In the graveyard of a small country church in Yorkshire, the following epitaph is carved for three unfortunate well-diggers.

'[Died while] venturing into a well at Marton when it was filled with carbonic acid gas, or fixed air. From this unhappy accident, let others take warning not to venture into wells without first trying whether a candle will burn. If the candle burns to the bottom, they may be entered with safety. If it goes out, human life cannot be sustained.'

This warning was given in 1812. It was assumed that the deaths were caused by carbonic acid (carbon dioxide) and the association, known in classical times, between the failing candle flame and the extinction of life, was highlighted.

Eighty-five years later, in 1897, a Board of Trade Commission investigated the air in the tunnels of the Metropolitan Railway (Figure 1) because of public concern about its safety. This investigation sets a very different style. The sources of contamination - trains, gas lamps and people - are identified and their respective contributions to the release of the pollutants carbonic acid, carbon monoxide and sulphurous acid are estimated. The levels of contaminants are measured and related to quantitative information on adverse effects. It is noted that there is a constant relationship between the concentrations of the three contaminants, and the level of carbonic acid is suggested as a method for judging the ventilation required. Control measures suggested include the burning of low sulphur coal to reduce the sulphurous acid content, but the major hazard is noted to be carbon monoxide which cannot readily be controlled. Those most at risk are identified as men working in the tunnels, rather than passengers. As is so often the case, these well-conducted studies were overtaken by events and the investigators conclude by stating that electric traction is to be introduced on the underground railway and by this means the Metropolitan Railway will rid the atmosphere in the tunnels of impurities (Oliver 1902).

Figure 1. Maggie Smith – Metropolitan Railway. (Courtesy London Transport Collection)

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The contrast between the resources available to the author of the epitaph and the advisers
to the Board of Trade Commission is striking. A whole new technology of railways and
tunnelling has been developed. Analytical chemistry has become able to measure low
concentrations of contaminants in the atmosphere. Medical science has established dose-
response relationships for the major contaminants and, perhaps most important of all, the
political will to investigate and, if necessary, spend money to control hazards and nuisances, is
in evidence. These developments laid the foundations for present-day occupational health
practice, and many of the debates which took place in relation to acute hazards during the last
century are equally appropriate to the longer term effects with which we are now preoccupied.

Lavoisier

The well-diggers’ epitaph reflects the state of knowledge in the early part of the nineteenth
century. The common features of respiration and combustion had been defined by the great
French chemist Lavoisier (Figure 2), who showed that both were oxygen-using, carbonic-acid-
producing processes which generated heat. He was able to undertake his studies because of the
earlier work of men such as Priestley and Black, who had identified the components of the
atmosphere including carbonic acid or fixed air and provided techniques for their detection.
At this time the work of Morgagni and others, who demonstrated that most bodily processes
were localized within certain organs, was influential and this may well have been the basis for
Lavoisier’s postulation that the process of carbon dioxide production using oxygen took place
within the lungs, with carbon and other toxins transported there from the tissues for
oxidation. This theory was supported by the darker colour of venous blood flowing towards
the lungs and measurements of apparent temperature differences between blood entering and
leaving the lungs. It was also subsequently used to explain the black deposits in coal miners’
lungs as being carbon deposits caused by inadequate oxidation taking place because of the
vitiated mine air; this view probably delayed the recognition that dust was the cause of coal
miners’ pneumoconiosis for many years (Rosen 1943).

Figure 2. Monsieur and Madame Lavoisier. (Courtesy Science Museum, ref 1250/52)
An important consequence of this theory was that both oxygen lack and carbonic acid excess were considered to prevent the 'purification of the blood within the lungs' and the prime culprit for the adverse effects of a vitiated atmosphere was held to be carbonic acid, not least because of the apparent lack of recognition of oxygen deficient atmospheres in the workplaces of the early nineteenth century (Thomas 1830, 1831).

Technical change
Wells and mines were locations in which abnormal atmospheric conditions had long been known. During the nineteenth century chemical processing in enclosed vessels increased and the hazards of vessel entry were appreciated in an empirical way. During the century, sources of exposure to abnormal atmospheres occurred as a consequence of the use of compressed air caissons and high altitude balloon flights. In essence, the hazards in mines had changed little over the centuries except that the development of improved water pumping and haulage methods led to a worsening of the problems of ventilation, which became manifest in the coal mines by a series of disastrous mine explosions rather than by fatalities from abnormal atmospheres. Although Davy's invention of the safety lamp reduced the number of sources of ignition in the mines, it was not until the science of ventilation was better developed that major gas and dust explosions became relative rarities and attention was directed at the other hazards of mine atmospheres.

