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FRONT COVER
Lorenzo Monaco, *The Coronation of the Virgin* (NG 215, 1897, 216) (detail of Plate 1, p. 44)

TITLE PAGE
Carlo Crivelli, *The Dead Christ supported by Two Angels* (NG 602; detail), after cleaning and restoration

Pollution and the National Gallery

DAVID SAUNDERS

London Pollution and the National Gallery in the Nineteenth Century

When the National Gallery was founded in 1824, London was already a polluted city, mainly because of the many coal-burning industries and utilities located within the city. Coal was not a new fuel, having supplanted wood as the major source for heating as early as the thirteenth century.[1] However, as London's population increased, so more 'sea coals' were transported from the north east of England to London to satisfy the need for domestic heating and to support industries, including dyeing, brewing and tanning. The diarist John Evelyn, in the mid-seventeenth century, also blamed 'Lime-burners, Salt and Sope-boylers' in his *Fumifugium*.[2] This book, subtitled *The Inconvenience of the Aer and Smoake of London Dissipated*, was presented to Charles II in 1661; it described the ill effects of smoke ('that Hellish and dismall Cloud of SEA-COALE'[3]) on buildings, furnishings and paintings, suggested the use of fuels that generated less smoke and proposed that obnoxious industries be relocated to a site some miles east of London, where the prevailing winds would carry smoke away from the city.[4] This site may well correspond to the promontory at Greenwich, at present occupied by the Millennium dome. Throughout the eighteenth century, increased industrialisation, notably the introduction of steam engines in the latter part of the century, contributed to London's reputation as a smoky city, although, compared to the industrial cities of the North, its pollution was relatively mild.

The period in the 1820s during which the National Gallery was established coincided with the earliest moves to introduce modern smoke-abatement legislation. The MP for Durham, M.A. Taylor, introduced a bill that required furnaces to consume their own smoke, but like later legislation, it was weak and poorly enforced, having little effect on the level of pollution.[5]

By 1839, when the Trustees' attention was drawn to 'the heat & foulness of the air in the rooms',[6] the National Gallery had moved from its original site in Pall Mall to Trafalgar Square. The same correspondent, a Mr Joseph Hume, complained again in 1842 of the 'want of sufficient ventilation in the Galleries'[7] and drew the attention of the Trustees to the *Report of the Select Committee of the House of Commons on National Monuments and Works of Art* of June 1841, evidence to which had described the Gallery as 'wretchedly ventilated'.[8] It is clear that the Trustees of this period wished, on the one hand, to ensure adequate ventilation, while expressing concern over the amount of dust and smoke admitted to the rooms through open skylights. In 1847 the Keeper, Charles Eastlake, 'stated to the Trustees that he has found it necessary to cause the floors of the Gallery to be watered occasionally to lay the dust that conduces so much to disfigure the frames of the pictures – and that he has employed the Stoker for this purpose – and recommends to the Trustees a small remuneration to him for his additional labour'.[9]

Meanwhile, during the early 1840s a Committee to enquire into the *Means and Expediency of preventing the Nuisance of Smoke arising from Fires and Furnaces* gathered information from scientists, including Michael Faraday. However, two early smoke-abatement bills were defeated in the House of Commons and although the 1846 Public Health Bill incorporated a clause on the prevention of smoke, further smoke-abatement bills in the 1840s fell or were withdrawn.

Faraday was also a member of a number of Select Committees looking at the problem of smoke and pollution in the context of the National Gallery. In his evidence to the *Select Committee on the National Gallery* in 1850, he describes the different types of pollutant 'that can exist in the atmosphere of a great city like London', mentioning 'both the inorganic fumes from chimneys and the organic miasma from the crowds that are in the town'.[10] Faraday also differentiated between sulphuretted gases that emanated from the sewers and 'animal exhalations and the perspiration' and 'the sulphurous acid which is directly in the atmosphere

