything worse can be limited by removing the affected worker from respirable dust.

With PMF the lung contains one or more dense masses of fibrous tissue. Their presence seriously affects the lung function. A chest X-ray shows large shadows more than 10 mm in diameter. There is no known cure for the condition and even removal of the victim from a dusty environment will not halt its progression. Eventually the lung function becomes so severely impaired that death occurs.

Progressive Massive Fibrosis will only develop from simple pneumoconiosis. However, not every case of the simple pneumoconiosis develops into PMF. Unfortunately it is not possible to predict which will and which will not. Certainly the evidence is that it is not wholly dependent upon the respirable dust exposure. This means that whilst removal of some sufferers of simple pneumoconiosis to a clean environment will arrest the progression of the disease in others it will not. Consequently there is a clear case for setting a target of zero airborne respirable dust for underground coal workings. This is, however, unlikely to be realistically attainable. Thus it is vitally important that any new cases of pneumoconiosis be identified as early as possible. This will then maximise the chance that progression will be arrested.

Further support for a target of zero respirable dust in underground work places is provided by the uncertainties that still exist in the understanding of the hazard dust actually represents. Consider the case of silicosis. This is known to be caused by the inhalation of silica containing material. However, it has been found that not all are equally toxic. For example, shale contains high levels of silica yet has seemed to be harmless. Even as late as the 1990’s it was being stated (12) that the dose of silica bearing dust that would initiate fibrosis had not been quantified. Thus the only way of minimising the hazard from all respirable dusts is to minimise exposure.

Despite uncertainties that may have existed, and still do, in the understanding of the factors that cause pneumoconiosis, in the pursuance of its aim of identifying all cases in their early, and thus potentially treatable, stage in 1958 the NCB began offering chest X-rays to all its workers. This was done on a five year cycle. It also enabled data to be collected relating to the incidence of the disease within Britain’s coal mines. From this it was possible to assess the effectiveness of any dust prevention and control measures in place.

Using the information available it has been estimated (13) that the number of new cases of pneumoconiosis amongst British coal miners reached a peak of 5807 per year in 1949. By 1969 this figure had fallen to 1213. In 1990 there were none (14). In 1999 it was reported that a group of men, possibly up to ten, at a single Nottinghamshire mine had been diagnosed as showing signs of pneumoconiosis. Clearly this strengthens the case for maintaining routine health checks on coal miners and also for improving the standards of underground dust suppression and monitoring.

Within the population including retired miners there were some 344 new cases of pneumoconiosis certified by Department of Social Security in 1990 (14). The average age of these victims was about 70 years, confirming the observation that the disease was capable of developing after removal from exposure to respirable coal mining dust. As to the liability such a behaviour presents the British coal industry with, as recently as 1993 it was estimated (15) that a reserve of £2bn needed to be set aside to cover future pneumoconiosis compensation payments.

Recent evidence in the press (16) has suggested that coal miners may be susceptible to respirable diseases other than pneumoconiosis. These include bronchitis and emphysema. However, their potential existence seems to have had no influence on the application of underground monitoring instruments and so they will not be considered further in this monograph.

9.2 Alleviating the underground dust hazard

As outlined above, serious problems with a rising incidence of silicosis began to appear during the early years of the nineteenth century. The recognised cause was the inhalation of airborne dust created during the drilling of shot holes in siliceous strata using powered tools. In response, the 1911 Coal Mines Act required that dust suppression be applied in such circumstances. It led to the development and application of drill based dust collection systems. Assessments of their effectiveness were made using the Kotze konimeter to be described in Section 9.4.1.

After nationalisation of the British coal industry the pace of underground mechanisation accelerated. This led to the introduction of many more sources of respirable dust than just rock drills. Included were mechanical coal cutters, where the mineral is broken from the solid by fast moving picks, and conveyor belts, which include transfer points where the material is dropped down chutes. At the same time, there was an increasing awareness of the dangers associated with the inhalation of airborne dust. Consequently, the NCB initiated its own programs to develop new and improved dust suppression techniques. Rather than consider them in detail, this monograph will only contain a very brief overview.

From a suppression point of view it is better not to create dust than have to collect it afterwards. If this is not possible then it is better to collect at source rather than after it has become dispersed on an air current.

At the coal cutter and rock drill it has been recognised since the 1920's that less dust is produced by sharp tools. Later, research showed that the amounts could be reduced still further by slowing down the cutter speed (17). Such findings have had a strong influence on the design of coal mining machinery.

Dispersion of dust on the air current is prevented by directing water at the creation point, namely the cutting tip. Here there is a high probability that a particle will be struck by a droplet. Once this has happened they are more likely to coagulate and produce large particles that quickly settle out. In hot mines this can lead to unacceptably high levels of humidity. This can have an adverse effect on the health and safety of coal miners, as described in Chapter 11.

On conveyor systems the dispersion of dust on the air current is prevented by wetting the coal. This binds the small particles together and prevents them from being swept away on the air current. Again the practice can lead to unacceptably humid conditions in hot mines.

Collection of dispersed dust can be achieved by using filtration. As an example, in machine cut headings the intake of an exhaust ventilation system is positioned near the cutting zone. This allows the dust created to be sucked into the ducting, thereby isolating it from the general body. The contained air can then be passed through an inline filter before being returned to the main ventilating current.

Although the application of dust prevention and collection measures have led to a decrease in the general dust levels found underground, as detailed in the next section, instances will sometimes occur when the quantities produced in a particular operation are unacceptably high. Under these circumstances recourse must be made to the use of face masks, an approach described by Agricola in 1556 (1). Using modern materials comfortable, disposable filters have been produced. Under regulations introduced in 1975 these must be made available to all underground personnel.

9.3 Airborne dust regulations

Responding to the recognised hazard, the 1911 Coal Mines Act contained a requirement that dust suppression systems be used in conjunction with rock drilling operations. Also, every case of industrial disease in coal mines was to be reported. Although 'silicosis' was not specifically mentioned, it was noted that dust from drilling rock could lead to the development of a respirable disease. Consequently, it is concluded that silicosis became a reportable disease in 1911. However, the incidence statistics collected at this time would have been far from reliable due to the absence of reliable means of obtaining early diagnoses.

Silicosis was first named in law in 1929 and from 1931 compensation was paid to sufferers, but only where certain criteria were fulfilled. These included the presence of 'silicotic nodules' on a chest X-ray and a history of employment on processes involving siliceous rocks. Interestingly, according to a Mines Inspector in South Wales (6) the use of dust prevention measures underground increased following the introduction of these rules.

By the early 1940's evidence was emerging of a dust induced respiratory disease that differed from silicosis. However, sufferers were not eligible for compensation under the 1929 rules because they did not fulfil the criteria laid down therein. The anomaly was removed in 1943. Under this new scheme, men with the disease called pneumoconiosis were suspended from work in mines. The hardship this caused through the removal of wage earning capacity from a family led to a disincentive to report the disease (18). Despite this, from 1943 to 1947 about 20,000 men were forced to leave the coal mining industry. Most of these were from South Wales, leading to severe unemployment problems in the district (19).

In an attempt at remedying this situation, and yet limit the likelihood of pneumoconiosis progressing, in 1948 revised regulations were introduced. These allowed sufferers to continue working in mines, but only in conditions with approved degrees of dustiness. Details of the maximum allowable dust concentrations and the ways in which conditions were to be assessed were contained in two documents, 'The employment of pneumoconiosis cases' and 'The sampling of airborne dust for the testing of approved conditions'.

In the formulation of these documents, it seems reasonable to assume that use was made of the results of the MRC study into pulmonary disease amongst coal miners of South Wales (9). This was published in 1943 and recommended that the concentrations of respirable dust (particle size less than 5 μm) underground should not exceed 10 to 20 mg/m^3 for coal and 1 mg/m^3 for rock. Responding to the use of particle counting instruments in coal mines, it was noted that the corresponding restricted count range (1 to 5 µm) figures were 700 coal particles/cc of air and 60 non-coal particles/cc of air. The maximum dust concentrations actually included in the in the 1948 regulations were:

Stone dust - 450 particles/cc with a size range from 0.5 to 5µm;

Anthracite dust - 650 particles/cc with a size range from 1 to 5µm;

Coal dust - 850 particles/cc with a size range from 1 to 5µm.

It will be seen that whilst the chosen size ranges to be used for the counts were similar to the MRC recommendations, the limiting concentrations were largely different. Why this was so, and the criteria used in the development of the statutory limits, has not been uncovered.

Eventually the approved conditions became accepted as the target levels for the conditions at all working places underground, not simply those suitable for the employment of pneumoconiosis sufferers.

Originally it was intended that compliance with the above be determined using 'short running' thermal precipitator instruments described in Section 9.4.3. However, initial problems with availability caused a continued use of the older and less accurate konimeters (see Section 9.4.1) and PRU hand pumps (see Section 9.4.2). Samples were to be collected at least once per year in the return airway at the period of maximum dustiness. The evidence is that measurements were typically taken more frequently than this, for example quarterly or monthly.

Revised regulations detailing the approved limits for respirable dust in coal mines and the assessment procedures to be used were issued in 1956. In addition to a reduction in the maximum allowable particle counts, a single size range from 1 to 5 µm was to be used for both coal and stone. This simplified the counting procedure by removing any need to decide whether a particle was coal or rock.

The original regulations required that measurements be taken at the period of maximum dustiness. In practice this proved difficult to determine. To overcome this problem, the new rules required that the short running thermal precipitator be used to take a multiplicity of samples over a whole working shift. Unfortunately, this approach was not without its own operation difficulties. For example, the instrument was only capable of sampling for up to thirty minutes. This meant that to cover a shift lasting up to eight hours a large number of samples had to be collected underground, transported to the surface and then counted in a laboratory. This was a very time consuming and costly process. In part, the problem was reduced by the development by MRE of a 'long running' thermal precipitator instrument described in Section 9.4.3. Broadly similar to its predecessor, it could operate continuously for a whole shift, producing one sample for counting. From 1965 this instrument was used as the standard coal mine dust sampler.

By the mid-1960's MRE had developed a reliable gravimetric sampler. This was adopted as the new standard instrument when revised respirable dust regulations were introduced in 1970. These incorporated concentrations expressed in mass units. A working place was 'approved' if the mean level of respirable dust was less than 3 mg/m^3 in stone roadways and less than 8 mg/m^3 in all other locations. Measurements were to be taken continuously over the period men were at work. For coal faces and roadways being driven in stone the sampling frequency was once per calendar month whilst at other locations, notably on conveyors, it was once per quarter. Approval was assessed from the mean of three sequential monthly results.

As with other limiting dust concentrations, it is not clear why the figures contained in the 1970 regulations were chosen. Unlike the earlier ones, however, it is possible that they were derived using statistical data available from the Pneumoconiosis Field Research by this time. If this was the case, then they are more likely to have some significance in respect of the development of pneumoconiosis than their predecessors.

In 1975, yet another set of respirable dust regulations were issued for coal mines. These form the basis of those in force during the mid-1990's when this monograph was being prepared. Whilst the basic provisions were similar to the earlier versions, from 1970 the expression for the limits of dustiness at which sanctions were imposed became considerably more complex. For example, in the event of the previous monthly respirable dust concentration being greater than 5 but less than 7 mg/m^3, five of the next seven shifts on which similar operations were being carried out were to be sampled. If the higher limit was exceeded, remedial measures were to be introduced. These may include a cessation of production.

The dangers from silicosis were not forgotten by the modern dust regulations. As an example, for roadways not being wholly driven in the coal seam if the respirable dust concentration exceeded 3 mg/m^3 but not 5 mg/m^3, the average quartz content in the dust was to be determined. If this exceeded 0.45 mg/m^3, sanctions were imposed at the lower level.

Data given in Section 9.1 shows that in recent years there has been a reduction in the incidence of pneumoconiosis amongst mineworkers. In view of the recognised link between dust concentration and the development of the disease it is probable that the increasingly stringent regulations, and the dust control measures introduced as a consequence, had an influence on this. An indication of the actual changes that have taken place underground is provided by the median dust concentration for all United Kingdom coal faces. In 1970/1 was 5.8 mg/m^3. However, within twenty years it had fallen to 3.1 mg/m^3. Over the same period, the overall productivity of coal mines had risen by about 1.7 times (17).

9.4 The measurement of respirable dust

The requirement to measure respirable dust in coal mines falls into three distinct phases. The first was a desire to assess the effectiveness of dust collection systems developed for use with mechanical drills. These were introduced in response to a respirable disease specific to rock drillers. Once dust induced respirable diseases began to appear in coal mines, instruments were required to determine what the conditions were like underground. Once this had been done and some idea obtained as to the target dust levels that should be maintained, devices were required to ensure these were not exceeded.

This section considers the dust samplers developed during each of these phases.

9.4.1 Konimeters

By 1903 it was being suspected that a contributory factor to a high mortality rate amongst South African gold miners could be the presence of airborne stone dust in the underground workings. Consequently, steps were taken to reduce the levels present by the application of dust collection methodologies. To determine their effectiveness, in 1916 Sir Robert Kotze produced what was probably the first respirable dust sampling instrument. Designated the 'Kotze konimeter', it was used to count the number of airborne dust particles collected from a measured volume of air. An improved version of the device was produced by Carl Zeiss in about 1937.

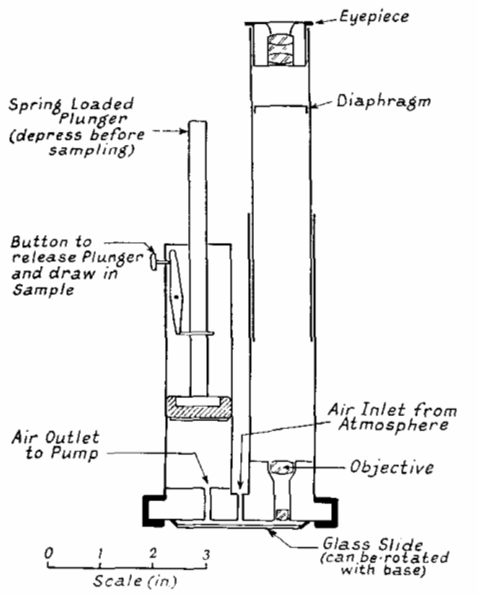


Figure 9.2 A schematic diagram of a konimeter dust sampler (copyright Cleaver-Hume Press Limited)

A diagram of a konimeter is given as Figure 9.2 (20). It consisted of a spring loaded plunger that could be caused to move rapidly in its chamber. As it did so a preset volume of air, 2.5 or 5 cc, was drawn through the inlet. Typically, this was 0.5 mm in diameter. A combination of the speed of the plunger and the small size of the inlet resulted in intake speeds for the air and dust of about 80 m/s. Immediately on entering the device the flow was caused to turn through ninety degrees immediately in front of a circular glass disc. Due to their inertia, the dust particles were unable to change direction quickly enough, impacted on this disc and became trapped in a sticky substance with which it was coated. After each test, the operation of a thumb wheel allowed an unexposed portion of the collection disc to be placed beneath the inlet orifice.

By this method up to thirty samples could be taken before the glass needed to be replaced. The range of dust particle sizes captured on the slide was not restricted to the respirable range. Each sample collection typically took around one second.

Examples of exposed slides are reproduced as Figure 9.3. Their evaluation, which involved particle counting and sizing, could be undertaken on site using the integral microscope. Alternatively, the slide could be removed from the konimeter and sent to a laboratory for evaluation. Whilst this process would have been relatively easy with 'light' samples, as represented by the lower slide in Figure 9.3, the upper sample would have been extremely difficult to count. Further, it is likely that many particles overlap with their neighbours making the results to both the count and sizing operations unreliable.

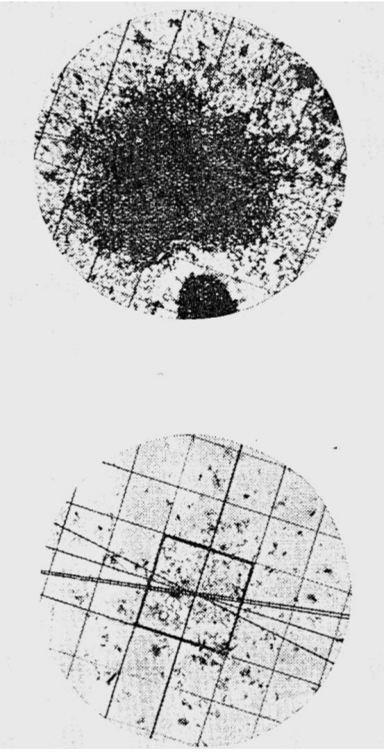


Figure 9.3 Exposed konimeter slides (copyright National Coal Board)

To try and simplify the evaluation of konimeter slides the British Colliery Owners' Research Laboratory developed a semi-automatic system. This operated on the concept that a light beam passing through the sample would be attenuated by an amount related to the number of particles of dust present. In practice the system suffered from a number of shortcomings. Not the least of these was its inability to determine the sizes of the particles present. This was a distinct disadvantage when only those smaller than 5 μm were of interest and thus needed to be counted. Further, the accuracy of the system output versus particle count was not constant between samples. In this respect, significant variables included the size and shape distributions of the particles and their refractive indices.

Possibly because there was not alternative, from about 1920 onwards konimeters became widely used in British coal mines in connection with dust suppression and respirable disease studies (15). Also, from 1948 onwards, they were used for routine inspections required under the dust regulations. In this case it was due to availability problems with more advanced instruments.

Despite their initial popularity, by the early 1940's it was being realised that konimeters were far from the ideal instrument for assessing the respirable dust hazard. For example, although the apparatus collected all the incident 2.5 μm particles, it only captured about 10% of the 0.5 μm (21). Such a characteristic meant that not only were the results biased towards the larger sizes, but they were also dependent upon the particle size distribution of the dust cloud being measured. Other problems that could lead to misleading counts included a tendency for some particles to fracture on impact with the slide and for others to aggregate to form dust that appeared outside the respirable range.

Attempts at overcoming some of these limitations led to the development in the USA of a group of dust sampling instruments called 'impingers'. In these, airborne particles were collected in a liquid. This type of system does not appear to have found widespread use in this Britain. The reason for this has not been discovered.

9.4.2 Filtration samplers

As concerns over the incidence of dust related respirable disease in British coal mines increased so did appreciation of the limitations of the konimeter as a sampling instrument. Those of main concern included its inability to sample over an extended period of time, provide a gravimetric assessment of the dust concentration, and provide sufficient material for chemical analysis. As a result, alternatives were sought. The simplest of these, and one that was probably used by the Mines Department for its 1925 studies, involved drawing a sample of dust containing air through a filter. Typical forms used included a plug of granular material, or a thimble shaped filter paper.

Plug filters used sugar or naphtha. As air was drawn through them any suspended dust stuck on the granules. In a laboratory, the two were separated by dissolving the carrier in an appropriate solvent. This released the dust for subsequent study.

Earliest reports of 'sugar tube' filters date from 1905 when they were used in the subways of New York (22). In this country, the Medical Research Council made use of naphtha devices in their 1943 studies (9). These were 10 mm in diameter and filled with ground material that had passed through a 20 mesh (about 780 μm hole size) screen. Typically, a total metered air throughput of about 5 litres was used. For sample times in the region of 5 minutes a hand pump was used to provide the necessary flow. For longer periods a water aspirator was used. The system was believed to collect about 99% of the airborne dust.

One of the problems with granular filters concerned difficulties in obtaining repeatable packing densities and hence pore size. The result was that the size range of the collected material varied. It was removed by the 'Soxhlet thimble' apparatus, developed in Britain around about 1939. Shown in Figure 9.4, it incorporated a standard porosity paper filter, approximately 25 mm in diameter and 80 mm long. To ensure that the particle size distribution of the collected material was representative of that in the environment, it was important that the inflow speed exactly matched that of the ventilating current. If it was too high then a bias was introduced towards smaller particles and vice versa.