Public concern
The Royal Commission on the Employment of Children in Mines of 1842 focused attention on conditions underground, using sketches of children at work with dramatic effect (Figure 3). As has so often been the case, concern about health and safety developed hand in hand with issues of welfare and morality. This led to the first effective legislation on safety in mines. Much of the legislation on occupational hazards at this time concentrated on vulnerable groups such as women and children or on dangerous trades. Specific chemical hazards received much less detailed attention. One notable exception was concern about the effects of soda works which were devastating their surroundings with releases of hydrogen chloride. Such adverse effects of industrial development on the wider environment were a cause for action, not least because the administrative mechanisms instituted by Chadwick and others had at last made it possible to achieve effective communal action – which could override vested interests – against obvious nuisances. The House of Lords Enquiry on Injury

Figure 3. Children in the mines (Royal Commission 1842)
from Noxious Vapours of 1862 received the following evidence from Thomas Ansell, the Medical Officer of Health for Poplar:

'There are four factories and distilleries dealing with the refuse of gas, commonly called naphtha; seventeen manure works for making manure, chiefly from fish, decaying organic matter and night soil; there are ten works connected with the boiling of bones and other animal matter, including a candle factory and a soap factory; there are five varnish makers; there are eleven manufacturing chemists manufacturing various articles such as vitriol and muriatic acid including one smelter of antimony; there is one set of coke ovens and one gas works.

He was asked, as a medical man, "Are you able to say that the emanations from the whole of these works are injurious to the health of the neighbourhood", and replied "I am".

This interview both reflects the new found authority of the Medical Officer of Health and paints a picture of the conditions in Poplar 120 years ago. The enquiry led eventually to the Alkali Works Regulations, the forerunner of our present-day pollution control legislation.

Understanding hazards

Technical and social changes provided the impetus for further investigation and analysis of the hazards of abnormal atmosphere. The ideas of Lavoisier about oxidation in the lungs and their influence on medical thinking were gradually modified during the century. A discussion took place at the Westminster Medical Society at which Mr Snow – later Sir John Snow of cholera and anaesthetic fame – questioned whether observation that 8-10% of carbonic acid gas in the atmosphere is fatal was derived from experiments on gas generated by fermentation, respiration or combustion (Snow 1838). In doing so he highlighted the possibility that the reduced oxygen content of gas from combustion or respiration could play an important part in aggravating the risks.

The evil repute of carbonic acid was undoubtedly enhanced by ill defined concerns about the hazards of expired air in relation to the diseases which were subsequently found to be infectious in origin (Elmore 1840). This issue was actively debated in the popular press, especially in relation to the widely observed effects of prolonged church services on the worshippers, as seen in the Pictorial Times of April 1846:

'No buildings are more deficient in ventilation than places of public worship. Air loaded with the products from the consumption of gas, oil and candles, chilling draughts from an immense surface of glass, inequality of heat, emanations from graveyards and sometimes from dead bodies under pews in the very centre of the building, and in some places the poisonous emanations of an open charcoal brazier passing from the corridor into the church, may all be observed producing deleterious effects.'

It is no surprise that prominent ventilators are to be seen on most churches and chapels built in the second half of the nineteenth century. Clear distinctions between the hazards of carbonic acid (carbon dioxide) and carbonic oxide (carbonic monoxide) were rarely made and, as late as 1853, poisoning by carbonic acid from charcoal braziers is noted as a fashionable means of suicide in Paris (Andrew 1853).

The way to a new understanding was led by investigators such as Gustaf Magnus who, in 1837, showed that oxygen was transported to the tissues of the body and carbon dioxide was transported from them to the lungs; hence separate and distinct effects could be expected from oxygen deficiency and carbon dioxide excess. Claude Bernard showed that carbon monoxide was specifically bound to haemoglobin and this allowed the effects of the two oxides of carbon to be more clearly identified. These fundamental studies opened the way for many detailed quantitative investigations of atmospheres, such as those of Pettenkofer in Munich and Letheby in England (Letheby 1862). All are notable for a new crispness of approach and readiness to quantify the relationships between exposure and effects which was lacking in the earlier reports. It was, however, some while before the relevance of carbonic acid to air quality was rigorously questioned, but, in 1865, Wanklyn firmly stated that 'the air in the crowded room is not bad by reason of its carbonic acid content or from any deficiency
of oxygen' and then went on to suggest that minute concentrations of very active gases such as carbonic oxide and prussic acid may be responsible for any adverse effects.