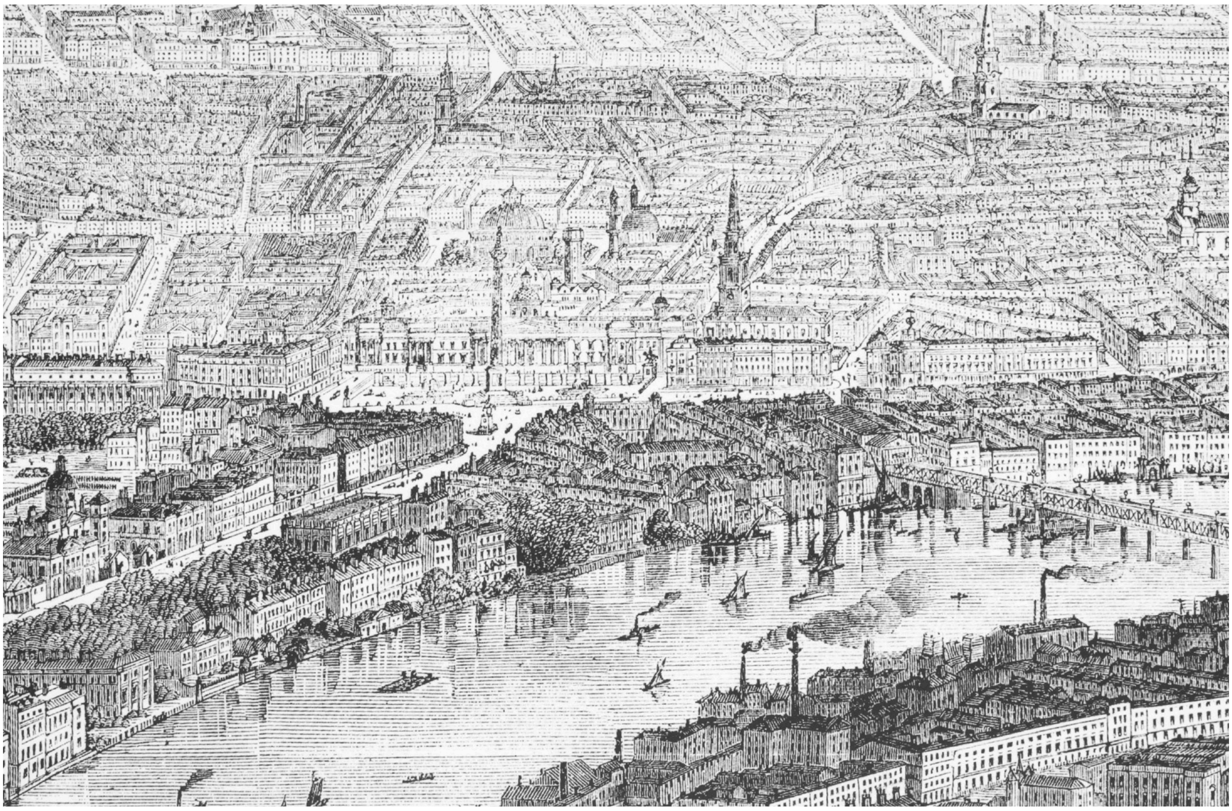

Fig. 1 Aerial view of London from the *London News*, 1861; note the surrounding chimneys and the steam boats on the Thames.

[that] proceeds to a very large extent, from the coal burnt in London'.[11] Both Faraday and Thomas Uwins, the Gallery's Keeper, describe the blackening of lead white by sulphuretted hydrogen (hydrogen sulphide).[12] Faraday also described the effect sulphurous acid (produced by combination of the sulphur dioxide and water generated during the combustion of coal) had on a 'copper apparatus' at the Athenaeum club-house, producing a 'large body of sulphate of copper'.[13]

One of the questions examined by the 1850 Select Committee was whether the Gallery might experience less pollution were it to be sited away from the centre of the metropolis where it was in the 'vicinity of several large chimneys, particularly that of the Baths and Washhouses ... and that part of the Thames to which there is constant resort of steamboats'[14] (see Fig. 1). Faraday thought that wherever the Gallery was sited near the centre of London, smoke would carry towards it on the wind. However, because of the 'prevalence of westerly winds' he thought it would be best if the Gallery were sited at 'a point to the westward of which there was no coal burning'.[15] Although the Committee were 'not prepared to state that the preservation of the pictures and convenient access for the purpose of study and the improvement of taste would not be better secured in a Gallery further removed from the smoke and dust of London' they did not 'positively recommend its removal elsewhere' as they were 'in ignorance of the site that might be selected', which might offer no benefit over the current site and involve considerable expense.[16]