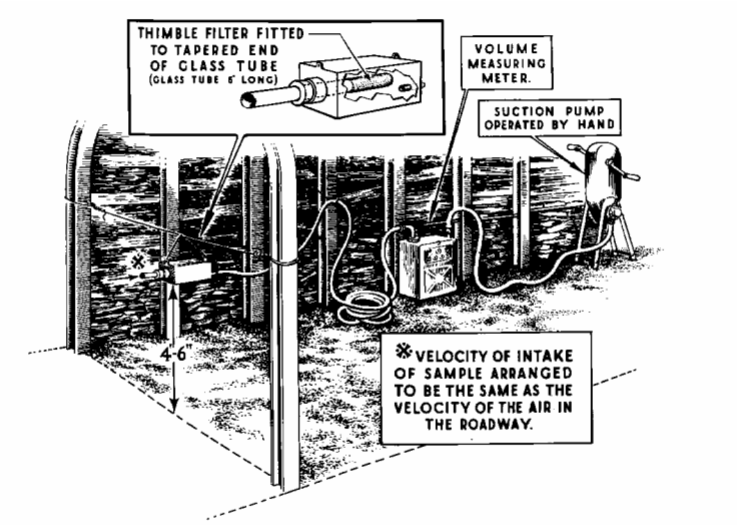


Figure 9.4 The Soxhlet thimble dust sampling apparatus

On completion of sampling, the exposed thimbles were sent to a laboratory for analysis. Usually this involved comparing its weight following exposure with its clean value. Knowing the volume of air passed that had through the apparatus it was thus possible to determine the mass concentration of dust collected per unit volume of air. Above the filter pore size both respirable and non-respirable dusts were collected. This reduced the usefulness of the apparatus in connection with pathological studies. Despite this the Soxhlet thimble apparatus was used in coal mines until the 1970's (23). Its roles included investigations into the behaviour of different dust suppression techniques and how changes in working patterns affected environmental conditions (21).

An important form of filter type dust sampling apparatus was the 'PRU hand-pump' described in 1948 (20). This was developed by the Pneumoconiosis Research Unit (PRU) from wartime gas sampling equipment and used to provide rapid, if not necessarily highly accurate, assessments of underground airborne dust concentrations. In it, a hand pump was used to draw a measured volume of air through a piece of white translucent filter paper. This produced a dark stain about 10 mm in diameter.

Analysis of the stained filter papers was undertaken on the surface using an electro-optical system developed by the British Coal Owners' Research Laboratory. As had the apparatus used for the rapid evaluation of konimeter slides, this used the attenuation of an optical beam to provide an estimate of the number of deposited dust particles. However, to try and minimise the calibration uncertainties associated with variations in the refractive index and size distribution of the particle cloud being sampled, at each site being investigated a multiplicity of simultaneous dust samples were collected using a standard short running thermal precipitator instrument and the PRU hand pump. From these it a particle count versus optical attenuation chart was produced. This allowed for the rapid evaluation of subsequently exposed filter papers. Despite the application of this procedure, (24) suggests that there was still doubt as to the accuracy of the results provided by the apparatus.

Irrespective of any reservations over the accuracy of the results provided, as late as 1960 the PRU hand pump was still reportedly the most widely used dust sampler in British mines (20). Its primary role was in connection with the assessment of conditions under the 1948 dust regulations and later 'approved conditions' standards of the NCB. It is postulated that this apparent popularity stemmed from its simplicity of operation and subsequent sample evaluation. This facilitated the taking of many samples over the period of a shift, thereby minimising the possibility that one was not taken at the time of maximum dustiness as required by the regulations.

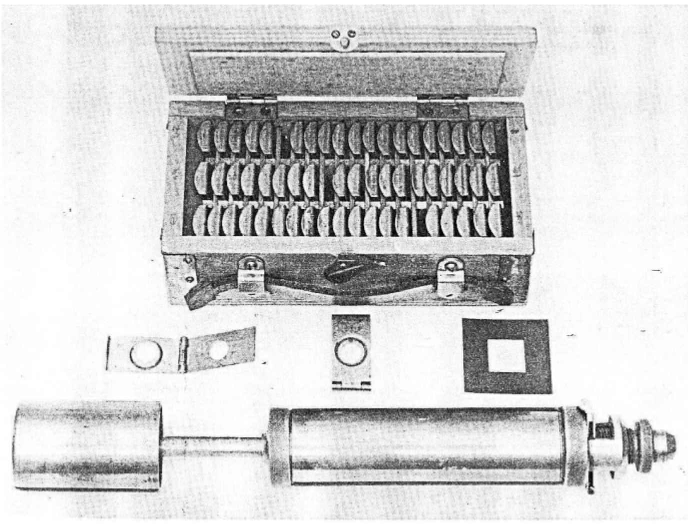


Figure 9.5 The PRU hand-pump (copyright National Coal Board)

As with many of the other instruments described, the PRU device it was eventually replaced by the MRE gravimetric dust samplers described in Section 9.4.6.

9.4.3 Thermal precipitators

By about 1935 it was being postulated that whilst the number density of airborne particles could have an influence on the development of pneumoconiosis there were other potentially significant variables that should also be considered. Included were the chemical composition of the dust and its particle size and shape distributions. Following a review of the samplers available, a Medical Research Council report concluded (25) that none were suitable for use in the studies necessary to investigate such matters. Consequently it was decided to develop a completely new device. The apparatus subsequently produced became the first in a series of respirable dust samplers called 'thermal precipitators'.

The operating principle used in thermal precipitator dust samplers was discovered during the nineteenth century. Then it was found that a heated wire placed with its longitudinal axis horizontal in an initially uniform cloud of dust caused a clear zone to be formed around it. Below the wire the periphery of this region was equidistant from the hot surface, whilst above it a tail extended in the direction of the convection currents. Increasing the temperature of the wire increased the radius of the dust free area.

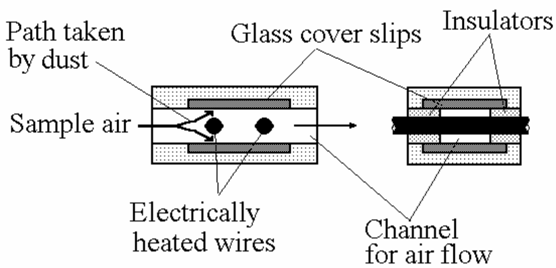
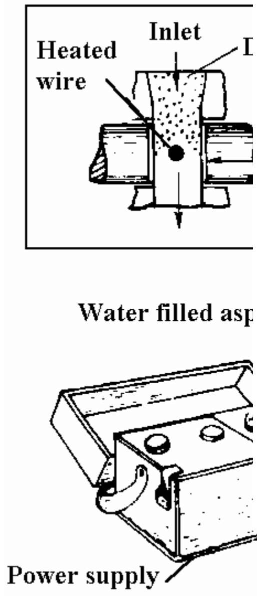


Figure 9.6 Green and Watson's thermal precipitator

A schematic diagram showing how this idea was used by Green and Watson to produce a dust sampling instrument is given as Figure 9.6. By heating the wires to an appropriate temperature any dust suspended on the sample air current was caused to move along the paths shown and precipitate out onto the glass cover slips. These could be removed from the apparatus for evaluation.

Soon, thermal precipitator dust samplers were being produced with only one hot wire. An example is shown in Figure 9.7 (26). For the purposes of this monograph, this particular device will be called the 'short running' thermal precipitator. In it the sample channel was 0.51 mm deep and the wire 0.254 mm in diameter. Using power from a battery, the latter was heated to a temperature of approximately 100°C. This caused virtually all the 0.2 to 10 μm dust particles supported on the sample air to precipitate out on to two glass slips. Using the water filled aspirator, sampling times up to 30 minutes could be achieved.

Evaluation of the collected samples was carried out in a laboratory. Here, the exposed cover slips were placed under a microscope and the deposited particles manually counted and sized. This was an extremely laborious process.



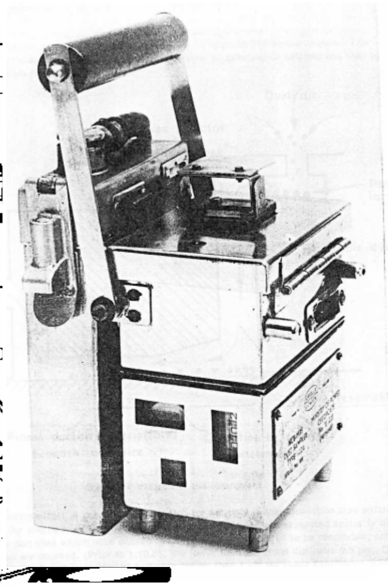


Figure 9.9 The MRE long running thermal precipitator (copyright National Coal Board)

Figure 9.7 The short runn... Sir Isaac Pitman and Sons Limited)

A report from 1943 (9) notes that the thermal precipitator 'provides more complete and reliable information about the particle size distribution of the dust than any other existing instrument'. From 1948 the apparatus was the adopted standard for statutory underground environmental dust assessments.

From 1954 a more compact Mk III unit, shown in Figure 9.8, was used for routine measurements in coal mines. Although the sampling head appears to have remained unchanged, the large floor mounted power supply was replaced by an integral cap lamp battery and the aspirator changed in shape.

In practice, the short running thermal precipitator proved too complicated and laborious for routine, non-statutory, use in coal mines. Consequently, it tended to be used as the standard against which faster methods, notably the PRU hand pump, were periodically compared. Also, at only thirty minutes, its sampling period was short relative to a shift length. This meant that determination of the period of maximum dustiness, as required by the law, needed the exposure and evaluation of a large number of glass slips, a costly process. A further problem was related to the fact that the collected dust was deposited on the glass slips in a narrow line. In heavy dust concentrations this made it difficult to produce reliable count results.

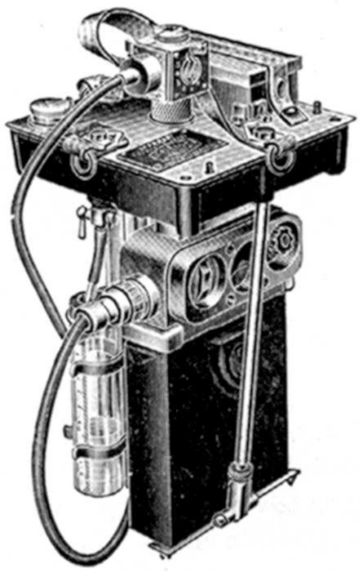


Figure 9.8 The Mk III short running thermal precipitator (copyright Casella CEL Ltd.)

Responding to these shortcomings, by 1957 MRE had produced a 'long running' thermal precipitator. An early version, designated NCB/MRE Type 101C, used a clockwork driven pump to draw in sample air and an internal battery to heat the wire. By 1960, a unit fitted with an electric pump and powered by a modified miner's cap lamp battery was being supplied. Designated NCB/MRE Type 112, and shown in Figure 9.8, it was extremely portable and capable of unattended and continuous operation for up to eight hours, about the length of a working shift. The collected dust was deposited on a single glass slide, rather than the two of the short running instrument.

A diagram showing the dust collection arrangement used in the Type 112 thermal precipitator is given as Figure 9.10. This was designed to facilitate the sizing of the collected material and to minimise the counting problems experienced when high dust concentrations were sampled. Firstly, the intake air was passed through an aerodynamic size selector of the type to be described in the next section. This removed those particles too big to have reached the lungs of a human, leaving only the respirable fraction. Next, the air, with its remaining dust, was passed round a right angle bend and along the shaped channel shown. This introduced a degree of size discrimination into the deposition process and ensured that the material was spread out along the slide. At its beginning the larger particles settled out under gravity, with thermal precipitation only being used to remove the smallest material left suspended at the channel end.

In 1965 the MRE long running thermal precipitator replaced the short running unit as the standard reference instrument for underground use.

9.4.4 Aerodynamic particle sizing

As proposed by the MRC, the assessment of underground environmental dust the count of 1 to 5 μm particles was based on the assumption that a fixed relationship existed between this and the pathologically significant mass concentration. The validity of this belief began to be questioned when it was realised that the probability of a particle being deposited in the lungs was typically dependent on its settling speed rather than simply its geometric size. Further, the relationship between the two varied with the source of the dust, namely between collieries (27). Responding to this, MRE began working on a continuously operating dust discriminating procedure that better approximated to the processes taking place in the respirable tract than did the hitherto used manual selection of material on the basis of geometric size. One of the systems evaluated was called a ‘horizontal elutriator’. This was formed from a stack of horizontal channels that were very much longer than they were wide and very much wider than they were high. Irrespective of the presence of any turbulence at the intake, the flow through them was laminar. This allowed some of the dust particles carried on the flow to settle out under gravity. By appropriate choice of geometry and air flow rate the probability that a particle with a given settling speed would pass through a channel could be varied.

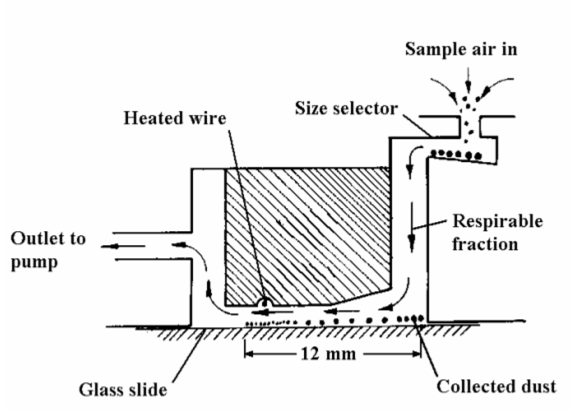


Figure 9.10 The dust collector in the long running thermal precipitator

The horizontal elutriator respirable dust selector was so well received that in 1952 the Medical Research Council adopted it for use in ‘standardised’ respirable dust sampling instruments. For these the particle size versus probability transfer function, referenced to unit density spheres, was zero at diameters above 7.1 μm and 50% at 5 μm. This size selection curve, shown in Figure 9.1, was accepted internationally by the 1959 pneumoconiosis conference in Johannesburg.

Although other forms of aerodynamic dust discriminating systems have been produced, notably the ‘cyclone’, the horizontal elutriator has been most widely used on sampling instruments produced in this country. For this reason the others will not be considered further herein.

9.4.5 The Hexhlet sampler

One of the earliest applications of the horizontal elutriator in Britain was on a system called the ‘Hexhlet sampler’. This dates from about 1954 (28) and is shown in Figure 9.11. In it the respirable dust that penetrated the size selector, formed from 118 ducts each 35.5 mm wide, 251 mm long and 8 mm high, was collected on a Soxhlet thimble filter shown at the right of the picture. Air flow through the apparatus was provided by a compressed air injector. The Hexhlet could be used to sample dust over a whole working shift. In a concentration of 850 particles/cc (the maximum allowed under the 1948 regulations) about 1 g of material was collected (28). This was suitable for particle counting, as required by the legislation, and gravimetric assessment and chemical analysis.

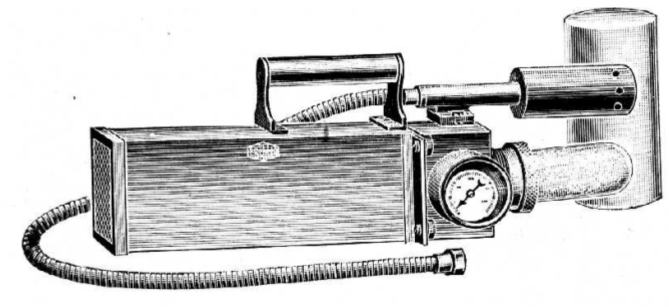


Figure 9.11 The Hexhlet sampler (copyright Casella CEL Ltd.)

A problem with the Hexhlet was its need for a supply of compressed air. In 1957, at the request of the Pneumoconiosis Field Research Scheme, MRE produced an electric version. However, a lack of references to it suggests that it was not widely used. This was probably due to the development by MRE of the gravimetric dust samplers to be discussed next.

9.4.6 MRE and MRDE gravimetric dust samplers

In 1957, at the same time as they reiterating the view that the mass concentration of respirable dust might prove the most appropriate parameter for the assessment of the hazard it represented, the Medical Research Council urged the development of suitable measuring instruments. The desire was for a fully portable and self contained system. By 1963 MRE had produced prototypes of an instrument to meet this requirement. Designated the ‘NCB/MRE Gravimetric Dust Sampler Type 113A’, the unit is shown in Figure 9.12 (a and b). Powered by an internal rechargeable battery, the unit was certified intrinsically safe for use underground in coal mines. Selection of the respirable fraction of the dust was achieved using a four channel horizontal elutriator. At a sample flow rate of 2.5 l/min, it had the standard transfer characteristic shown in Figure 9.1. The respirable dust was collected on a removable glass fibre membrane filter.

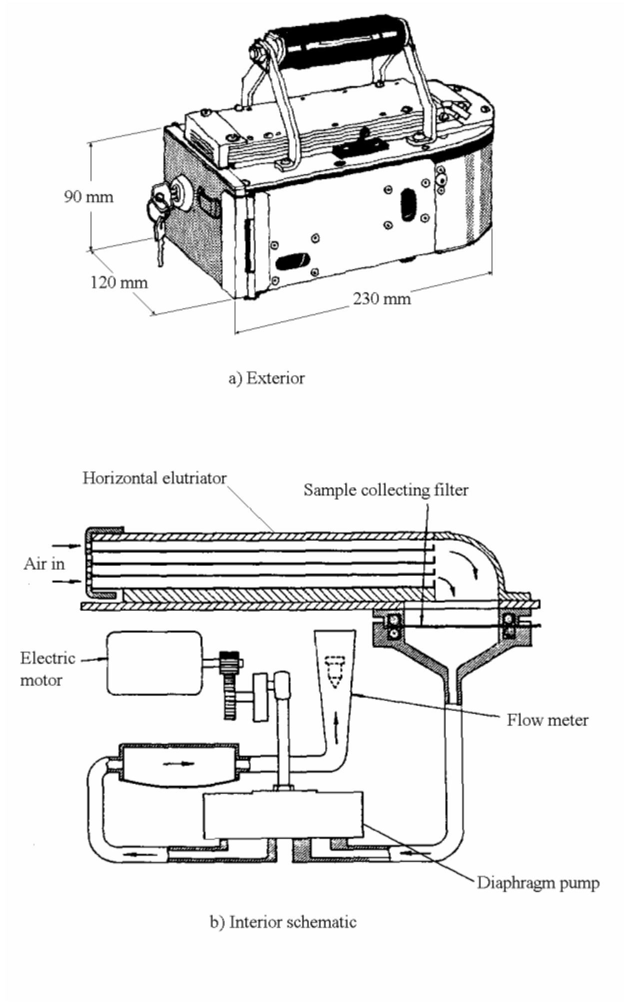


Figure 9.12 The NCB/MRE Gravimetric Dust Sampler Type 113A (copyright National Coal Board)

Once a pre-weighed filter was loaded,

taking a sample of respirable dust with the Type 113A was a relatively simple operation. All that had to be done was for it to be hung at the desired location with the elutriator facing the air current and the pump switched on. At the end of the assessment period, which could be up to 8 hours, the motor was switched off and the instrument removed from the mine. In the laboratory the exposed filter was re-weighed. From the volume of air sampled, determined from the change in an externally visible motor revolution counter, the shift mean mass concentration of respirable dust could be calculated. Separation of the coal and non-coal fractions was achieved by incineration at approximately 500°C followed by re-weighing. The quartz content was determined using X-ray diffraction or infra-red spectroscopy.

Evaluation of the Type 113A instrument initially involved comparing its performance with that of the then standard long running thermal precipitator. Although no direct comparison of the results was possible, since the former measured mass of dust and the latter particle count, side by side sampling at a given site did reveal a fixed relationship between them (29). Clearly this was considered acceptable since the NCB/MRE Type 113A dust sampler soon became adopted as the instrument approved for use in conjunction with both statutory and routine respirable dust assessments underground. This was still the case up to at least the mid-1990's.

Should a monthly dust assessment exceed a specified limit, after 1975 became a statutory requirement that sampling was to be carried out over a further five shifts. This was an extremely laborious process using the Type 113A because it had to be taken to the surface at the end of each shift for the exposed filter to be removed and evaluated. In an attempt to simplify this procedure a number of 'multi-shift' gravimetric dust samplers were developed.

An early example was the 'MRDE Type 115'. Although basically similar to the Type 113A, it included a clockwork driven control system to start and stop the electric pump. By this means respirable dust could be sampled over the required five shifts. This was deposited on a single glass fibre filter. The five shift average respirable dust concentration was calculated from the total mass of dust deposited divided by the total volume of air drawn through the instrument.