Although the hazards of carbonic dioxide had by this time been put in a more rational perspective, the search continued for evidence to support the presence of hazardous substances in expired air. The hunt for such substances continued and as late as 1889 Foster stated that 'inhaling one per cent of carbon dioxide derived from breathing is highly injurious, possibly because of the presence of ptomaines – the products of putrefactive decomposition'.

The importance of reduced oxygen concentrations as a hazard received little attention in comparison with the earlier part of the century, possibly because of the continuing search for substances with specific harmful effects. One insight is provided by a letter to the *Lancet* in 1880, which also indicates the ability of new technology both to create problems and aid the definition of existing ones. Dr Neill was called to a Mr Fleuss who was experimenting with a diving suit. While Fleuss was walking under Fishbourne Creek in the Isle of Wight, breathing through a closed circuit apparatus of soda lime to absorb carbon dioxide, a failure to admit more oxygen led to a sudden loss of consciousness. Happily rescue was successful and it was stated that Mr Fleuss was aware of any symptoms of any carbon dioxide build-up but unprepared for the sudden and dramatic effects of anoxia.

**J S Haldane**

The detailed and non-speculative observation of abnormal atmospheres seen in Dr Neill's letter is demonstrated by both the approach to investigation and the experimental work of J S Haldane (Figure 4). It was Haldane who, during the 1880s and 1890s, devised critical experiments, performed in the main on himself, and undertook the transformation of the mass of uncertainties, fears and prejudices about vitiated air into a coherent and modern scientific
synthesis. He was an active field investigator and would visit mines and wells where accidents had occurred to make measurements of the atmosphere, as well as spending long hours shut inside a sealed box breathing atmospheres with abnormal concentrations of oxygen and carbon dioxide to determine their effects upon himself (Haldane & Lorrain Smith 1893a). Much of his work was aimed at removing myths. He repeated many of the studies of earlier investigators and determined that there were no poisons in expired air and that much of the previous work could be faulted on technical grounds (Haldane & Lorrain Smith 1890). For instance, studies to show that condensate from expired air was poisonous were shown to have demonstrated nothing other than the hazards of injecting distilled water into an animal (Haldane & Lorrain Smith 1893b). He also determined the tolerable concentrations of carbon dioxide and oxygen in the atmosphere and produced dose response relationships for carbon monoxide exposure (Haldane 1895, 1899). All his papers show a firm and determined style of presentation: he argued only from experimental observation and had no truck with unsupported hypothesis or speculation. Almost all his investigations were performed to answer questions of great practical importance, notably in the mining industry. For example, his analysis of the clinical features of poisoning by black damp, the gas produced by slow oxidation of carbon in mines, clearly notes that the prime and hazardous effect is anoxia, although the elevated carbon dioxide concentration is responsible for the dyspnoea which is regularly observed (Haldane & Atkinson 1895).

Haldane's studies provided the basis for effective preventive measures, based on a sound analysis of the nature and scale of risks. Their practical application to the Metropolitan Railway has already been discussed. Virtually all the principles of good occupational health practice are clearly deployed in these investigations of acute hazards and they can still provide a point of reference for scientific excellence when current concerns about longer-term risks such as occupational carcinogenesis are debated without critical assessment of the nature and scale of risk. Now, as in the last century, intervention to investigate and control occupational health hazards remains a product of technological change, political attitudes to relationships in the workplace and available techniques for investigation. These factors continue to influence the practice of occupational health, frequently excluding the likely scale of any risk from its central place as a guide to resource allocation.

References
Andrew T (1853) Domestic Medicine and Surgery. Blackie, Glasgow
Elmore (1840-41) Lancet ii, 437–439
Haldane J S (1895) Journal of Physiology 18, 430–462
Haldane J S (1899) Journal of Physiology 25, 225–229
Haldane J S (1899) Journal of Physiology 25, 225–229
Haldane J S & Atkinson W N (1895) Federation Institution of Mining Engineers Transactions 8, 549–567
Haldane J S & Lorrain Smith J (1893a) Journal of Pathology and Bacteriology 1, 168–186
Haldane J S & Lorrain Smith J (1893b) Journal of Pathology and Bacteriology 1, 318–321
Letheby H (1862) Lancet i, 219–220
Neill C (1880) Lancet ii, 557–558
Snow J (1838–9) Lancet i, 418–421
Thomas J (1830–31) Lancet ii, 779–783
Thomas J (1831–32) Lancet i, 23–27
Wanklyn J A (1865) Lancet i, 60–61