As a means of temporary preservation, the Committee recommended that 'pictures of a moderate size should be covered with glass, and that the backs of all pictures should be carefully protected; provided always that such measures of protection should be adopted with the utmost caution and under the immediate direction and control of practical men' and that 'increased attention should be paid to . . . the ventilation of the Gallery'.[17] In response, the Trustees, meeting in February 1851, 'requested Sir C.L. Eastlake and Mr Russell to examine the pictures in this Gallery, at their earliest convenience, in order to ascertain which of them especially require protection by means of glass'(see Fig. 2).[18]

Over the next decade paintings were glazed and the backs protected from dust; for example, 'During the year [1856], 86 pictures, including 34 by Turner,

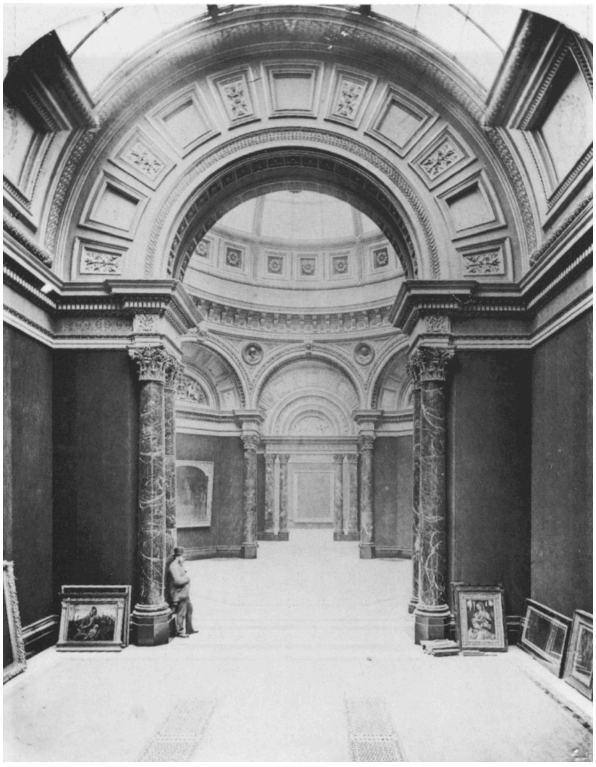

Fig. 2 Paintings leaning against the walls of the 'new rooms' in 1876; from the reflections it is clear that the paintings have been glazed.

have been protected so as to exclude dust from the backs. The material at present used for this purpose is glazed brown holland, the glazed surface being outside . . . it is proposed that on all occasions when pictures not previously so treated are moved, . . . the backs of the pictures should be protected in the same or some other effectual mode.'[19] By April 1860 the Director was able to report that 'with the exception of one picture, on wood – the Orcagna No. 569, the frame of which does not admit of a canvas being attached to it – all the pictures and drawings in the National Collection, whether in Trafalgar-square or at South Kensington, are protected at the back'.[20]

The choice of backing material had been the subject of considerable research: 'After many experiments with a view to select a light, impervious, and sufficiently incombustible substance to protect the backs of pictures (experiments in which great assistance has been rendered at various times by Professor Faraday, Mr. Barlow, and Mr. Warren de la Rue) the least objectionable substance for the purpose has been found to be canvass [sic] prepared in the ordinary way for painting, the primed or painted surface being outside ... The system will be adopted with all future acquisitions.'[21] This material was preferred to glazed brown holland, 'patent parchment, at first used for the backs of some small pictures', but which was found to 'contract and break'[22] and tin foil, which was an early suggestion by Faraday.[23]