Although tests indicated that the Type 115 was suitable for routine use underground it was never accepted by the coal industry. The main reason appears to have been its inability to show dust concentrations for the individual shifts (30).

With the advantages to be gained from multi-shift dust sampling all too apparent, MRDE decided to develop the Type 115 unit further. The result was the 'MRDE Gravimetric Dust Monitor' shown in Figure 9.13 (31). As with its predecessors, sample air was drawn into the apparatus through a horizontal elutriator and the respirable dust deposited on a membrane filter. Unlike them it contained the means by which the mass of material collected during each shift could be determined. This was formed from the β-ray radioactive source and the Geiger-Muller tubes shown. Under the control of a microprocessor, at the end of each shift the attenuation of the radiation beam passing through the dust on the filter was determined. This was compared with the previous result, allowing the change in mass of deposited dust to be determined. Using the volume of air that had passed through the apparatus, a shift average mass concentration of respirable dust could be calculated. The result was stored in a solid state memory and shown on a local liquid crystal display. On removal of the instrument from the mine, the filter could be weighed to provide a check of the results downloaded from memory (30)(31).

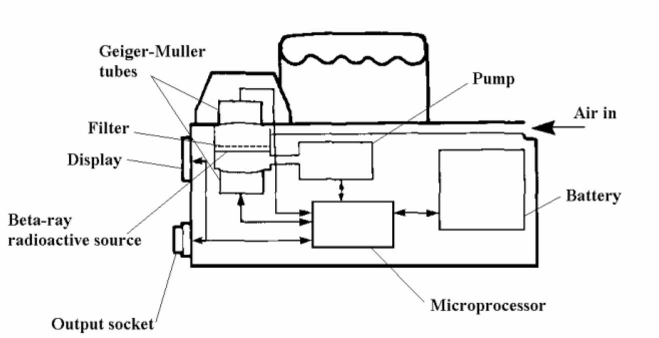


Figure 9.13 The MRDE Gravimetric Dust Monitor (copyright National Coal Board)

The MRDE Gravimetric Dust Monitor was certified intrinsically safe for use in coal mines in 1982/3. Subsequent evaluation revealed good agreement between the results provided and those from the MRE

Type 113A. According to King (32), however, its underground use did not go much beyond this point. The reason probably stems from the fact that although the operation of the older, single shift, instrument was more labour intensive it remained approved under the mining regulations. Further, with the number of operating collieries in decline there were a large number of instruments available to replace any that were irreparably damaged in use. Taken together there were thus no incentives for colliery operators to incur the costs of replacing their Type 113A units.

9.4.7 Optical dust monitors

The gravimetric samplers described above were designed to measure shift average respirable dust concentrations. None were capable of showing the presence of relatively short term variations, such as may be required during studies into the efficiency of a particular dust control technology. Although a number of ‘short period’ samplers have been described that may seemingly have been capable of fulfilling such a requirement, and did so on occasion, they were restricted to producing particle counts only. This section contains brief descriptions of series of fast response monitors designed by SMRE and its successor organisations. All were intended to provide gravimetric dust assessments from measurements of the intensity of light scattered by respirable particles.

When light passes through a cloud of dust some will be scattered. It has been shown that the intensity along a line making an angle of about 4^o to the incident main beam direction is related to the volume concentration of particles present. Thus if the material density is known then light intensity measurements along this line can provide an indication of the mass concentration of particles in a sampled dust cloud (33). A problem with the practical implementation of this idea was associated with the small scattering angle and difficulties in differentiating between the low intensity dust signal and the direct beam. Consequently, when SMRE first developed an optical dust monitor they used the radiation scattered over very much larger angles, 12 to 20^o. However, the intensity along these directions has been shown to be related to projected particle surface area rather than mass concentration (33)(34).

Despite this, SMRE announced the development of an optical dust monitor called ‘Simslin’ (Safety in Mines Scattering Light Instrument) in 1974 (33). In this, mine air was drawn into the device through a standard parallel plate elutriator. The respirable fraction of dust that remained was then passed through a collimated beam of near infra-red radiation. A photomultiplyer tube was used to detect the intensity scattered along the specified range of directions and electronic circuits produced a corresponding output current for display on an external recorder. The result shown was intended to be related to the concentration of respirable dust passing through the beam. On discharge, the dust was captured on a membrane filter for gravimetric assessment or composition analysis.

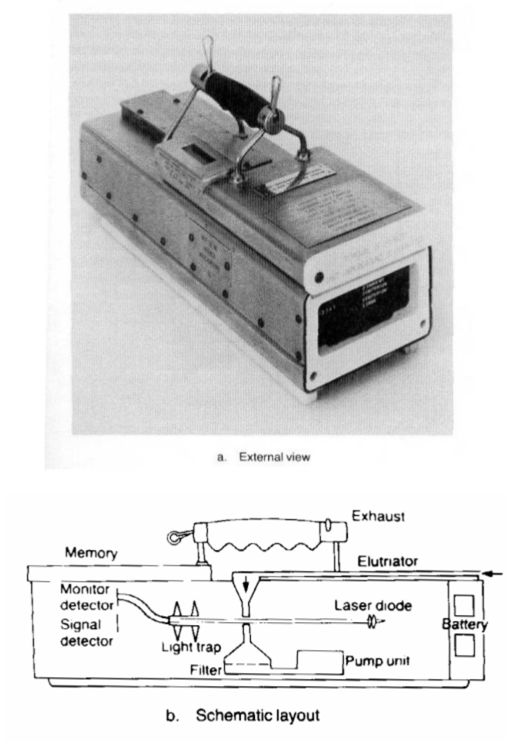


Figure 9.14 Simslin (copyright National Coal Board)

A later version of Simslin is shown in Figure 9.14 (a and b). It incorporated an infra-red laser and solid state radiation detector. This made it considerably lighter and lower powered than its predecessor. The sensed dust concentration was shown on an externally visible digital display. It was also available as a dc voltage or a serial pulse train. The full range input for these outputs could be selected as being either 0 to 20 or 0 to 200 mg/m^3 (34).

Underground tests of the earlier version of Simslin were carried out by MRDE during 1976/7. Unfortunately they failed to show any correlation between the indications provided and those from an MRE Type 113A sampler operating alongside. No suggestions as to why this was so have been located, but it may have been due to the response of Simslin being dependent on particle material and size distribution. Such behaviour had been noted as occurring when optical techniques were used to evaluate konimeter slides and PRU hand-pump filters.

With the later version of Simslin it was the practice to weigh the collection filter at the end of a known sample period and then to adjust the instrument calibration such that it showed the same reading (34). By this means it was anticipated that the reliability of successive results would be improved, provided the instrument was not relocated or the source of dust changed.

By 1989, the Engineering Laboratories of the Health and Safety Executive, formerly SMRE, had produced a new optical respirable dust monitor called Osiris (Optical Scattering Instantaneous Respirable dust Indicating System). From the description available (35) its operating principle seems to have been similar to the later version of Simslin. Underground, the concept was to install a multiplicity of instruments and link them to a computer. This controlled their sampling sequences and evaluating the collected data.

Laboratory evaluations of Osiris showed (35) that once a unit had been calibrated for a given dust, the response varied linearly with that provided by an MRE Type 113A sampler over a concentration range from 0 to 40 mg/m^3. However, since the optical instrument responded to projected surface area, the slope of this line showed considerable variation when the particle size of the sampled and material were changed. This meant that in use, each unit would have to be uniquely calibrated for the dust being monitored, as had been the case with the earlier optical dust monitors.

Despite the noted problems, optical dust monitors have been used in dust control work where relatively high frequency changes in concentration are required to be indicated. However, it always seems necessary to carry out an on-site calibration using a Type 113A gravimetric dust sampler.

9.5 Conclusions

From the data reviewed it is concluded that the precise causes of pneumoconiosis and the factors that govern its development are still uncertain. As a result the current limiting concentrations for environmental dust are based on an analysis of the disease incidence data rather than its pathology. Consequently, it is concluded that research into pneumoconiosis should continue. Only then will it be clear that the control measures in place are in fact appropriate to the actual hazard.

Modern coal mines still contain airborne dust producing processes and the very recent occurrence of several new cases at a single Nottinghamshire mine indicates that there is no room for complacency regarding the effects of its inhalation. Consequently, there appears to be no case identified for a relaxation of the stringent rules being applied to the control of airborne dust. If anything, further research is required into the physiological effects of mine dust and a general reduction of the exposures to which miners are subjected.

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Chapter 10 Ionising radiation

An environmental problem closely linked to pneumoconiosis relates to the presence in mines of the naturally occurring radioactive gas radon and its decay products. This chapter describes how a realisation that these materials may lead to an enhanced risk of miners developing lung cancer led to the introduction of measures aimed at limiting the exposures to them.

10.1 Physiological effects

For the purposes of this chapter, α-particles are of primary concern. As they pass through biological tissue they interact with the atoms and molecules, initiating chemical changes that represent physical damage. The amount caused is related to the energy absorbed per unit mass of material. This in turn is related to the number of incident particles, their energy and the type of tissue. Applied externally to the human body, α-particles are incapable of penetrating the surface layers of dead skin. However, exposing the more sensitive internal organs to such radiation can lead to the development of cancers.

Radiation doses can be expressed in 'Sieverts' (Sv). An assessment in these units requires knowledge of the type of radiation and the susceptibilities of different organs of the body to radiological damage. An exposure unit more specific to radon and its decay products is the 'Working Level' (WL), with integrated doses being expressed in, for example, 'Working Level Months' (WLM). Both are measures of absorbed energy.

10.2 Radiation in coal mines

Within the earth are the elements uranium^{238} and thorium^{232}. Both are radioactive and head decay series containing the radon isotopes radon^{222} (often called simply radon) and radon^{220} (often called thoron). Whilst most of the preceeding elements in the decay series are solid these are gases. As a result they can migrate through cracks in the strata and appear on a mine's ventilating current. Here they continue to decay, passing through a group of short half life α-emitting elements called the radon and thoron 'daughters'. Some of these are solid.

In 1924 the suggestion was made that the presence of radon in underground environments may cause lung cancer amongst underground miners (1). However, some fifty years were to elapse before sufficient data had been collected to clearly demonstrate that a correlation did exist between the incidence of the disease and measured Working Levels (2).

Even before the link between underground radon and lung cancer had been firmly established, studies were conducted to see if airborne radio-nuclides were likely to represent a hazard to coal miners. Carried out during the 1950's and 60's they returned negative results (2). Later, in 1968 radon was detected in coal mines. The concentrations were typically less than 14% of those found in metal mines. Despite these low levels, the fear expressed was that the solid daughters could attach themselves to airborne respirable dust particles. By this means they could be transported deep into the lungs, irradiating the sensitive tissues present, and effectively enhancing the hazard represented by the low levels of radiation. At the time it was not possible to consider this matter further because there were no underground radiation measurement systems that could be used with particulate sources.

From Section 10.4 it will be seen that by 1972 a detection methodology based on the NCB/MRE Type 113A gravimetric dust sampler had been developed by which the Working Level of particulate radio-nuclides could be assessed. Using this, an extensive study was carried out into the presence of radon, thoron and their daughters in British coal mines (3). Over an eight year period sixty-one radiation level measurements were made at eleven collieries. The results showed that radon and its daughters generally made the largest contribution to the overall radioactivity of mine air, with thoron only being the largest contributor when the overall levels were low, typically below about 8 mWL (4). At only one colliery did the shift average measurements of total activity exceed a then anticipated legal maximum of 30 mWL. Thus it is concluded that the underground radiation levels were not likely to represent a danger to the health of coal miners.

Subsequent studies have shown that concentrations of radon, thoron and their daughters vary considerably both between collieries and with location underground. The elements are rarely found in intake roadways and appear to be mainly associated with disturbed ground, old workings and waste areas (5)(6).

The view held at the time of writing (1995) seems to be that radon and thoron by themselves do not pose any threat to the health of coal miners. This is because they are present at only very low levels and, being gaseous, are not retained by the body in appreciable quantities. Despite the known hazard their daughters represent to metal miners, a study within the coal industry (3) failed to show any similar relationship between the incidence of lung cancer and exposure. However, the imposition of statutory regulations governing the maximum allowable levels of ionising radiation underground, to be described in the next section, has ensured the development of radon and thoron daughter monitoring procedures. Provided the work is completed, these will help ensure that the situation is kept under review.

10.3 Regulations

Although regulations covering ionising radiation in industry were introduced in 1968 they did not apply to coal mines, nor did they make any specific reference to radon or thoron. Both these shortcomings were removed in 1985. Then new regulations were issued specifically stating that they were to apply to those coal mines where a person was exposed to an atmosphere containing radon/thoron concentrations greater than that equivalent to a dose of 30 mWL. With this regulation came the necessity for collieries to provide themselves with means of assessing underground radiation levels. The systems available are described in the next section.

More specifically, the 1985 regulations and the subsequent revisions stated that those working areas in which the annual dose exceeded 5 mSv (equivalent to 30 mWL for 1 year) were to be designated ‘supervised’. In each, whole shift measurements of worker exposure to ionising radiation were to be regularly made. Where the annual dose was found to exceed 15 mSv (100 mWL for 1 year) the area was to be designated ‘controlled’. Entry to these locations was to be restricted to authorised personnel wearing personal dose meters. In 1992 there were two collieries with supervised areas and none with controlled (5).

10.4 Underground radiation assessment

As identified above, initial interest in airborne radiation underground was directed at the gaseous radio-nuclides of the uranium^{238} and thorium^{232} decay series. An early method of determining the concentrations of radon and thoron involved the use of flasks lined with a luminescent material (zinc sulphide and silver) and fitted with a transparent window at one end. Underground, these were filled with mine air. They were then taken to a surface laboratory and placed in a scintillation counter. From the detected rate of radioactive decay the concentration of radio-nuclides present in the original sample could be determined (1)(7). In practice it was found that the flasks were susceptible to damage underground and so it became the practice to collect the samples in pressurised cylinders using the NCB sampling pump described in Appendix II. Their contents were decanted into the flasks on the surface (7). It is believed that this methodology may well have been that used for the 1968 radiation survey of British coal mines mentioned in Section 10.2.

By 1972, when the more extensive survey of mine radiation levels was begun, it was clear that a proper assessment of the hazard required whole shift measurement of the radon and thoron daughter concentrations. For this, the flask method was inappropriate, mainly because it could only be used for gaseous elements and those of interest were solid. As an alternative, use was made of the MRE Type 113A gravimetric dust sampler described in Chapter 9. Operating for a whole shift, it collected those radio-nuclides being carried on respirable dust and deposited them on a filter. Back on the surface the rate of radioactive decay could be measured and the Working Levels of the collected radon and thoron daughters determined.

Despite its advantages over the earlier approaches, even this new method was far from the ideal. One shortcoming stemmed from the fact that the radioactive decays were not counted until the end of a shift that may last several hours. This meant that the short half life radio-nuclides collected at the beginning had decayed before they could be registered. Although a theoretical correction was developed to minimise the associated errors, it still led to significant uncertainties in the results provided.

An alternative approach, devised by the UK's National Radiological Protection Board (NRPB) made use of 'actively etched track detectors'. These were formed from a polycarbonate film that was visibly damaged by the passage of α-particles. Thus radiation dose could be determined from the observed damage. Unfortunately, the evaluation could only be done at a specialised laboratory, with it taking up to six months before the results were returned to the user. Also, the accuracy of the approach was seemingly low.

Despite these problems, and in the absence of any alternative, by 1993 actively etched track detectors were being used by British Coal to monitor the Working Levels of radon and thoron daughters underground in coal mines, as required by the 1985 regulations. The methodology developed involved collecting a twenty minute sample of airborne dust on a filter and placing it in close proximity to the sensitive film. For radon daughter concentration determinations the system was left for three hours. For thoron daughter concentrations a second film was placed near the filter at the end of this first period and left for a further ten hours (7). After exposure the films were sent to the NRPB for evaluation.

In view of the slowness with which the etched track results became available and the fact that they did not cover whole shift lengths British Coal's Technical services and Research Executive (TSRE) was tasked with developing a radon and thoron daughter monitoring procedure that better suited the requirements of the British coal mining industry. As a first stage, this involved the adaptation of an existing radiation monitor manufactured by the Canadian company of Thomson and Nielsen. This apparatus was made more robust, its sensitivity improved, modified counting methods incorporated and it was certified intrinsically safe for use in coal mines. The result was called the 'Industrial Working Level Meter' (IWLM)(7).

The operation of the IWLM involved passing a 'grab' sample of 75 litres of mine air through a filter. This collected any suspended dust along with any attached radon and thoron daughters. The decay of these elements was monitored using an internal silicon detector. Determination of the Working Level involved collecting the necessary sample volume over a ten minute period, waiting for two minutes thirty-eight seconds and then counting for ten minutes. At this point it was estimated that the contribution from the thoron daughters was negligibly small, making the result approximately equivalent to the radon daughter activities only. The thoron daughter levels could be obtained by waiting a further nine hours before making a count. By this time any contributions from radon were believed to be negligibly small. It has been estimated that the accuracy of the results provided by the IWLM are better than ±20% (5)(7).

Experience with the IWLM in coal mines showed that it performed within the expected specification. Also, the indication of radon daughter concentration was provided within twenty-three minutes (5). However, it was still not capable of fulfilling the statutory requirement for a shift long measurement of radiation exposure. For this, TSRE continued the development of the MRE Type 113A gravimetric dust sampler based system. Unlike its predecessor the newer approach included an integral radioactive decay counting system. This took the form of a multiplicity of thermoluminescent detectors (TLD), mounted in close proximity to the dust collecting filter (8). Although these had to be evaluated in surface laboratories, the results were returned very much faster than with the etched track detectors.

Preliminary evaluation of the TLD system in mines indicated that its detection threshold was equivalent of 4.3 mWL over a seven hour shift. This was well below that at which the 1985 Ionising Regulations became applicable. Consequently it was concluded (7) that the system would be suitable for monitoring radiation levels underground in compliance with the regulations. However, in 1992, the publication date of the latest available report on the system, development work had not been completed (5). It has not been possible to discover what happened to the project following the closure of TSRE in 1994.

10.6 Conclusions

The current understanding is that airborne radio-nuclides do not represent a major danger to coal miners. However, the existence of two collieries with 'supervised' areas suggests that it would be appropriate to keep the situation under review. For this the coal industry needs the necessary instrumentation. Since it was found necessary for British Coal to initiate its own research on the subject, this may involve a continuation of the studies being undertaken prior to 1992.

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Chapter 11 Heat and humidity

The presence of modest amounts of heat and humidity underground can be beneficial to the welfare of miners. For example, heating of the return air can augment the ventilating currents flowing through the workings. Also, the detection of increasing levels of moisture has been used to provide an early warning of developing spontaneous combustion. However, at locations where the environment is very hot and humid, miners may feel uncomfortable. This has been shown to lead to a fall in their working efficiency and an increased susceptibility to accidents.

This chapter considers the general impact the 'thermal environment' has on humans and the steps taken to control it underground. Included are descriptions of the methodologies used to assess human comfort. A review of the terms used is given in Appendix IV.

11.1 The physiology of heat

Under normal circumstances a human's core temperature will be between about 36 and 40°C. Excursions outside this range give rise to increasing sensations of discomfort through the sensation of feeling too cold or too hot. In extreme circumstances death will occur.

When work is performed the body derives the necessary energy from the oxidation of consumed food, an exothermic reaction. To prevent the core getting too hot, the excess heat generated must be lost to the surroundings. This is done at the skin surface where the transfer processes involved include radiation, conduction and evaporation.

In coal mines, the amount of heat a human loses by radiation is generally low, due in part to the relatively high temperature of the surrounding strata, as described in Section 11.3. Further, modern collieries contain much high powered electrical machinery. Even under normal operating conditions this can get very hot leading to the potential for humans working close by to gain heat by radiation. In cold environments this may make them feel more comfortable, but when they already feel warm the level of discomfort may increase.

A body's ability to lose heat by conduction is affected by temperature relative to the surrounding air. Making the latter colder will increase the rate of heat transfer by conduction and lead to a greater sensation of coolness.

Heat is lost when sweat secreted onto the skin surface evaporates. The loss rate falls as the vapour pressure of water in the atmosphere and relative humidity rise.

The conduction and evaporative heat transfer rates are both affected by the wind speed past the body. In low speeds, a boundary layer of hot, saturated air will be formed adjacent to the skin surface. This is a poor conductor of heat and moisture. However, in increasing wind speeds its thickness decreases allowing heat and moisture transfer rates to increase.

Should the body's heat loss mechanisms prove unable to keep the core temperature below its 40°C limit the brain increases the blood flow to the skin surface thereby transporting more heat away as it does so. It also reduces the activity level until the heat produced balances that being lost. The result is that working men begin to feel tired and their productivity falls.

Evidence also exists to show that increasing a body's degree of thermal discomfort can lead to an increased susceptibility to accidents. Early data to this effect was obtained during the First World War from a study of munitions workers. Later, in 1940, Bedford showed (1) that in rising temperatures the accident rate amongst coal miners increased. The changes were, however, strongly related to worker age. At temperatures below 21.1°C all men showed a roughly similar accident rate, whereas at over 26.7°C those aged 40 to 49 were at considerably greater risk. This phenomenon was attributed to the latter performing physically harder tasks.

11.2 Indices of comfort

Since the sensation of comfort experienced by a worker in a given thermal environment affects his working efficiency and liability to accidents, it is important that the conditions underground be maintained such as to maximise the former and minimise the latter. This can be done by measuring a number of environmental parameters and using them to produce an ‘index of comfort’ related to human sensations.

One of the oldest of these is the dry bulb temperature. Since at least the eighteenth century this has been measured using a liquid in glass thermometer. Although the approach is simply to apply, according to Bedford (2) it is only valid between 10 and 24.4°C and where the air movement and relative humidity are both ‘low’. From the discussions in this monograph it will be apparent that such limiting conditions are unlikely to occur very often in coal mines. This means that the dry bulb temperature alone can not provide a valid index of comfort underground.

The potential for a body to lose heat by evaporation can be assessed from measurements of the atmospheric moisture content. Such can be obtained using the dry bulb temperature and simultaneous measurements of either the wet bulb temperature or relative humidity. As will be seen from Section 11.6.2 a combined wet and dry bulb hygrometer has been available since at least 1817. Unfortunately, as noted in Section 11.1, the heat lost by evaporation is dependent upon the speed of any air currents passing over the body. This means that atmospheric moisture is only likely to be a valid indicator of human comfort in still air or low wind speed conditions. Despite the fact that these are unlikely to occur in coal mines, wet and dry bulb temperature measurements have been widely used to asses underground thermal environments. This is probably due to the ready availability of the necessary measuring apparatus and its simplicity of use.

One of the earliest indices of comfort that attempted to combine the cooling effects of heat, moisture and air flow is due to Herberden in 1825 (3). He called it ‘sensible cold’. It was determined from observations of the rate at which a pre-heated thermometer cooled in the environment under investigation. Although details of this approach were published in the Royal Society’s transactions, it seems to have been subsequently ignored, or as claimed by Hill and his colleagues (4) lost, only to reappear at the turn of this century under a different name. This new manifestation of sensible heat was called the ‘kata index’. It was developed by Hill for an investigation into possible links between the relative susceptibility of indoor and outdoor workers to epidemics and their sensations of thermal comfort.

The kata index of an environment was obtained using a ‘kata’ thermometer. As described in Section 11.6.3, both ‘dry’ and ‘wet’ versions were available. As with sensible cold, it was determined by observing the rate at which a heated thermometer cooled down. At wet indices below 20 the environment felt warm and there was an increasing sensation of discomfort due to heat, between 20 and 30 the conditions felt comfortable, whilst above 30 the sensation was of increasing coldness (2)(5).

Although the dry kata thermometer tended to be used for measuring low wind speeds underground, from about 1919 onwards the wet version became a very popular means of assessing the cooling power of thermal environments in coal mines. By the late 1930’s, however, it was becoming very apparent that the results provided were not correlating well with the sensations actually experienced by workers. In one example (2), a wet kata index of 8.5 was found to be very much more comfortable when the dry bulb temperature was below 34°C than when it was above 37.9°C, all other factors being equal. Eventually it was realised that such inconsistencies appeared because of the large difference in the sizes of the kata thermometer bulb and a human body. The result was that the cooling power of a given environment was generally overestimated, but by an amount that varied unpredictably with the conditions being assessed.

By the late 1940’s the popularity of the kata thermometer was on the wane in British coal mines. Instead, a comfort index called ‘effective temperature’ was being favoured. Not only was this very much simpler to apply but, as will be seen from Section 11.6.3, it was derived from measurements made using instruments that were familiar to underground workers. These were the conventional wet and dry bulb hygrometer and the anemometer. This index of comfort is still in use in British coal mines.

The concept of effective temperature was developed between 1923 and 25 by Houghton and Yaglou. They were working under the auspices of the American Society of Heating and Ventilation Engineers and the US Bureau of Mines. As with the kata index, it is a single figure representation of the physical sensation expected to be experienced by a human in a given thermal environment. However, rather than measure this directly, the result is obtained from an empirically derived nomogram using readings of dry and wet bulb temperatures and the wind speed. Originally two scales were produced and called ‘basic’ and ‘normal’. The former was appropriate to subjects naked to the waist and the latter to those wearing indoor clothing. Although both have been applied in coal mines, evidence suggests (6) that the former is now the more widely used. The measurement methodologies are described in Section 11.6.3.

Validation of the use of Basic Effective Temperature (BET) in coal mines was carried out by the Institute of Occupational Medicine in 1981 (6). This showed that over the range 18.4 to 33.6°C BET the indication correlated well with the measured physiological response of subjects. As to the significance of a particular value, it is generally accepted that 28°C BET is the maximum at which climatic conditions in coal mines can be considered 'comfortable' (7).

11.3 Heat and humidity in coal mines

The deeper a mine is, the hotter the surrounding strata becomes. The rate of temperature rise with depth, or 'geothermal gradient', varies with location, but in Britain is around 30 m/°C. Thus along with increased concentrations of firedamp the expansion of the coal industry that occurred during the eighteenth, nineteenth and early twentieth centuries also led to hotter mines. For example, it has been estimated that between 1911 and 1984 the average strata temperature rose by about 6.3°C.

Whilst some heat is transferred from the strata to miners by radiation, the main transport mechanism is conduction from the ventilating current. This is heated up as it passes through the workings.

An early reference to excessive heat in coal mines is due to Moxon (8) in 1866. He notes that the conditions at the Oaks Colliery were so bad that one miner had to keep moving away from the face. Since rock temperatures are unlikely to vary widely over the short distances he could have travelled, it is presumed that he simply moved to a location where the wind speed was higher and hence its cooling effect greater.

By the turn of this century a potential decline in the working efficiency of miners in hot conditions was considered so serious as to warrant the attention of two Royal Commissions. Initially the belief developed was that limiting working conditions occurred when the dry bulb temperature of the strata exceeded that of the human body. Using the accepted value for the geothermal gradient this led to 4000 ft (1219m) being given as the theoretical maximum working depth for mines. What influence this actually had on colliery development and operation is not clear, but it may have led to the concept that only dry bulb temperatures needed to be measured in the assessment of the workability of underground environments.

Later, it was realised that atmospheric moisture was also an important factor in determining the working efficiencies underground. In this respect it was noted (9) that hard work was 'practically impossible' if the wet bulb temperature exceeded 80°F (26.7°C), irrespective of the dry bulb temperature. Some of the water that led to uncomfortably humid conditions came from the strata. However, as identified by Cadman and Whalley in 1909 (10), another significant source was that used to hold dust on the ground and prevent it from contributing to the propagation of explosions, as described in Chapter 5.

Eventually, concerns over a lack of information as to the effects the exploitation of deep, and consequentially hot, coal seam was having on miner working efficiencies led the Institution of Mining Engineers to form a committee to consider subject in detail. Set up in 1918, within ten years some sixteen reports had been published covering a wide range of related topics. Whilst it is not the intention to review all of the results in detail, a summary of the more salient ones will be presented.

The first report (11) of 1919-20 contained a review of the physiological effects of high environmental temperatures. It noted the importance of controlling the wet bulb temperature and maintaining a current of air over the workers. Nothing was reportedly found to suggest that working in hot mines was injurious to health or shortened lives. Further, only one case of heat stroke or disablement had been recorded. As to the future avoidance of problems, the Committee concluded that at the working depths and operating practices then being contemplated the available ventilation technology was adequate to ensure sufficient supplies of cool air could be provided underground.

As to the actual conditions found in coal mines of the day, this was considered by Rees (12) in 1920-1. For this work he made use of a 'whirling hygrometer' designed by a Mr Storrow. This is described in Section 11.6.2. During the studies it was shown that the moisture content of air rose very sharply as the air moved over freshly cut coal on the face. Here the mineral was at its hottest and soaked with dust suppression water applied during cutting.

The sixth and ninth reports revisited the effects of heat on the working capacity of miners. For this study environmental assessments were carried out using the wet kata thermometer. One of the findings was that miners could become acclimatised to hot conditions. Further, such men could work continuously in a wet kata cooling power as low as four (13). From Section 11.2, which notes that conditions were considered uncomfortable where the index was below 20, such an environment is likely to have been extremely hot and humid.

Even after ten years of deliberation the Committee felt unable to make a statement defining acceptable limiting conditions for men working in hot and humid conditions underground. Despite this, the reports did promote an interest in the state of the thermal environment, assisted by the fact that adverse conditions meant low productivity.

Some time after the publication of the sixteenth report of the above committee, the report of the 1938 Royal Commission on Safety in Coal Mines (14) noted that there were only a few coal mines where the conditions were uncomfortably hot and humid. However, from comments made by the Medical Inspector of Mines it appears as though at these few conditions were bad. For example, he said he was aware of cases where men were close to collapse at the end of shifts due to heat.

In the years that followed the publication of the 1938 Royal Commission report interest in heat and humidity in coal mines declined. Although the precise reason for this is not clear, it is possible that it was due to a slowing down in the rate of increase in coal mine depths and the replacement of water by stone dust for explosion protection.

When MRE was set up in 1953, coal mine heat and humidity once again became the subject of scrutiny. Here the aim was to predict the climatic conditions that would occur when hot seams were developed. What change in circumstances led to this new interest is not clear, but by the late 1970's the work had achieved great importance. This was because of a rapid rise in the power of the machinery installed underground and the widespread use of water at the coal face for dust suppression purposes. Rather than simply being spread along roadways, it was sprayed in fine droplets at the cutting point. This increased the surface area available for evaporation and hence it liability to increase the wet bulb temperature. The instruments used for these studies are described in Section 11.6.

Unfortunately it has not been possible to locate any data that indicates what affect the above changes in working practices had on the expected comfort levels in underground workings. However, a survey of 739 faces and 710 headings carried out during the 1970's revealed underground Basic Effective Temperatures of up to 31.9^{o}C. More generally the figures were below this, with only 3.7% of former and 2.7% of the latter being above 27^{o}C BET (15). It is worth noting that it was during this period that the suggestion was made that 28^{o}C BET be used as the limiting temperature for moderate work. From the data given it is clear that although there were some collieries likely to be experiencing problems with heat and humidity, the vast majority were, from a thermal point of view, comfortable to work in.

The results to an MRDE study of the relative importance of the different sources of heat and moisture underground were presented by Whittaker in 1979 (16). This was carried out in the working districts of six coal mines. Information collected included continuous recordings of air temperature, humidity and flow rate, machine power, heat emitted by the coal on conveyor belts and the heat absorbed by the dust suppression water. Commercial thermohygrographs were used to provide the temperature and humidity measurements and electronic anemometers of the type described by Unwin (17) the ventilation flow rates.

It was found that nearly half the total heat input to a district came from the strata. Of the remainder, conveyor belts were the largest single contributor, possibly adding up to 40% of the total. Much of this would have been conducted from the hot cut coal lying on the belt with its large surface area exposed to the cool intake air current. This material was also saturated with dust suppression water. As such it would also have represented a major source of atmospheric moisture for the air being fed to the workers on the face.

Since the 1950's the installed power of underground machinery has risen by greater than an order of magnitude. According to Swift and Nash (18) whilst some of a motor's power performs useful work about

70% emerges as heat at the machine casing. Here surface temperatures up to 60°C have been recorded (19). In addition to conducting heat to the air current, the radiation can have a serious warming effect on men working close by.

In apparent recognition of the potential problems associated with the operation of high powered machines underground, MRDE and its successor organisations continued working on the amelioration of hot conditions until up to the time they ceased to exist in 1994. During the course of this program, inadequacies became apparent in the existing thermal environment assessment methodologies. As a consequence, consideration was given to the development of new instrument systems that could be used to monitor temperature, humidity and Basic Effective Temperature underground. These will be reviewed in Section 11.6.

11.4 Alleviating poor conditions

Ventilating the workings with cool, dry air has been the main method by which comfortable thermal conditions have been maintained underground. However, whilst the flow rates must be high enough to remove any heat and moisture present, they must not be so great as to create unacceptably cold conditions in the intake airways, or stir up dust that has settled on the floor.

The amount of heat collected by the air current from the hot strata before it reaches the face can be minimised by ensuring that the roadways are as large and as short as possible. This minimises both the air/strata contact area and the wind speed for a given quantity flow. The latter reduces the likelihood of problems from excessive cold and dust.

Another approach to minimising the heating of an air current before it reaches the coal face involves placing any conveyors in the return airway instead of the intake, as is the more usual. However, high firedamp concentrations are more likely to occur in such locations, leading to enforced shut down of transport operations and a cessation of production, a problem that has possibly limited the application of this arrangement.

Should the above measures fail to maintain adequately comfortable conditions at underground work locations recourse may have to be made to the installation of air coolers. Ice and liquid air were reportedly being used as such in continental ore mines as long ago as 1903 (20). In Britain, at about the same time, the cooling effects of expanding compressed air and evaporating water were being noted. Later, in 1928-9, Haldane (13) remarked that whilst trials of local refrigeration had been carried out in coal mines in Britain the results were disappointing. Tests on more modern systems, reported during the late 1980's (6), showed that although the observed effects were less than expected they did reduce the effective temperature in the area being fed by the cooled air.

11.5 Regulations and recommendations

During the nineteenth century no consideration seems to have been given to the regulation of the thermal environment underground in coal mines.

In 1901 regulations were introduced for surface industries specifying the maximum allowed atmospheric moisture contents at given dry bulb temperatures. Whilst no comparable statement was included in the 1911 Coal Mines Act, it was made a requirement that hygrometers be placed at conspicuous positions in the workings. However, rather than being used as indicators of thermal comfort, the readings were probably intended to provide early warning of developing spontaneous combustion, a subject discussed in Chapter 6. For the sake of completeness the instruments used for this purpose are described below.

By the time the 1938 Royal Commission began its deliberations it was being realised that guidance was needed as to what underground thermal conditions were considered acceptable. However, there was considerable variance of opinion as to what these should be and how they should be measured. Some witnesses favoured the wet kata. However, there were clearly doubts as to the validity of the results provided and the Commission decided not to recommend the introduction of a legal standard based on this approach. The existence of the effective temperature scale was noted, but it was felt that insufficient data was available for them to pass an opinion on it (14). In conclusion, the Commission recommended that more work needed to be done on the subject of heat and humidity in mines. This was despite the fact that Institution of Mining Engineers had been busy on the subject for nearly twenty years.

Clearly not enough was deemed to have been done over the next decade and a half. In 1954 the new Mines and Quarries Act also failed to make any statement regarding the maximum allowable levels of heat, humidity and comfort. Instead it simply stated that the manager was to try and maintain ‘reasonable conditions’. However, rather than necessarily being evasive and erring on the side of danger it is possible that the form of words was chosen because the temperature and humidity monitoring instruments available were not adequate to allow for the enforcement of anything more stringent.

Despite a lack of a statutory guidance, in 1980 the NCB and the National Union of Mineworkers (NUM) published their own agreement as to what were considered to be unacceptably hot working conditions (21). This stated that extra payments were to be made if miners were exposed to a Basic Effective Temperature exceeding 28^{o}C for 1.5 hours. The methods that have been used for the associated assessments are described in Section 11.6. Interestingly, the payment threshold was the same as a limit recommended by the World Health Organisation for moderate work.

By the early 1990’s it was being believed that a limit of 30^{o}C Basic Effective Temperature was soon to be introduced for underground work places. In apparent response British Coal resurrected a project to produce the instrumentation by which the necessary measurements could be made. The results will be reviewed in Section 11.6. As of 1995, the anticipated legislation is not believed to have been introduced.

11.6 Instruments to monitor the thermal environment underground

In the assessment of thermal environments there are three significant variables, the dry bulb temperature, the atmospheric moisture content and the wind speed. Measurements of each can be noted separately or their combined cooling effect used in a single figure index of comfort.

The measurement of wind speed in coal mines has been reviewed by Unwin (17), and will not be considered further here.

11.6.1 Temperature

In coal mines conventional liquid in glass thermometers have most frequently been used to measure temperature. Such devices have been available since at least the beginning of eighteenth century.

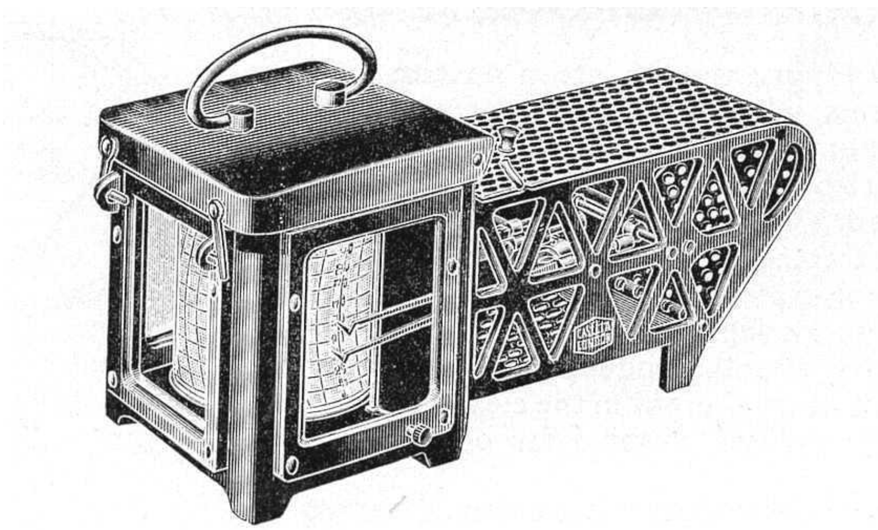

Figure 11.1 Thermohygrograph (copyright Casella CEL Ltd.)

For the climatic studies carried out by MRDE during the 1970’s, continuous records of temperature and humidity were required. These could not be obtained with conventional thermometers and so commercial thermohygrographs of the type shown in Figure 11.1 were used. Their temperature sensor was a bimetallic strip, This was mechanically linked to a pen that moved over a graduated paper chart fixed to a clockwork driven drum, producing a permanent record of temperature as it did so. The humidity recording component is described in the next section. One of the problems experienced with this apparatus was its fragility. Faced with this and other difficulties MRDE undertook the development of a potentially more robust electronic system. This is described in the next section.

11.6.2 Wet bulb temperature and humidity

Rather than determine the moisture content (or relative humidity) of the air directly, one of the most popular approaches has been to derive it from the indications provided by a 'wet and dry' hygrometer. These have been available since at least 1817.

One of the simplest forms, called Mason's hygrometer, is shown in Figure 11.2. It consists of two thermometers mounted on a wooden frame. One of these, that on the left, is a conventional thermometer and shows the 'dry bulb' temperature. The other has its bulb encased in a muslin sheath, kept wet using the water filled reservoir shown between the two thermometers. On exposure to the environment the liquid evaporates from the sleeve extracting the latent heat of vaporisation from the thermometer bulb. This causes the indicated temperature to fall. Eventually a state of equilibrium is reached whereby the heat conducted down the stem of the thermometer equals that lost during evaporation. The indication shown is called the 'wet bulb' temperature.

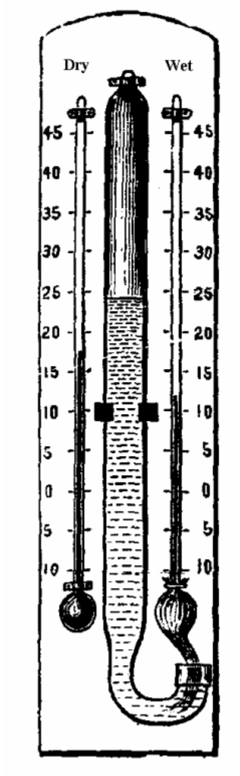

Figure 11.2 Mason's wet and dry bulb hygrometer

Until the late 1920's 'unventilated' hygrometers such as Mason's were widely used underground in coal mines. Here they found application as the statutory instrument required to be installed under the 1911 Coal Mines Act. They were also used in many of the early investigations into the thermal environment. Readings were taken by hanging the instrument in a roadway. However, the results obtained were recognised as being 'notoriously unreliable' (22). This was because the hygrometer was often used in locations where there was very little air movement. Under these conditions a saturated boundary layer formed close to the surface of the wet sleeve reducing the rate of moisture evaporation. The wet bulb temperature indication provided under these conditions was higher than expected and resulted in an over estimate of atmospheric moisture content.

Experiments eventually showed that the uncertainties with unventilated wet bulb hygrometers could be reduced if the wind speed past the instrument was above about 3 m/s. A method of achieving this was to wave the instrument around until the readings on the two thermometers were constant. This procedure was made easier by a development due to a J. T. Storrow of the Doncaster Coal Owners' Association Laboratories. In about 1914 he devised the 'whirling hygrometer' shown in Figure 11.3. Although broadly similar to its 'unventilated' predecessor, it differed by having a handle fitted to the top of the wooden mounting frame. This allowed the thermometers to be whirled about in the environment under investigation, thereby ensuring that the air speed over the wet muslin sleeve was greater than that necessary to give a stable wet bulb indication.

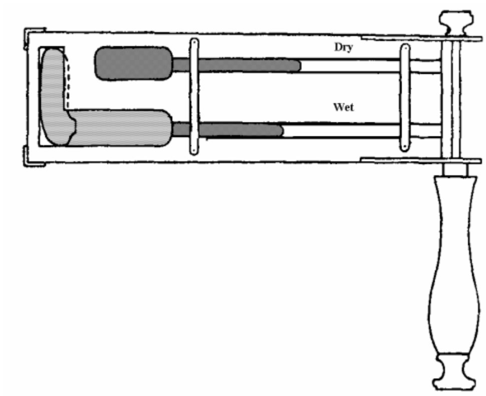

Figure 11.3 Storrow's whirling hygrometer

With extreme care the accuracy of the relative humidity indication provided by a whirling hygrometer can be ±2% RH. However, this figure is strongly influenced by the presence of contaminants such as dust and oil on the muslin sleeve. These can dramatically alter its hygroscopic properties and hence the reading provided in a given relative humidity.

Since its invention, the whirling hygrometer has become extremely popular. At the end of the twentieth century it was still being supplied to colliery ventilation engineers.

Over the years other types of 'ventilated' wet and dry bulb hygrometers have found occasional use in coal mines, particularly for special investigations. Their failure to become as popular as the Storrow is seen as being due to their relatively high purchase prices, lack of robustness and complexity of use.

Once wet and dry bulb temperatures have been measured a calculation must be carried out to produce the corresponding reading of atmospheric moisture content or relative humidity. An early attempt at producing a governing expression was made by Apjohn in about 1835. From this work, in 1853, Regnault produced the relationship:

$$P = P_w - A*B*(T_d - T_w)$$

where 'P' is the vapour pressure at dry bulb temperature 'T_d', 'P_w' the saturated vapour pressure at the wet bulb temperature 'T_w' and 'B' the barometric pressure. The quantity 'A' is called the 'psychrometry constant' and has a standard value for each type of hygrometer (23). The relative humidity (RH) is given by:

$$RH = P/P_w * 100\%$$

Although alternative formulae have been produced, Regnault's seems to be one most widely used. To simplify its evaluation the values of relative humidity appropriate to a whole range of wet and dry bulb temperatures and barometric pressures have been produced in tabular form. Simple 'slide rule' type calculators are also available.

Since at least the seventeenth century, it had been recognised that the linear dimensions of organic substances such as hair, leather and wood expand and contract in conditions of changing humidity. This process is largely reversible, enabling such materials to form the basis of automatic and continuously operating hygrometers. A typical example, the 'hair hygrometer', incorporates a hair held under tension. One end is clamped and the other mechanically linked to a pointing device. This may be a needle or a pen capable of drawing a line on a rotating chart. In either case, changes in atmospheric moisture content cause the hair to expand and contract and the indicator to move as a consequence.

Their use of a fine sensor makes hair hygrometers extremely fragile and thus unsuitable for general use in coal mines. Also, when held under permanent tension the hair can be irreversibly distorted, particularly in dry conditions. This leads to a drift in instrument calibration with time. As a consequence, the accuracy of the results provided by hair hygrometers is low.

Despite its shortcomings, the ability of the hair to be formed into a recording hygrometer ensured its use underground in coal mines. One early application (22) occurred during the 1920's as part of the program of work sponsored by the Institution of Mining Engineers. The thermohygrograph used by MRDE during their environmental studies carried out during the 1970's (see Figure 11.1) also incorporated 'hair' hygrographs. It was found that problems with poor levels of accuracy could be minimised by carrying out periodic checks using a standard hygrometer. These were used to produce correction factors that were later applied to the recorded results.

Concerns over the robustness and general reliability of the mechanical thermohygrographs led MRDE to begin development work on and electronic temperature and humidity monitor for coal mines. Designated the 'BTH1 Temperature and Humidity Monitor' it was intended to be broadly similar in its appearance and general operating principles to the other environmental monitors produced around the mid-1970's, such as the BM1 methane monitor shown in Figure 5.16.

The temperature sensor to be used in the BTH1 was a small thermistor mounted in a protective metal cage. For the humidity sensor it was decided to investigate possibility of using one of the solid state devices that were becoming commercially available by this time. These were typically formed from a hygroscopic material with an electrical parameter, often dielectric constant, that changed in a predictable way with atmospheric moisture content. Unfortunately all those evaluated showed unacceptably high temperature coefficients of response and levels of drift in the high humidities typically found underground in coal mines (24). On this basis they were considered unsuitable for inclusion in the BTH1.

Despite a failure to find a reliable humidity sensor, by 1979 ten prototype BTH1 systems had been produced and certified intrinsically safe. However, none are believed to have been used underground on a routine basis, possibly as a result of the problems being experienced with the humidity sensor.

In view of the continued requirement for an underground electronic temperature and humidity monitor MRDE and its successor organisations maintained a watching brief for new developments in humidity sensing technology. Eventually a device was identified that appeared adequate for British Coal's needs. Development work on a monitor that incorporated it was undertaken by Sieger Limited at their own cost. Designated the TH1, the unit was similar in its overall design to the later British Coal environmental instruments, a general example of which is shown in Figure 6.5. It is to be noted however that the BCO1 shown had an internal sensor whilst the TH1 had a remotely mounted detector head that incorporated a platinum resistance thermometer and the humidity sensor.

Underground experience with the TH1 showed its performance to be satisfactory in humidities up to about 75% RH in dry bulb temperatures of over 30^{o}C. In hotter, damper conditions drift in the humidity reading caused serious problems, sometimes leading to indications of over 100% RH (25). On this basis it is clear that the problem of sensing atmospheric moisture in coal mines had not been solved.

By 1992 the continued review of humidity sensing technology had revealed a range of new devices that had not previously been evaluated. These were made from materials such as ceramics and polymers. Further, they appeared to be more tolerant of water than those considered hitherto (24). On this basis, examples of six different makes were purchased and evaluated in the laboratory at relative humidities from 10 to 95% RH and temperatures of 20 and 45^{o}C. In such conditions the earlier forms of sensor had exhibited unacceptable levels of drift in their response characteristics. With the closure of TSRE the work was undertaken by International Mining Consultants Limited.

After two months it was concluded that the stability of performance of four of the six sensors was such as to justify further consideration in respect of their possible inclusion in a temperature and humidity monitor for coal mines. Such a study would include their response to moisture in atmospheres containing the pollutant gases routinely found underground as well as the design of a housing to prevent contamination of the hygroscopic material by dust. With the privatisation of the British coal industry it is uncertain as to whether this work was undertaken.

11.6.3 Indices of comfort

In Section 11.2 it was noted how attempts at producing an index of comfort that combined the effects of temperature, humidity and wind speed in a single figure led to the development of the kata thermometer. This is shown in Figure 11.4. Although broadly similar to conventional instruments, its bulb was larger and the stem had only two engraved temperature marks. Depending on the intended application, these could be at: 100^{o}F (37.8^{o}C) and 95^{o}F (35^{o}C), 130^{o}F (54.4^{o}C) and 125^{o}F (51.7^{o}C), or 150^{o}F (65.6^{o}C) and 145^{o}F (62.8^{o}C). As with the wet bulb temperature, the bulb of the wet kata was enclosed in a fabric net sheath wetted with distilled water.

A reading of the kata index involved first heating up the thermometer bulb in hot water. In the case of the dry version, this was then thoroughly dried. On exposure to the environment under investigation the time taken for the indicated temperature to fall between the two engraved marks noted. The result was then divided into a 'kata factor' to give the appropriate index.

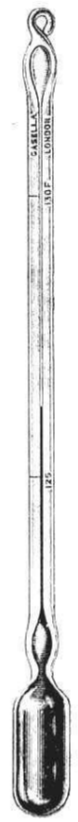

Figure 11.4 The kata thermometer (copyright Casella CEL Ltd.)

At its concept, the aim of the kata's developers had been to produce an instrument that did not need to be individually calibrated. This had been one of the criticisms they had levelled at sensible cold. In practice it proved impossible to blow glass bulbs with exactly the same dimensions and so the kata factor had to be determined experimentally for each unit made. With such a seemingly significant sensitivity to small variations in the geometry it is surprising that the system's developers were not suspicious that the indicated rates of cooling may not be appropriate to those of a very much larger human body, as was later shown to be the case.

Despite the uncertainties in relating the kata index to the sensation of comfort experienced by humans a relatively recent catalogue from Casella London Limited (26) still shows the kata thermometer. It is also stated that they are used for assessing comfort in mines.

From the data available it is probable that this last statement does not include those of coal. Here the preferred method of assessing human comfort in thermal environments is to use the Basic Effective Temperature scale. This is derived from measurements of dry and wet bulb temperatures and wind speed. These are combined on a nomogram shown in Figure 11.5 to give the appropriate result.

Details of how Basic Effective Temperature is to be determined in the mining context are provided by (21). The air velocities are derived from the statutory measurements noted in the colliery ventilation record book. The wet and dry bulb temperatures are measured when any installed machinery is working normally. It is believed that the whirling hygrometer is used.

Many of the humidity transducers included in the International Mining Consultants study (24) also contained a dry bulb temperature sensor. Coupled with their low power requirements, it was felt that this made them potentially suitable for inclusion in a small hand held monitor for underground use that could also be used to show the Basic Effective Temperature. Given an input of the local wind speed, obtained using a separate anemometer, the necessary calculation would be carried out automatically by an internal microprocessor. To prove the feasibility of this approach, a computer program was produced that accepted inputs of wind speed, dry bulb temperature, and atmospheric moisture content and automatically evaluated the nomogram given in Figure 11.5. This had been digitised and stored in memory. Evaluation of the methodology proved its effectiveness by revealing that for a given set of input values the program calculated Basic Effective Temperature to within ±0.4°C (±0.8°F) over a range from 0 to 35°C (32 to 95°F).

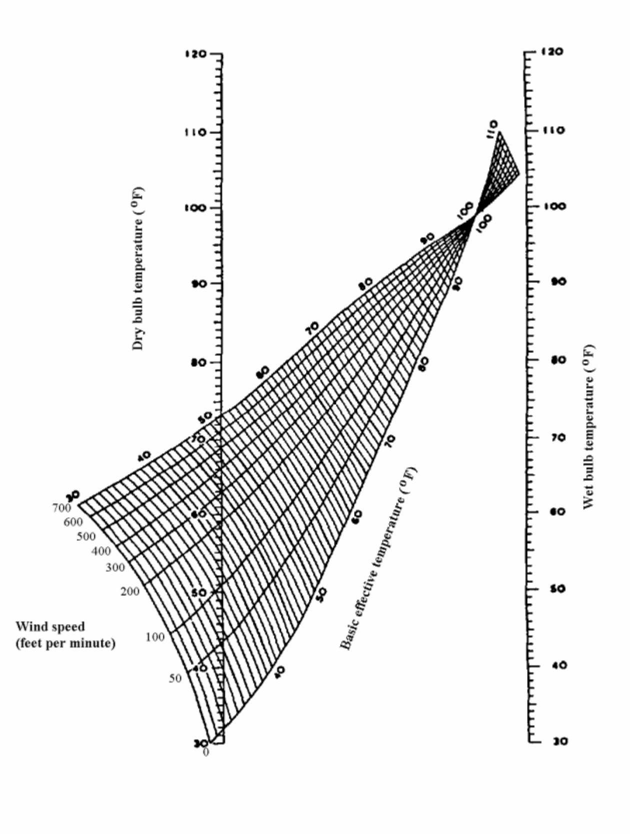

Figure 11.5 A Basic Effective Temperature nomogram

As with the humidity sensor evaluation program, further development of a direct reading Basic Effective Temperature instrument appeared to cease with the privatisation of British Coal. It is not known whether any further work was done despite the advantages that could accrue from producing a system that provides immediate environmental assessments at the press of a button.

11.7 Conclusions

The reason why legislation has not been introduced to limit the thermal conditions found in coal mines appears to be due to the absence of a simple means of indicating humidity and consequently enforcing the law.

Recent studies have identified some modern electronic humidity sensors that appear to be suitable for use underground. Further a simple method of using their outputs to provide a rapid indication of Basic Effective Temperature has been devised. If the coal industry is serious about the state of the underground thermal environment then the necessary work to develop these ideas further should be undertaken. Some financial return on the investment may accrue from commercial exploitation of the signal processing technology.

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Chapter 12 Lighting in coal mines

Other than possibly near a shaft no natural light penetrates a coal mine. Consequently artificial sources must be provided to enable the men to see. This chapter reviews the development of coal mining lighting systems, how their form has been influenced by a desire to avoid explosions of firedamp, and the effects they have had on health of underground workers. A review of the terms used is given in Appendix V.

12.1 Mine lighting and explosions

When the Neolithic flint mines of Grimes Graves in Norfolk were being worked between about 2500 and 2200 BC, small oil lamps formed in hollowed out lumps of chalk were used to provide illumination. Although similar devices may have been found in early coal mines, by the eighteenth century candles were a common source of light. However, the occurrence of explosions attributed to their naked flames igniting firedamp was leading to a search for a safer alternative.

One of the more successful of these was the 'flint mill' shown in Figure 12.1. Its invention is frequently attributed to Spedding in 1763 but was apparently based on an older idea (1). In this device a flint was held against a rapidly rotating ferrous metal disc driven by a crank. Light was radiated by a stream of glowing sparks. At the time it was believed that these were incapable of igniting firedamp. As a result, and despite the fact that the light produced would have been very feint, the flint mill became widely used in coal mines. Eventually it was found that the sparks could ignite firedamp, although possibly not so readily as a candle flame. Despite this, the apparatus continued to be used because there was no alternative if 'gassy' mines were not to be abandoned with the consequential financial losses to the owner.

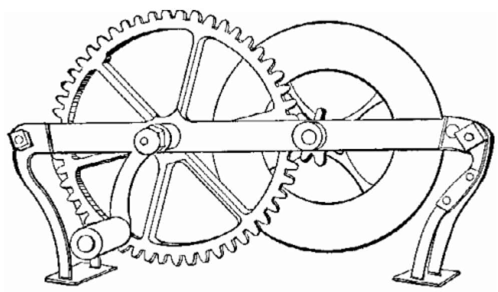
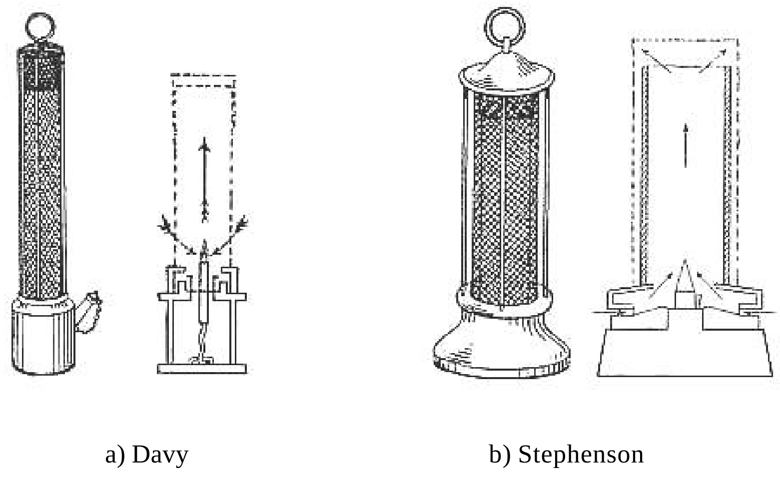


Figure 12.1 The flint mill

The eventual demise of the flint mill occurred with the introduction in 1816 of the 'flame safety lamps' of Stephenson and Davy. Shown in Figure 12.2 (a and b), both consisted of an oil lamp whose flame was completely enclosed in a gauze cylinder. This allowed it to burn whilst at the same time preventing the ignition of any explosive gases in the surrounding environment. Both lamps soon became extremely popular, with many thousands in use by the end of the nineteenth century. The reason for this is clear. For the first time it was believed that apparatus was available that allowed men to work in mines previously found too dangerous from the presence of firedamp. Unfortunately, accident data collected during the 1830's suggested that this trust was sorely misplaced. Rather than a hoped for reduction in fatalities due to explosions, following the introduction of flame safety lamps the number increased. Leaving aside the interpretation that mines did in fact become safer because the fatality rate (total deaths divided by number employed) fell, the recorded death toll caused so much concern that between 1818 and 1830 demands were made for the



a) Davy b) Stephenson

Figure 12.2 Early flame safety lamps

prohibition of flame safety lamps from coal mines. Although vandalism, poor maintenance and damage have been cited as the causes of some of the reported ignitions, others were attributed to the performance characteristics of the devices themselves.

In an attempt to improve the safety of flame safety lamps the 1887 Coal Mines Act included a clause that allowed the government to decide which types were to be allowed underground. Since the death rate from explosions did fall after the introduction of the Davy and Stephenson lamps, this approach was preferable to the imposition of a total ban on their use. Also, by this time flame safety lamps had become the primary means by which underground workers could show the presence of firedamp and hence gain some advanced warning of a developing danger.

Despite the introduction of the 1887 regulations, flame safety lamps continued to be the cause of a significant number of explosions of firedamp; between 1896 and 1907 it was over 40% of the total. Eventually, however, safer versions were produced and a diagram showing their general design is given as in Figure 5.1. These were typically fitted with steel bonnets that both protected the now multiplicity of gauzes from damage and reduced the danger from high speed currents of explosive gas. Tamper proof locks were used to prevent vandalism. Also, the lamps were designed such that the flame was automatically extinguished in gas concentrations above about 5% methane. This was below that at which the protective gauzes became hot enough to cause an explosion in the general body.

With these developments, concerns over the safety of flame safety lamps seem to have diminished. To some extent this will have been influenced by a reduction in their general use in mines. This occurred as a result of the introduction underground of portable electric lanterns. Flame safety lamps are still used underground in coal mines. Now their primary role is as detectors of pollutant gases rather than providers of light.

12.2 The health and safety implications of underground lighting levels

Lamps are used to provide light by which humans can view their surroundings. The greater their output, the better they are for seeing with.

Tests with a ‘common pit candle’ showed (2) that it had a luminous intensity of up to 2.1 candela (see Appendix V). Measurements on a Davy lamp revealed (3) a corresponding figure of only about 0.13 candela. By the beginning of this century it was being recognised that in addition to being an inconvenience, such relatively low light outputs were also having an adverse effect on the general health of coal miners. This was through the occurrence of a disease called nystagmus.

As identified by a Dr Gillet of Sheffield in about 1854, the eyes of a victim of nystagmus oscillate uncontrollably. This makes it difficult, if not impossible, for him to see properly. Although the precise cause of the condition was the subject of debate, by 1912 it was being generally accepted that it was a direct result of men having to work in poor lighting. Under these conditions, objects in the field of view scatter insufficient light into the eye for the brain to register their existence. Consequently the muscle control signals produced vary in such a way as to cause the eyes to move continuously, searching in the process for a bright object on which they can fix. Eventually the movements become involuntary, occurring even in good light.

In coal mine environments nystagmus develops only slowly. Initially eye movements are only likely to be temporary and brought on, for example, by physical exertion or rapid changes in light level. They can typically be controlled by looking downwards. Transferring a thus affected miner to employment in a brighter environment such can put the disease into remission (4). Failure to take any remedial steps allows the nystagmus to develop to such an extent that nothing can be done to prevent the eyes oscillating. At this stage the victim may become incapable of work.

One of the earliest reviews of nystagmus in coal mines was carried out by the Royal Commission of 1906 to 1909 (5). From the evidence presented it is clear that sufferers were not always moved away from underground work. As an indication of the consequences of such a philosophy, in a sample of forty officials about half were found to have the disease. This situation had potentially severe safety implications since it was these men who were charged with detecting flammable gases underground. From Chapter 5 it will be seen that this involved having to see a very feint cap on the flame of a flame safety lamp. This would have been very difficult to do if the eyes were in constant motion. More poignantly, (4) notes how some miners with severe nystagmus had to be met by their wives at pit top and guided home.

In 1912 it was estimated (4) that up to 20% of British miners had some form of nystagmus. Acceptance that this was occurring as a direct consequence of the low light outputs from flame safety lamps being used resulted in the development of brighter versions. This was encouraged by new mining lamp approval requirements included in the 1911 Coal Mines Act. As will be seen from Section 12.3.1 these included an assessment of light output. An example of a brighter flame safety lamp is the Marsaut shown in Figure 5.1. This was widely used in British coal mines from about 1925 onwards. It had an output of 0.45 candela. An even better lamp was the Protector CT33A of about 1935. Shown in Figure 12.3, it had a peak luminous intensity of 2.5 candela.

Figure 12.3 Protector CT33A lamp (copyright Charles Griffin and Co. Ltd)

Despite the development of improved flame safety lamps it will be seen that even the best was not much better than a pit candle. On this basis they were seemingly considered inadequate for use as the primary source of light at underground work places. As an alternative, attention was directed at the application of electricity and incandescent filament bulbs. Davy had done this in 1816 (6) but it was not until about 1859 that his outline ideas attained practical reality. A typically electric mining lantern is shown in Figure 12.4. It consisted of a bulb mounted behind a protective glass on top of an accumulator. They were carried to the work place in much the same way as their flame counterparts. The expected light outputs were about four times that of the Marsaut flame lamp (7).

Figure 12.4 Electric miners lantern (copyright Charles Griffin and Co. Ltd)

Sometime before 1924 electric ‘cap lamps’ were developed for use in coal mines. An example is shown in Figure 12.5. With these, an electric bulb was contained in a small carrier that could be clipped to a miner’s hat. It was connected by a strong cable to a battery power supply carried on a waist belt. The main advantage of this approach was that it produced very high levels of light output, about ninety times that from a Marsaut flame lamp (7). This was contained within a relatively narrow beam that could be directed at the working point, as opposed to being spread over virtually a complete sphere as with the older lanterns.

Figure 12.5 A cap lamp (copyright Charles Griffin and Co. Ltd)

Initially the adoption of electric lamps by the coal mining industry was slow. For example, by 1914 they formed only 11% of the total in Britain. This stemmed from the fact that unlike their flame counterparts they were incapable of showing the presence of flammable gas and no practical means could be devised of making them do so. Eventually, however, strong evidence became available to show that their greater brightness would bring nystagmus under control. As an example, Llewellyn (8) noted that in US mines where cap lamps were universally accepted the disease was virtually unknown. Responding to data of this kind, regulations were introduced that facilitated the increased use of such non-gas detecting lamps underground. This was achieved by ensuring that a certain proportion of men were equipped with flame safety lamps, or another approved firedamp detector.

In 1949 it was made a requirement that all personnel underground in coal mines be supplied with a cap lamp. Since then the incidence of nystagmus has fallen such that between 1979 and 1982, the latest period for which data has been located, there were no recorded new cases in British Coal mines (9).

Occasionally thoughts have been directed at the safety implications of installing of fixed lighting systems in coal mines to provide more general illumination. These primarily stem from the fact that in bright conditions a worker is more aware of his surroundings and what is going on in them. This can make him less liable to stumbling and falling accidents. Also, good lighting speeds up the response of the eye and improves peripheral vision. This makes workers more aware of moving machinery and associated dangers developing on the edge of their field of sight.

Early experiments in the use of fixed lighting were undertaken at High Elsecar and the Oaks Collieries during the late 1850's and early 1860's (10)(11). Both used gas lamps. Electric lighting was first introduced underground in the late 1880's (12). Initially, only pit bottom areas and engine houses were lit, but gradually systems were extended to cover main trunk roads and eventually the coal face.

It was during studies carried out during the 1920's and 30's into effectiveness of the fixed systems then being installed that underground light levels were first measured. The methodologies used are described in Section 12.4.2. Results showed that the simple act of whitening roadway surfaces could increase the effective level of any illumination by up to four times (8). In a modern mine a very large proportion of the tunnel walls are thus treated. Also, machinery and other equipment, including the environmental instruments, are painted white. This makes them easier to see in what may still be dim lighting conditions.

12.3 Coal mine lighting regulations

12.3.1 Portable lamps

The earliest regulations relating to the provision lighting in coal mines were contained in the Act of 1887. These were made in response to the explosion hazard associated with some of the older types of flame safety lamp. They stated that those devices used in underground locations where naked lights were forbidden were to be so constructed that they could be safely carried against an air current, even were it to be flammable (13).

By the time the 1911 Coal Mines Act was being formulated there were developing concerns over the dangers associated with the low light outputs from flame safety lamps. Consequently a formal type testing scheme was introduced that all such devices had pass before being approved for underground use. This included an assessment of their light output. Further, because electric lanterns were being used in increasing numbers they were also to be approved.

Details of the tests to be carried out on safety lamps, be they flame or electric, were contained in a memorandum published by the Home Office in February 1913 (14). For flame lamps the minimum luminous intensity was to be 0.3 candle power (see appendix V) over a ten hour burning period. For electric lamps the figure was 1.0 candle power in the horizontal plane over a nine hour period. The former requirement was less stringent than the latter because of the widespread use of flame lamps for gas detection purposes. A brief review of the apparatus that was available to carry out the necessary tests is contained in Section 12.4.1. Here it will be seen that the restriction to measurements in the horizontal plane was dictated by the design of the available equipment.

The need to provide coal miners with bright portable lanterns whilst not depriving them of the means of detecting flammable gases caused the Government some concern. This is evident from the fact that in 1919 they set up the Miners' Lamp Committee with a remit that included consideration of the problem. Its findings were subsequently used by the Mines Department in 1930 to produce a set of proposals for legislation to cover lighting in coal mines. However, for some undiscovered reason they were never issued. Instead yet another committee was set up in 1932 to study the subject further. Their findings were used to produce a set of statutory regulations (15).

Issued in 1934, the Coal Mines General Regulations (Lighting) differed from their 1913 predecessors in a number of ways. Firstly, for portable lanterns, it was stated that at the end of a nine hour burning period the mean horizontal candle power was to be not less 1.5. This was to be the case irrespective of whether the lamp was electric or flame. By making this statement it was acknowledged that high output flame lamps were available. A minimum performance figure was also provided for cap lamps. For them, at the end of a nine hour burning period the mean spherical candle power was to be greater than 0.4. The means spherical candle power figure for other types of portable lantern was higher at 0.75. It is to be noted, however, that the light from a cap lamp was concentrated in a narrow beam whereas that from the latter was distributed over a very much larger solid angle, making it the brighter. The devices available to carry out the appropriate intensity assessments are described in Section 12.4.1. From this it will be seen that their extension to include the light integrated over a sphere was enabled by the development of electronic photocells.

From the report of the 1938 Royal Commission (15) it is apparent that the 1934 regulations were not leading to as large improvements in the underground lighting conditions as had been expected. In one opinion, that of the Mineworker’s Federation, under them they were not much better at the end of a shift than they had been under the older 1913 regulations.

Comments such as these appear to have been noted by the legislators for, in 1947, details of a new set of approval tests were published. Contained in a document called Testing Memorandum No. 1, or simply ‘TM1’ (16), they specified the minimum acceptable lamp outputs after 9 hours continuous use. These were considerably higher than those of 1934. For example, with electric hand lanterns the mean spherical candle power was to be greater or equal to 1.7, compared with 0.75 of earlier. Also, the mean horizontal candle power was to be not less than 2.3 compared with the earlier 1.5.

Yet another set of lighting regulations were issued in 1956 under the 1954 Mines and Quarries Act. It is believed that these are still in force at the time of writing (1995), although possibly under review. As with those issued in 1947, lamp approval was granted on compliance with the tests and performance specifications detailed in TM1. However, rather than assuming that a lamp suffered no serious deterioration in its output with time, a statutory program of routine testing at colliery level was required. This made it a duty of the mine manager to ensure that if at least half the lamps returned at the end of a shift were tested, then at least half of these would have outputs of not less than 60% of that specified in the approval documentation. The aim was clearly to assure the widespread quality of lamp maintenance.

In 1989 the minimum performance requirements for miners’ cap lamps were detailed in a British Standard (17). These were considerably higher than those set out in TM1. For example, the mean spherical intensity was to be 1.65 candelas as compared with 1 to 1.2 of the latter (depending on the bulb used).

12.3.2 Fixed lighting installations

Unlike portable lamps there do not appear to have been any regulations introduced specifying the minimum performance of fixed underground lighting installations. Initially, this would have been due to a lack of suitable measuring equipment by which any limiting conditions could be enforced. Despite this, rules were introduced to encourage the adoption of best mining practice. One example dates from 1934 and required that the roadway surfaces at engine rooms and haulage junctions be whitened. Later, in 1947, in an apparent attempt at reducing the potential for accidents resulting from an inability to see moving machinery, it was required that fixed lighting be installed at these locations.

Recent advances in electronic instrumentation have allowed for the production of low powered, portable ambient light meters. Whilst these appear suitable for use underground, subject to them being certified intrinsically safe, for some undiscovered reason they have not been incorporated in a set of statutory minimum lighting levels for coal mines.

Despite a lack of statutory rules, in 1972 Bell (18) presented a list of suggested minimum underground illumination levels for a range of locations including junctions and main roadways. From (19) it appears as though these may have been adopted for use by the coal industry. However, doubts about this come from a later British Coal document (20). This makes no reference to underground lighting whilst at the same time giving a list of minimum illumination levels for surface locations. It has not been possible to resolve this uncertainty.

12.4 Colliery lighting measurements

12.4.1 Lamp testing

It is difficult to determine precisely when the first miners' lamp light output assessments were made but it was certainly before 1852. Then, use was made of photometers in which the output from the unknown was compared with that from a standard lamp (see Appendix V). Two main types of 'comparator' were used. Designated 'shadow' and 'grease spot' photometers, they are shown in Figures 12.6 and 12.7. With both, images of a standard candle and of the lamp under examination were projected on to a paper screen such that they could be viewed together. In the case of the grease spot photometer this was enabled by the application of the small grease spot to the screen, thereby making it translucent in its centre. With both devices the relative positions of the two lights were altered until the images appeared to be of the same intensity. At this point the candle power of the unknown could be determined from the square of the ratio of the two lamp distances from the screen.

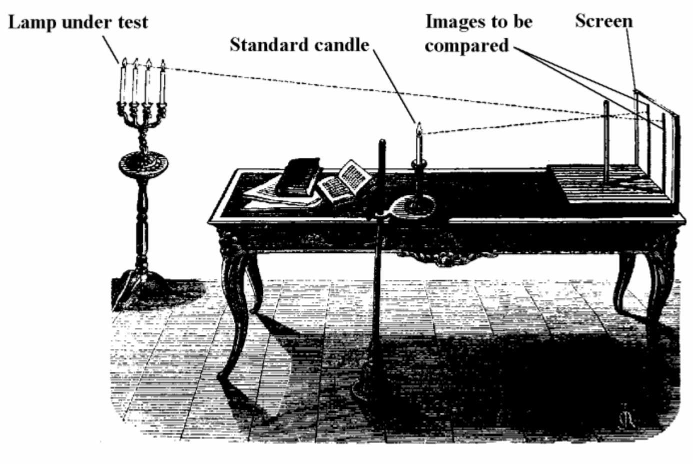


Figure 12.6 The shadow photometer

Comparator photometers similar to the above were used in the colliery lamp rooms until the 1930's. However, it is very apparent that they were not very convenient to use, nor were they particularly versatile. One problem concerned the fact that the shadows cast by the standard and unknown lamps were frequently of different colours. This made it very difficult to determine when their intensities were the same. Further, an inability to produce a standard light that radiated equally in all directions over a spherical surface meant that such photometers could only be used to compare outputs in the horizontal plane. This was a serious shortcoming since both mining flame and electric lanterns radiated significant amounts of light in other directions. It is possible that these difficulties and limitations contributed to the fact that the approved minimum lamp outputs were initially restricted to one plane only and that no statutory lamp testing was required to be done at collieries.

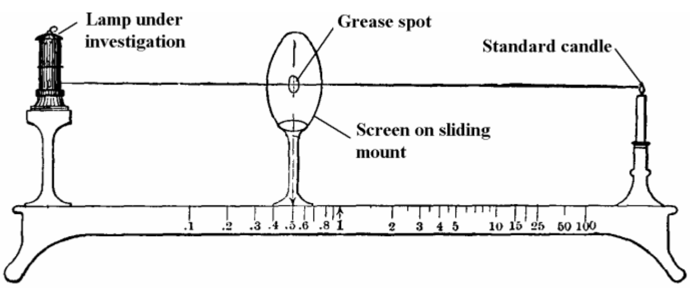


Figure 12.7 The grease spot photometer

In about 1930 it was discovered that a voltage was developed across the junction between an iron conductor and a selenium semiconductor when illuminated with light. Further, it was shown that if a galvanometer was connected to form a circuit then the current that flowed was related to the intensity of the incident radiation. Commercial photocells of this type, notably the Weston 'phototronic' cell, were available by 1933. The introduction of such devices had a major impact on colliery photometry. Almost instantaneously they were reported (21) as being incorporated in apparatus to monitor the output from flame and electric safety lamps.

An early colliery lamp photometer incorporating a phototronic cell is shown in Figure 12.8 (22). This device is believed to have been designed by a Captain Platt of the Mines Department in 1938. In it the cell was mounted on the end of the arm shown and its output terminals connected to a galvanometer. The lamp under test was placed on the table. To enable light to be measured outputs along non-horizontal directions the photocell arm could be raised and lowered. In use the apparatus was enclosed in a sealed box to minimise errors from stray light.

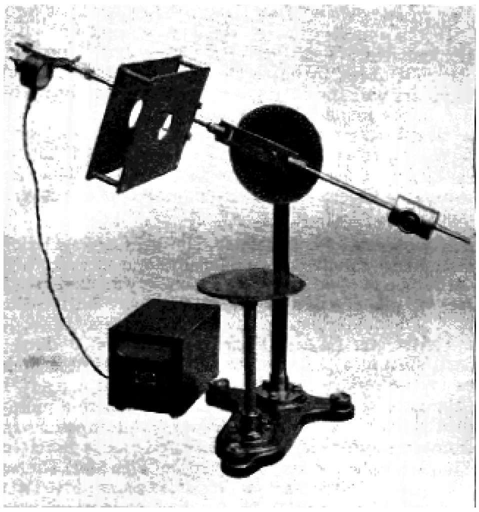


Figure 12.8 A colliery photometer incorporating a phototronic cell (copyright Charles Griffin and Co. Ltd.)

Photometers of the type shown in Figure 12.8 were simple to use, particularly when compared with their predecessors. Consequently they rendered themselves more suitable for use at collieries. Here routine lamp output examinations could be quickly and reliably carried out by relatively unskilled workers. The increased level of testing that could be carried out as a consequence will have improved the quality of lamps provided to underground workers and reduced their liability to nystagmus.

In about 1938 the lamp manufacturers of Ceag and Oldham introduced their own testing photometers. Although similar in concept to Platt's design, they appear to have been even simpler to use. Basically they consisted of a black painted box into which the lamp under test was placed. The photocell was mounted externally but enclosed in a brass tube that communicated with the interior. I could be raised and lowered at will to obtain light measurements in the non-horizontal directions.

Cap lamps were also tested using Ceag box type photometers. Later, when the requirement was for outputs to be expressed as the mean spherical candle power, 'integrating sphere' photometers were used. These operated on the principle that if a hollow spherical shell is created with a perfectly diffuse coating on its inside, the total reflected illumination at every point on the inside surface is equal to the mean spherical luminous intensity of a lamp placed within it.

Figure 12.9 An integrating sphere cap lamp photometer (copyright The Technical Press Limited)

A photograph of an integrating sphere cap lamp photometer is reproduced as Figure 12.9 (23). Such devices were available for colliery use by the late 1950's. The lamp to be tested was applied to the translucent window shown in the lower half of the sphere. Its mean spherical luminous intensity was automatically shown on the micro-ammeter above it.

In addition to the spherical types, a similarly operating cap lamp photometer was formed from a square wooden box. Both this and the spherical types were still being used at collieries for the testing of cap lamps in the mid-1990's. Clearly the simplicity of such systems will have encouraged the implementation of routine output assessment procedures at collieries. According to (24) this usually involved a monthly test of each lamp, the results to which were entered on a record sheet. If any output had fallen below the specified standard the unit was removed from service pending repair or replacement. This approach ensured that the quality of the lamps supplied to miners was maintained despite the rough handling they unavoidably got during normal usage.

12.4.2 Field photometry

Before the advent of electronic photocells any desire to monitor ambient light underground was hampered by a lack of suitable instrumentation. A group of devices that could be used were called 'brightness meters'. Their operation involved making a comparison between the perceived amount of light scattered by a standard surface when exposed to the field under investigation and when it was illuminated by a standard lamp.

A description of an early brightness meter is provided by Graham (25) in 1932. From this it is clear that the apparatus was unsuitable for routine use in coal mines. This was because of the serious effect on the reliability of the results contamination of the standard scattering surface by dirt would have had. Further, as had been the case with comparison type lamp photometers, a subjective judgement had to be made as to the relative intensity of two sources that were more than likely of different colours. This would have required a highly skilled operator.

Simpler brightness meters did subsequently become available, notably one manufactured by Salford Electrical Instruments Limited (23). Although used for occasional surveys, they were not adopted for routine use in coal mines.

One probable reason for the failure of brightness meters to become popular in coal mines was the availability from the 1930's onwards of ambient light meters incorporating photocells. An example is shown in Figure 12.10. Typically, the cell was mounted at the end of a long wire connected to an ammeter contained in a wooden carrying case. In use the apparatus would have been laid out in the location under investigation and the illumination level read off the meter. One of the problems with this approach stemmed from the fact that the cell response was non-uniform over all angles of incident light. This meant that the system output varied with the shape of the light intensity pattern being investigated. Making no allowances for this could lead to measurement errors of up to 40% (26). Eventually these were reduced by the introduction of 'cosine corrected' photocells (23).

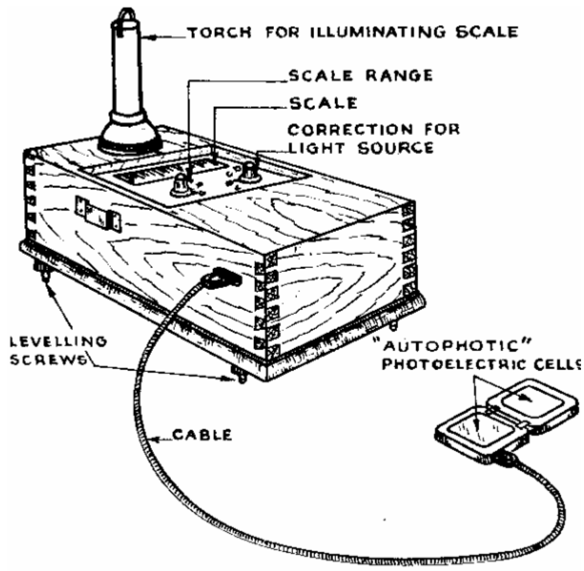


Figure 12.10 An ambient light meter (copyright Sir Isaac Pitman and Sons Ltd)

The seemingly low importance placed on ambient light measurements in coal mines can be gained from a lack of references to the subject in official industry publications. One of the more recent located (27) simply states that light meters are available for use underground. Unfortunately no details are given as to what they may be, how they were to be used, or where. It is possible that reference is being made to certified versions of the 'lux meters' advertised in electronic instrument catalogues. However, this is by no means certain since it has been noted (28), albeit as long ago as 1951, that for the low levels of light found in mines those meters intended for factories and offices are useless. The reasons why are not given.

12.5 Conclusions

From a safety and health point of view it is important that mine work places be well lit, be it by portable lanterns or fixed installations. Although regulations exist to ensure minimum standards for the former, none exist for the latter. Further little attention seems to be directed towards their provision. This may be because no problems are perceived to exist. Whist this may be the case, it seems appropriate that the situation be kept under review, possibly via studies of the incidence of accidents that could be attributed to an inability to see properly.

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Chapter 13 Noise

Sound is radiated as pressure waves from vibrating bodies. If this is unwanted or unpleasant then it is generally classed as 'noise'. Irrespective of the sensation excited, temporary or even permanent loss of hearing function can occur if the sounds impinging on a human ear are of sufficiently high intensity. Whilst it has long been recognised that such a danger exists from the loud report from explosions, it has only relatively recently been realised that a similar hazard exists from longer term exposure to quieter sounds.

This chapter considers the developing problem of noise in coal mines and the steps that have been taken to counteract its effects.

13.1 Hearing and the assessment of noise

Inside the human ear, sound pressure fluctuations are sensed by a collection of fine hairs. Each vibrates at a characteristic frequency and produces a signal for processing by the brain. Exposing the ear to noise can permanently damage these hairs. In its early stages this becomes apparent as a loss of hearing function at frequencies around 4 kHz. However, continued exposure can extend it to other frequencies. Eventually the understanding of speech may become difficult.

A human ear can normally respond to low level sounds with RMS pressures down to about 20 μPa. For loud sounds the threshold of pain is slightly over six orders of magnitude above this. The audible frequency range is typically in the region of 20 Hz to 16 kHz. Rather than being independent of frequency over this range(flat) the sensation of loudness varies, peaking at around 1 kHz. This non-uniformity of response has led to the use of two types of measurement methodology. These have been classified as 'objective' and 'subjective'.

Objective sound assessments:

> The pressures sensed by a microphone are processed by an amplifier with a flat response for display on a meter. As a consequence of the wide ranging sensitivity of the ear, the latter is usually fitted with a logarithmic ratio scale marked in units of decibels (dB). Zero dB intensity corresponds to an RMS pressure fluctuation of 20 μPa.

Subjective noise assessments:

> Allow for the non-uniform frequency response of the human ear. Originally they were obtained by referring the perceived 'loudness' of an unknown source to that of a standard. This was frequently a tuning fork. The results were expressed in 'phons', with zero representing the threshold of hearing. Since about 1956, developments in electronics have enabled electrical subjective noise meters to be developed with amplifiers whose frequency response matches that of a 'standard' ear. Noise levels measured using one particular form, called the 'A' weighed scale, are expressed in units designated 'dB(A)'. Although these are akin to the phon, there are frequency dependent differences between the two. This means that sound levels expressed in one set of units may not be directly transposable into the other.

Rather than being intensity dependent, the evidence is that the risk of noise induced hearing loss is also related to the time of exposure. A figure combining both these variables is called the 'equivalent continuous noise level', denoted on the 'A' weighted scale by 'dB(A)Leq', or 'dB(A)Leq(8h)' for an 8 hour exposure period. As will be described in Section 13.5, instruments are available that make such determinations directly.

13.2 A developing problem in coal mines

A very early reference to noise induced deafness was reportedly made as long ago as 1713 by Ramazzini. He noted that copper beaters became hard of hearing in old age (1).

In coal mining, problems with noise began to appear during the post-1918 period. They were associated with an increase in the use of machinery underground. By the 1930's worries were being expressed over the possibility that nuisance noise levels were getting so loud that audible warning sounds, such as those used to show when machinery was about to start, were being masked. This led to SMRB undertaking a program of research into the matter (2)(3).

For their studies SMRB developed a subjective type sound level meter. This is described in Section 13.5. Using this device it was found that the compressed air used to power coal cutters, conveyors and other machinery represented a major source of noise underground. However, the emissions could be significantly reduced by fitting silencing devices to the exhausts. Covering the motor casings with an asbestos blanket supported on an expanded metal base also had a beneficial effect. No specific reference seems to have been made to noise induced deafness in mines, although SMRB did note how personal ear protection had reduced noise exposures in gunnery and aircraft.

Subsequently, interest in industrial noise seems to have declined, particularly in connection with coal mining. It has not been possible to ascertain why this was, it may have stemmed from a lack of appropriate measuring apparatus for studying the problem.

During the 1950's, interest in noise began to increase again. For example, in 1953 a study of occupational deafness amongst boilermakers showed that loss of hearing seemed general amongst those who had been exposed to noise levels in the region of 130 dB for long periods. At about the same time, a study carried out in the USA indicated that most persons subjected to noise intensities above 120 dB for a few hours daily would eventually suffer permanent impairment of hearing, irrespective of the frequency composition of the sounds. Also, a large proportion of those exposed to levels between 100 and 120 dB could be expected to experience some damage (4).

In response to findings such as these, and a continued rise in the use of noisy machines underground, Cardiff University decided to undertake a study of noise in coal mines (4). For this, use was made of a commercial electrical sound level meter to be described in Section 13.5. The results showed that levels likely to cause hearing damage were commonly found underground. Further, compressed air powered machines formed one of the main sources. Electrically operated equipment was quieter.

Beginning in 1960, the Government began taking a lead in considering the potentially detrimental health affects associated with exposure to noise. To this end it set up a Parliamentary Committee to examine the subject. The findings were contained in a report (5) published in 1963. This showed that hearing damage increased with the sound pressure level and time of exposure. However, the Committee felt there was insufficient data for them to suggest a statutory enforceable noise limit that would eliminate the dangers.

Data that provided a more quantitative understanding of the noise hazard came from a research program begun in 1963. This was carried out under Professor W. Burns of the Medical Research Council and Dr D. W. Robinson of the National Physical Laboratory. The results, published in 1970, confirmed that the time weighted exposure to noise intensity was the significant variable in respect of hearing loss. Further, damage could be avoided if the maximum continuous daily exposure was less than 80 dB(A). For shorter exposures no unprotected ear should ever be exposed to sound pressures greater than 135 dB(A), again if damage was to be avoided (6).

Using these findings, in 1972 the Department of Employment issued a voluntary code of practice for reducing the exposure of persons to noise (7). Whilst the contents of this document are considered in Section 13.4, suffice it to say here that it recommended a maximum exposure of 90 dB(A)Leq(8h). It will be noted that whilst the sound intensity is above that suggested by Burns and Robinson, the exposure time is limited to 8 hours rather than being continuous.

During the above period of deliberation by the Government, the NCB seems to have paid only little attention to the subject of noise in coal mines. One study, carried out around 1964 in Yorkshire is claimed (8) to have shown that it was not a problem in coal mines.

Following the publication of the Department of Employment's 1972 voluntary code the attitudes within the coal mining industry underwent a very rapid and dramatic change. For example, within twelve months the NCB had set up an internal policy group to consider the problem of noise induced occupational deafness. Not only did they subsequently oversee the application of the appropriate parts of the Government code within collieries, but they also influenced the initiation of a range of other related activities. These included the carrying out of research into the control of noise, the training of persons to measure noise at collieries and the conduct of surface and underground surveys.

For the surface surveys, use was made of small, portable electronic sound level meters fitted with ‘A’ weighted networks. Described in Section 13.5, these were readily available commercially by 1972. For underground surveys, the NCB had a number of these instruments made intrinsically safe. By 1976 their use had revealed that a significant number of mineworkers were probably being exposed to noise levels in excess of the recommended 90 dB(A)Leq(8h). This threw doubt on the validity of the claims made in 1964.

Eventually personal noise dosimeters were produced that enabled the integrated noise exposures of individual underground workers to be determined. Using such equipment, a 1983 study revealed (9) that up to 72% of face workers, 89% of development workers and 45% of other underground workers were being subjected to noise levels at or above the recommended 90 dB(A)Leq(8h).

Since intrinsically safe sound level monitors became available and it became possible to investigate the size of the health hazard associated with environmental noise, much work has been undertaken to reduce emissions from machinery and to limit the exposure of workers. Despite this, relatively recent data shows (10) that noise induced deafness is still a problem amongst coal miners. Its extent is indicated by the fact that in 1990 British Coal’s estimated liability for compensation payments was £517m. This an extremely large sum and represents the potential savings to be derived from investment in measures to reduce noise.

13.3 The reduction of noise underground

Rather than attempt a chronological review of the development of noise abatement technology this section briefly reviews some of the practices that have been used to limit worker exposures in coal mines.

The most effective noise control methodology is to avoid generating it in the first place by using quiet machines. If these are not available, the installation must be designed to minimise any worker exposures. As an aid to this process, in about 1985 MRDE produced a computer modelling program. Using inputs of the noise source characteristics and the acoustic absorbing properties of its surroundings, workplace sound levels could be predicted. After installation, on site validation of the model results could be undertaken using the intrinsically safe sound level meters. Differences between prediction and measurement could be used to improve the model’s reliability.

Intrinsically safe sound level meters have also been used to carry out surveys of the noise emissions from existing machine installations. This has enabled excessively bad examples to be identified and corrective action taken, possibly involving replacement by a quieter alternative. As an example of the gains to be made by this approach, hydraulic rock drills are about 20 dB(A) quieter than their compressed air equivalents (11).

A program of replacement of all noisy underground machinery would be too expensive to implement, even assuming quieter alternatives were always available. Consequently silencing methods have been developed. During the 1930’s, SMRB used sound absorbing ‘blankets’ made from asbestos. More recently a recognition of the toxicity of this material has led to the development of safer alternatives. Typically formed from non-asbestos mineral fibres sandwiched between sheets of solid steel and perforated metal, they can be erected as a barrier between a source of noise and a machine operator. Using this approach reductions in sound level of up to 10 dB(A) have been achieved (12).

If the noise emissions from a machine can not be reduced below the maximum accepted level, it is now a requirement that all the affected areas be marked, as will be described in the next section. All persons entering these locations must wear personal protection in the form of ear muffs.

13.4 Regulations

In 1938 it was suggested (13) that the level of noise in underground coal mines be limited by statute. However, the absence of suitable instrumentation by which compliance could have been monitored seems to have prevented their introduction at the time. This situation continued to exist until the 1960’s, or possibly the early 1970’s. By this time developments in semiconductor electronics had led to the production of low powered sound level meters that were small enough to be carried around work places and simple enough to be used by semi-skilled operators. Eventually, intrinsically safe units were also produced.

In 1972 the Department of Employment published its code of practice for reducing the exposure of persons to noise (7). Although voluntary, it contained a number of important provisions that were later included in legislation. One of these was a statement to the effect that worker exposures to noise should be less than the equivalent of 90 dB(A)Leq(8h). Also, the boundaries of those areas where this figure would be exceeded were to be identified and classed ‘noise protection zones’. Entry was to be restricted to persons wearing appropriate ear protection.

Also included in the code were details of the methods and apparatus to be used for noise assessments. Ideally the sound level meters were to comply with BS4197:1967, Precision Sound Level Meters. This ensured that a minimum quality of data could be expected to be obtained. For sounds that varied widely in their intensity it was recognised that it may be necessary to take a tape recording on site for later analysis in the laboratory.

The NCB broadly accepted the principles laid out in the Department of Employment code and soon began work on its implementation in coal mines. Later, in the absence of any statutory noise regulations what had by then become the British Coal Corporation issued its own mandatory instructions on the matter. Published in 1981, they required that sound level surveys be carried out at all collieries and the results added to a data base. This was to be used in the planning of new machinery installations. At any place where potential worker exposures were found to be above 105 dB(A)Leq(8h) the levels were to be reduced immediately.

Statutory regulations aimed at limiting worker exposures to noise were introduced in January 1990. Briefly, where a daily personal exposure exceeded 85 dB(A)Leq(8h) but was less than 90 dB(A)Leq(8h), ear protection was to be provided on request. If the higher of these two figures was either equalled or exceeded, the provision of such equipment was mandatory. In line with the earlier code of practice, noise protection zones were to be created at all locations where employees were likely to be subjected to noise exposures of 90 dB(A)Leq(8h) or above.

13.5 Measurement of noise

At the work place, instrumentation has played a major part in the management of noise. Portable sound level meters have been used to identify source locations and the extent of the area likely to be affected by dangerously high levels. Also, personal dosimeters have been used to monitor the integrated exposures of individuals in noise studies. This section describes both types of system, with particular reference to those used underground in coal mines.

One early attempt at measuring sound underground is due to SMRB in about 1936 (2)(3). This involved the use of a subjective type instrument operating on principles outlined by a Dr Davis of the National Physical Laboratory in 1930. Briefly, the apparatus consisted of an open wooden box in which was mounted a 640 Hz tuning fork. This formed the reference tone. An ear piece was mounted on the box close to the tuning fork.

In use, one ear was placed in the ear piece and the other sealed. Then, simultaneously, the tuning fork was excited and a stopwatch started. Note was taken of the time that elapsed before the apparent loudness of the generated tone matched that of the environmental noises being assessed. Using this, and the fact that it took ninety seconds for the output from the tuning fork to decay from its initial loudness of 96 phons to zero, the loudness of the unknown source could be determined. The apparent need for the operator to make very rapid judgements as to the equality of two potentially widely differing sounds must have made this instrument very difficult to use.

Despite problems with it, the SMRB apparatus was used underground around 1938-9 to determine the effectiveness of noise reduction measures then being applied (3). This was done under the belief that, although the results provided may not have been accurate, they were reproducible.

From (3) it seems as though at least one electrical noise meter was in existence by the late 1930’s. Precisely what form it took is unclear, but it almost certainly contained thermionic valves. Their fragile nature and the potential for the necessary high voltage supplies to ignite firedamp would have made such equipment unsuitable for routine and widespread use underground in coal mines.

Even in 1956 when Cardiff University undertook their underground noise studies they used a sound level meter containing thermionic valves. This was a standard industrial type manufactured by the Dawe Instrument Company of London. It consisted of a microphone coupled to an amplifier whose output was fed into an ac meter calibrated dB. The frequency response of the system could be selected as being either flat or matched to that of the human ear. With the latter the results obtained were expressed in phons (4). For noise source frequency analysis, the output from the sound level meter could be fed into a separate audio frequency analyser. This showed the intensity of the sound within a restricted frequency band. This could be selected as being from 25 to 80 Hz up to 2.5 to 8 kHz. Although the complete system was battery powered it was not certified intrinsically safe. Consequently restrictions were placed on its use underground.

By 1975 the Dawe Instrument Company was making an intrinsically safe sound level meter (11). Designated the 'Dawe 1419' virtually no details of this device have been located, other than it was used by NCB during 1975. It is to be surmised that unlike its predecessor the unit was transistorised and thus operated at low voltages.

Modern sound level measuring instruments used within the coal mining industry were been supplied by CEL and Brüel and Kjaer. A schematic diagram showing an instrument produced by the former is given as Figure 13.1. Designated the Type 283Ex, it was certified intrinsically safe for use underground in coal mines. Sound sensed by a microphone at the end of the tapered nose was processed by transistorised circuits and the result displayed on the meter. Switches on the unit allowed various functions and display modes to be selected. These included the indicating range, the frequency response (flat or 'A' weighted) and the response time (fast or slow). The latter applied a time constant to the meter thereby facilitating the assessment of rapidly fluctuating signals. Operation of a switch also enabled the equivalent Leq(8h) value to be shown. Power was provided by internal batteries.

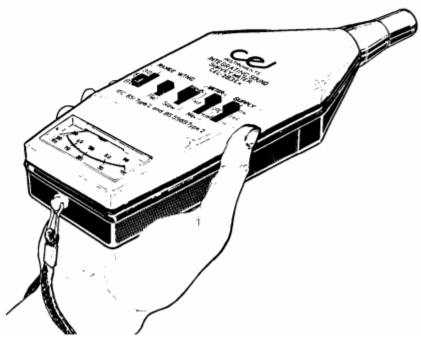

Figure 13.1 A portable sound level meter

The CEL instrument was extremely portable and thus suitable for routine use in the difficult conditions underground in coal mines. According to Broughton (14) at some time every British Coal colliery mine was equipped with a CEL Type 283 instrument. Here it was used to measuring the maximum sound levels at 1 m from any source of noise and at any working positions. The sound level meters were also used to define the 90 dB(A)Leq(8h) noise protection zone boundaries.

Alongside the above, in coal mines since the early 1970's use has been made of personal dosimeters for special investigations into individual worker noise exposures. Although such systems provided more precise data than would otherwise have been obtained using hand held instruments, unit costs of around £500 made it impractical to equip every worker with one on a routine basis.

Unfortunately no information has been located concerning the early personal sound dosimeters. However, data relating to a modern example shows them to be formed from a small microphone connected to a control unit via a flexible cable. Incorporating a microprocessor to control its operation, the latter can calculate and then store in a solid state memory the noise dose and the time averaged sound levels. The collected data can be downloaded into a computer for analysis.

Concerning the future of underground noise measurements in coal mines, contact with CEL during 1995 revealed that the company were no longer able to provide an instrument comparable to the Type 283Ex that has also been certified as intrinsically safe. This means that unless specials are made, any future noise measurement requirements of the British coal industry will have to be met using devices in stock. Later publicity from the same company reveals, however, that from March 1998 they were going to produce an intrinsically safe noise dosimeter. No details of this instrument have been obtained or of its likely use in coal mines.

13.6 Conclusions

Modern coal mines contain large amounts of machinery. Consequently it is concluded that noise underground is at best under control and at worst, from the high level of compensation payments identified, still a problem. Thus there is no case for relaxing the current levels of control. Further, they should be kept under review and possibly made more stringent should the rate of noise induced hearing loss amongst working and retried coal miners fail to decline.

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Chapter 14 General conclusions

The current accident and disease rates amongst coal miners appear to be relatively low. However, the evidence presented suggests that rather than having been eliminated altogether the causing hazards are merely under control. Consequently, it is concluded that there is no case for relaxing the stringent regulations that govern the safety and health of underground workers and the level of environmental monitoring applied. Any such action, it is believed, would result in the accident and industrial disease rates rising once more.

For all the underground environmental hazards discussed in this monograph, initial identification came from the recognition of common factors linking fatalities, or the occurrence of accidents or disease amongst groups of workers, be they colliers or from other industries. Consequently, it is important that continued attention be given to the collection and analysis of accident and health statistics across all the population, including working miners and those who have retired from the industry. Diseases amongst those outside the coal industry can point to the presence of as yet unknown hazards being faced by those still employed underground within it.

In the research reported above, a number of underground environmental variables have been identified where the current assessment and detection methodologies are inadequate, or non-existent. These include: the detection of carbon dioxide, the detection of fires, the assessment of the particulate and oxides of nitrogen emissions from diesel engines, the measurement of underground radon, thoron and their daughter concentrations, the assessment of comfort in hot environments, the measurement of ambient light. Since each has an influence on the safety and health of miners, it is concluded that the necessary development work should continue.

Whilst new mining methods are still being introduced, new environmental hazards are likely to appear. Thus it is concluded that whilst Britain has coal mining industry it should maintain a research function capable of considering the safety and health implications of any new technology. It must also be capable of monitoring the known hazards to ensure that they remain under control.

APPENDIX I The general properties of air and gases found underground

This Appendix reviews the general properties of the underground gases referenced in this monograph. Included are published (1) long-term exposure limits (8 hour time weighted average reference period) and short-term exposure limits (10 minute reference period). These are for use in general industry and not necessarily coal mines. Consequently, some differences may exist between them and the requirements of the Mines and Quarries Act.

AI.1 The standard atmosphere (2)

Nitrogen - 78.09%;

Oxygen - 20.95%;

Argon - 0.93%;

Carbon dioxide - 0.03%;

Helium, hydrogen, neon, krypton and xenon - trace.

AI.2 Blackdamp, chokedamp and afterdamp

Blackdamp and chokedamp: an atmosphere that is deficient in oxygen, or contains a higher than normal concentration of carbon dioxide.

Afterdamp: the gases left following an explosion. For most of the nineteenth century it was believed to have similar components to blackdamp. By the late 1880's it had been shown that carbon monoxide could also be present.

AI.3 Carbon dioxide

One of the constituents of blackdamp. Was discovered by Joseph Black in 1755. Its density is about 1.5 times that of air.

Exposure limits: Long term: 0.5%; Short term: 1.5%.

The effects of carbon dioxide on humans were first investigated during the nineteenth century. In 1808 it was found that air could no longer support life if it contained more than 9% of the gas. By about 1878 it was being appreciated that its action on humans was not simply one of displacing oxygen, but it also stimulated the respiratory centre of the brain. In 1893, Haldane showed (3) that at 3% carbon dioxide the rate of breathing was double that in fresh air.

Modern data on the effects of the gas shows (4):

0.5% - lung ventilation increases;

3% - breathing becomes difficult and a slight headache occurs;

10% - headache and visual disturbance, breathing becomes difficult after one minute, followed by unconsciousness.

AI.4 Carbon monoxide

Also known as whitedamp in coal mining. Is a constituent of afterdamp and is both toxic and explosive, although the former represents the major hazard underground.

Was identified by Lassane in 1776. It has a neutral density when compared with that of air.

Carbon monoxide is colourless, tasteless and non-irritating. This means that humans are provide with no sensory warning of its presence until actual disablement occurs and escape becomes difficult, or impossible.

Exposure limits: Long term: 50 ppm; Short term: 300 ppm.

Early studies into the effects of carbon monoxide on animals were carried out around 1858 (3)(5). It was found that under normal conditions oxygen in the lungs combines loosely with the haemoglobin of the blood to form what is now called oxyhaemoglobin. This substance acts as the transport medium by which oxygen is distributed to the bodily tissues. When carbon monoxide is present in the lungs this also enters the blood, forming what is now called carboxyhaemoglobin. This is much more stable than oxyhaemoglobin and its presence reduces the oxygen carrying capacity of the blood.

In 1895 Haldane (6) showed that the symptoms of carbon monoxide poisoning began to occur when the blood was about 30% saturated with carbon monoxide, and that acute symptoms appeared at 50%. Since the oxygen carrying capacity of the blood was being depleted these were similar to asphyxiation. Thus it is not surprising that the effects of inhaling in afterdamp were confused with those of blackdamp. However, post-mortem examinations showed a carboxyhaemoglobin compound that was bright red in colour, similar to oxyhaemoglobin, whereas oxygen depleted blood would have appeared blue.

The rate of response of a human to a given concentration of carbon monoxide increases with the respiration and heart rates. Thus an active individual is likely to succumb to the effects before one at rest.

Modern data on the effects of the gas show (4)(7):

35 ppm - no symptoms experienced during an eight hour exposure;

400 ppm - headache and discomfort with possible collapse after two hours if at rest, or forty five minutes if working;

1200 ppm - palpitation after thirty minutes at rest, or ten at work;

2000 ppm - exposures to this level are considered dangerous to health.

AI.5 Firedamp

Describes a flammable gas commonly found in coal mines. Is composed of naturally occurring hydrocarbon gases mixed with air. If inhaled, it is harmless.

Firedamp has a density about 0.56 times that of air, meaning that it can float on the top of a ventilating current.

In about 1550, Dr Kaye, or Keys, noted that certain coal pits in the North of England contained an explosive gas subsequently referred to as ‘sulphurous vapour’, or ‘sulphur’(8). By 1733 it was also commonly being called ‘hydrogen’.

In 1816 Davy concluded (9) that the flammable component of firedamp was methane. It is now recognised that other hydrocarbons (and hydrogen) may also be present. Typically these include ethane and propane. Their total concentration can, however, be expected to be less than 5% of the methane content. For the purposes of this monograph it is assumed that firedamp is a mixture of methane and air.

In the presence of heat and oxygen methane will explode. This occurs at concentrations between about 5 and 15% by volume.

AI.6 Oxygen

Is vital for the survival of humans. Underground processes such as breathing humans and burning lamps cause concentrations below that on the surface to occur.

By the late 1870’s it had been discovered that the transfer of oxygen to the blood stream was dependent on the gas partial pressure rather than volume concentration in the lungs.

The physiological response of humans under varying oxygen partial pressures shows (10):

17 kPa partial pressure (17% by volume at 1 atmosphere pressure) - impairment of judgement begins to be detected;

16 to 12 kPa partial pressure (16 to 12% by volume at 1 atmosphere pressure) - breathing and pulse rate increase, muscular co-ordination is impaired;

14 to 10 kPa partial pressure (14 to 10% by volume at 1 atmosphere pressure) - although the patient is still conscious, emotional upsets are experienced, abnormal fatigue on exertion, disturbed respiration;

10 to 6 kPa partial pressure (10 to 6% by volume at 1 atmosphere pressure) - nausea, vomiting, inability to move freely, loss of consciousness may occur;

less than 6 kPa partial pressure (6% by volume at 1 atmosphere pressure) - convulsive movements and gasping respiration occur, followed by a cessation of breathing and death.

AI.7 Oxides of nitrogen and nitrous fumes

In this monograph these terms are used to describe mixtures of the gases nitric oxide and nitrogen dioxide. Whilst they can exist on their own, they are frequently found together.

Nitric oxide is colourless, non-flammable gas. In the presence of air it combines with oxygen to produce nitrogen dioxide.

Nitrogen dioxide is a red-brown gas. It is highly reactive and will adsorb very readily on to virtually any material, except possibly glass, stainless steel and PTFE.

Exposure limits:	Nitric oxide:	Long term: 25 ppm	Short term: 35 ppm
	Nitrogen dioxide:	Long term: 3 ppm	Short term: 5 ppm

Nitric oxide is considerably less toxic to animals that nitrogen dioxide. Some workers believe that its physiological effects can be ignored (7). The problem with this is that in the presence of air, nitric oxide readily oxidises to nitrogen dioxide and this is very toxic.

Although the toxicity of nitrogen dioxide was well known by the end of the first decade of this century, the nature of its action has only recently been discovered. It is now believed (7) that inhaling the gas results in pulmonary oedema. This condition may take several hours to develop, with the victim being virtually unaware that he has been exposed to a potentially fatal dose of the gas.

A summary of the effects on humans of exposure to nitrogen dioxide shows (4)(7)(12):

10 to 20 ppm - mild irritation of the nose;

50 ppm - moderate irritation of the eyes and nose, pulmonary oedema after one hour's exposure;

75 ppm - humans may be able to tolerate this level for 30 minutes

80 to 90 ppm - workers exposed to these concentrations for 30 minutes showed signs of pulmonary oedema;

100 ppm - humans experience marked irritation of the larynx and cough, severe pulmonary oedema, probably fatal.

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APPENDIX II Surface laboratory gas analysis techniques

For some of the gaseous hazards described in this monograph, on occasions there have been no suitable measurement methodologies for direct underground use. Under these circumstances samples of mine air have been collected for analysis in surface laboratories. This appendix reviews the methodologies used. They are not necessarily specific to coal mining.

AII.1 Gas sample collection

One of first mine air collecting vessels was the rubber bladder. In 1733, Sir James Lowther used them to send gas from the Whitehaven collieries to the Royal Society in London (1). They are still used occasionally, typically when a large number of samples are needed to be collected over a short period. Advantages of bladders include the fact that they are easy to carry when empty and can be quickly filled on site. Against this, they are semi-permeable to gases such as hydrogen, methane and carbon dioxide.

By the beginning of the nineteenth century gas containers made from glass or metal were being used. Samples were usually taken by connecting them to a separate water filled vessel. This was allowed to drain slowly drawing in mine air as it did so. By this method, sample times of several hours could be obtained.

A faster method of filling the smaller vessels was to use a pump formed from a rubber aspirator bulb.

To collect 'snap' samples of gases produced during transient events such as shot firing, small evacuated brass cylinders or glass vials have been used (2)(3).

By 1973 the main application of glass vessels was in diesel emission assessments. This continued use of such fragile vessels was due in part to the highly reactive nature of the gases present, namely oxides of nitrogen.

The NCB developed its own mine air sampling pump (4). It is shown being used underground by Ram Patel in Figure AII.1. The apparatus was used to force the air being sampled into small, detachable cylinders. One is shown projecting from the side of the pump in the photograph. They were made from aluminium alloy and connected via a bayonet fitting. Typically it required about fifteen pumps per sampling operation. This meant that the collection time could be unacceptable, particularly in the presence of toxic gases.

Figure AII.1 NCB Sampling pump (copyright National Coal Board)

AII.2 Arrangements for the analysis of mine air samples

Prior to nationalisation there was no comprehensive scientific service within the coal mining industry to carry out routine mine air analyses. Some of the larger collieries had small laboratories, but others relied upon, for example, local universities.

On its formation, the NCB set up its own scientific service, operating a network of laboratories. These were equipped with apparatus to analyse the mine air samples collected at collieries.

Also, in response to the report on an explosion at Burngrange oil shale mine in 1947 (5), the NCB set up a number of mobile laboratories. These enabled mine air analyses to be undertaken at collieries during emergencies.

AII.3 General analysis methods

The earliest laboratory based mine air analysis methodologies relied on the measurement of the change in volume of a sample at fixed pressure (or change in pressure at fixed volume) as the gas under investigation was absorbed from the whole by a suitable reagent. Analysers of this type date from about 1772. A list of chemical absorbers used is given in Table AII.1.

From about 1750 flammable gas concentrations were determined by burning the combustible component in a closed chamber. During the process, carbon dioxide was produced. This was absorbed using lime water, enabling the volume of combustible gases in the original sample to be determined.

Gas	Reagent	Approximate date of first use
carbon dioxide	lime water	1783 (6)
carbon dioxide	barium hydroxide	pre 1924
carbon monoxide	iodine pentoxide	1807 (6)
hydrogen sulphide	aqueous silver nitrate	pre 1807(7)
moisture	sulphuric acid	1890 (8)
nitric oxide	iron sulphate	pre 1807 (7)
oxygen	nitric oxide	1783 (7)
oxygen	pyrogallol	1852 (6)
oxygen	chromous chloride	1885 (6)

Table AII.1 Reagents used in absorption gas analysers

Two absorption type gas analysers that were widely used by the mining industry for many years are the Haldane apparatus of about 1898 (8), an example of which is shown in Figure AII.2, and the Bone-Wheeler apparatus of 1908 (9). Both operated on similar principles to those described above.

Absorption type gas analyses were complex and very slow at returning results. Despite this, they continued to be used in mine air laboratories at least until the early 1960's. However, in about 1951 the NCB laboratories had begun using non-dispersive infra-red gas analysers for methane, carbon dioxide and carbon monoxide determinations. These systems were very simple to operate, providing accurate results in seconds. A detailed discussion of them is given in (10).

For 'special' investigations gas chromatography has been used. Such systems became widely available in about 1955 (10) and were soon being extensively used within the NCB. As an example, by 1965 there were sixteen units in the Scottish Division, four being in mobile laboratories (11).

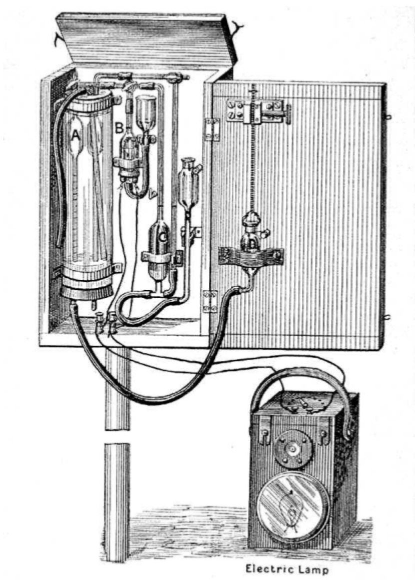

Figure AII.2 Haldane's apparatus

AII.4 Non-absorption methods for specific gases

AII.4.1 Flammable gases

In about 1894 the 'Shaw' tester was devised for flammable gas concentration determinations. With this apparatus the unknown gas concentration was determined from the volume of 100% methane that had to be added to make it explosive (12)(13).

AII.4.2 Carbon dioxide

Precision gas metering pumps contained in the Shaw gas tester were reportedly used in a procedure for determining the concentration of carbon dioxide in mine air (13). In this, a metered volume of the sample was bubbled through lime water. This produced solid calcium carbonate in suspension and gave the liquid a milky appearance. By comparing the appearance with standard solutions the unknown concentration could be determined.

AII.4.3 Carbon monoxide

One of the earliest methods of detecting carbon monoxide in mine air samples involved the use of blood. As noted in Appendix I, there is a strong affinity between the two, with the resulting carboxyhaemoglobin being a brighter red colour than oxyhaemoglobin.

In 1889 it was described (2) how a spectroscope was used to determine the integrated carbon monoxide exposure of mice from the colour of their blood. The animals had been suspended in a roadway for the measurement period and then killed on return to the surface.

Later, in about 1895, Haldane devised a carbon monoxide determination method that involved making a visual comparison between the colour of fresh blood plus sample air and that of a range of standard solutions made from blood and carmine (8). It was believed that the test could be used to show between 0.01 to 0.2% carbon monoxide in air (14).

Alternatives to the above were eventually produced that involved a chemical reaction between carbon monoxide and iodine pentoxide. This resulted in the liberation of iodine and carbon dioxide. Discovered in about 1870, it was used for analytical purposes from 1888 onwards (14). In its subsequent practical implementation, gas concentrations have been determined using measurements of the volume of carbon dioxide produced or the mass of iodine liberated. A variation of the approach found suitable for use in mine fire detection was developed by Graham in 1919 (15).

Within the coal mining industry the iodine pentoxide method was eventually replaced by infra-red gas analysis described earlier.

AII.4.4 Oxides of nitrogen

The detection of nitric oxide and nitrogen dioxide can be done singly or as a mixture.

Although nitric oxide is odourless, nitrogen dioxide has a pungent sweet smell at just below 5 ppm (16). In view of the highly toxic nature of the latter, detection by smell is clearly not to be recommended. Despite this danger, workers involved in the testing of diesel vehicles underground have noted that smell can provide an indication that an engine requires servicing.

It is not clear what methods were used in the early studies of the oxides of nitrogen emissions from shot firing (see Chapter 7), but it may well have been an absorption technique such as described in Section AII.3.

More recently, alternative techniques such as the ‘phenoldisulphonic acid’ method have been developed. This was first used underground in British coal mines in about 1921. It is, however, generally only applicable for concentrations above 20 ppm. Below this, methodologies such as the ‘Greiss-Saltzman’ are used. Techniques from which this was developed became available in 1943, or possibly earlier.

Within British Coal, since the early 1970’s undiluted diesel exhaust fumes have been sampled using evacuated glass vessels. These containing an oxidising agent that converts the any oxides of nitrogen present into a liquid nitrate. The original gas concentration in the exhaust fumes is then determined using an ion sensitive electrode and a calibration chart obtained using standard nitrate solutions.

A laboratory based non-chemical method of determining the nitric oxide and nitrogen dioxide concentrations in air samples is available in the form of the ‘chemiluminescent’ analyser. These are capable of operating over a very wide range of input concentrations, typically from 0.005 to 10000 ppm.

AII.4.5 Oxygen

Alternatives to the absorption method for oxygen determinations were available by the late 1960’s. In mine air laboratories use has been made of a ‘paramagnetic’ analyser described in detail by Verdin (10). For many years, oxygen analysers operating on these principles have been manufactured by Servomex.

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APPENDIX III The Wheatstone bridge circuit

This circuit, shown in Figure AIII.1, is used to compare resistance values. When the bridge is balanced:

$$V = 0$$

and:

$$\frac{R_c}{R_d} = \frac{R_1}{R_2}$$

If (R1+R2) >> (Rd+Rc), any increase in Rd will lead to a proportional rise in the ‘out of balance’ voltage, V. Typically this is used as the ‘output’ from the system.

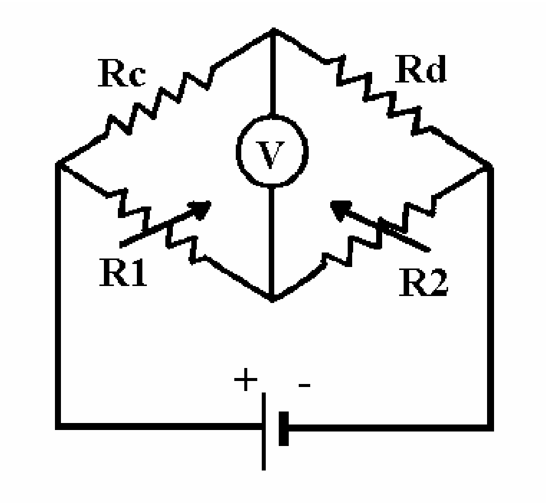

Figure AIII.1 The Wheatstone bridge circuit

APPENDIX IV Heat and humidity - general terms

Dry bulb temperature: The temperature of the air as recorded by a ‘conventional’ thermometer. Example of units: ^{o}C.

Wet bulb temperature: The temperature shown by a thermometer whose bulb is encased in a fabric sleeve saturated with distilled water. Example of units: ^{o}C.

Wet bulb depression: The difference between the dry and wet bulb temperatures. Example of units: ^{o}C.

Vapour pressure: The partial pressure of water vapour in a given environment. Example of units: Pa.

Saturated vapour pressure: The maximum equilibrium vapour pressure possible given the air dry bulb temperature. Example of units: Pa.

Absolute humidity or humidity: The mass of water vapour per unit volume of air. Example of units: kg m^{-3}.

Relative humidity: The ratio of actual vapour pressure to saturated vapour pressure. Can be derived from the wet bulb depression. Units are % RH.

Dew point: The temperature to which a sample of air must be reduced before it becomes saturated with water. Example of units: ^{o}C.

APPENDIX V Lighting - general terms

Luminous flux: The total light output from a source. Example of units: 'lumen'.

Luminous intensity: The luminous flux per unit solid angle. Originally termed 'candle power' and measured in units of 'candles'. Since 1948 units called 'candela' have been used, with 1 candle approximately equal to 1 candela.

Mean horizontal candle power, or mean horizontal luminous intensity: The average candle power, or luminous intensity, of a source averaged over all directions in the horizontal plane with the lamp at its centre.

Mean spherical candle power, or mean spherical luminous intensity: The average candle power, or luminous intensity, of a source averaged over a spherical surface with the lamp at its surface.

Illumination: The luminous flux falling on a surface per unit area of that surface. Originally the units were foot candles, or meter candles, but now the 'lux' is used. To convert from 'foot candles' to 'lux' divide by $(0.3048)^2$.

Brightness: The amount of light reflected from a surface. Will depend upon the reflectance factor of that surface.

The standard lamp: Since 1847, measurements of the output from lamps have been referenced to a standard. Initially this consisted of a spermaceti candle weighing 75.7 gm and burning at a rate of 7.8 g/hour. In about 1898 this was replaced by a pentane flame. This in turn was replaced during the 1940's by a standard light formed from a black-body radiator at the temperature of solidification of platinum.

ACKNOWLEDGEMENTS

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