In 1857, the *National Gallery Site Commission* reconsidered other possible sites for a new National Gallery building, including the British Museum site, two sites at Kensington and Regent's Park, but 'found our choice, in fact, limited to two sites, the site of the present National Gallery, sufficiently enlarged, and the Kensington Gore Estate'. They concluded that although the site at Trafalgar Square was inferior to that at Kensington in terms of 'atmospheric impurities', the former site was 'incontestably more accessible – more in the way of all classes, and, from long usage, more familiar to them, than any position in the outskirts of the metropolis'. They again recommended a 'more general protection of the pictures by glass, which is strongly recommended by some of our more competent witnesses' and hoped that 'recent legislation, which has done much to purify the metropolitan atmosphere, and may do more, would probably much improve its present condition'.[24]

But progress with smoke abatement in the latter part of the nineteenth century was not as fast as had been expected and, although less smoke may have been produced as a result of more efficient furnaces and chimneys, there was no effective monitoring of the level of smoke to define this decrease. Perhaps because of the increased frequency and thickness of fogs during this period, the smoke and pollution seemed to be getting worse.

The Gallery continued to face a dilemma: if the skylights were closed to exclude dust and smoke, the air in the poorly ventilated rooms rapidly became foul and over heated; 'all endeavours to exclude the smoke which sometimes abounds in the vicinity, are counteracted by the necessity of keeping the sky-lights open when the rooms are crowded.'[25] The situation became worse when it became evident that the new galleries designed by Barry in the 1870s were particularly prone to poor ventilation. Although there were concerns about the effect of gases, particularly 'sulphuretted hydrogen' (H_2S) in the foul air, more potentially damaging was the desiccating effect of overheated air on panel paintings. Mr Bentley, a restorer used by the Gallery, reported '. . . that the panel pictures of the National Gallery had suffered very considerably since their removal to the new rooms; that he attributed this deterioration to the over heated atmosphere and to foul air arising from bad ventilation; that the damage to the pictures had diminished in consequence of the measures taken to improve the condition of the atmosphere, but had not ceased.'[26] One such improvement, instigated by the then Director, Sir Frederic Burton, to counteract blistering, was 'that towards the close of last winter he had ordered zinc troughs filled with water to be laid down under some of the gratings in the floor over the hot air outlets with the view of moistening the hot air'.[27]

Although all the paintings were backed by the end of the 1860, routine dusting of the painted surface, or its covering glass, and of the frames and backs was still required. As early as 1852 William Russell informed the Trustees that 'The constant deposit from atmospheric and other sources ... leads to a dull appearance in the pictures which amounts to a denial of enjoyment of them to the public' and went on to suggest they 'authorize the allowance of a proper remuneration to Mr Seguier for attending from time to time to keep the pictures, by the timely & proper use of the silk handkerchief, in a sufficient state of cleanness so that they may be fairly seen by the Public'.[28] Other methods used to dust or clean the paintings included dry or moist cotton,[29] 'soft full feather brushes'[30] or a combination of materials. 'The pictures in Trafalgar Square, and at South Kensington have been carefully wiped and polished with cotton and a silk handkerchief ... and in some few cases sponged also, previous to polishing.'[31]

Cleaning the surfaces of the painting was not to be repeated unnecessarily and should be 'undertaken only by the person employed by the Director', while 'The Keeper will see that the glasses by which some of the pictures are protected are cleansed as often as may be necessary'.[32] It was recommended in 1862 that 'the senior assistant porter, at Trafalgar Square, should have ordinary charge of the frames of pictures to keep them well dusted'.[33]

The annual Gallery closure, or vacation, allowed dust to be swept from the cornices and walls, but it was not until after Sir William Gregory had 'called attention to the risk of injury to which the pictures in the Gallery were exposed from being unprotected by any covering ... during the annual cleaning' in 1879[34] that steps were taken to protect the paintings during this operation, the Trustees resolving that 'it is expedient that the pictures in the National Gallery should be covered with brown holland or some such material during the annual cleaning'.[35] This practice seems to have been adopted, but not before a bureaucratic wrangle between the Gallery and Her Majesty's Office of Works, after the latter declined to supply the required materials.[36]

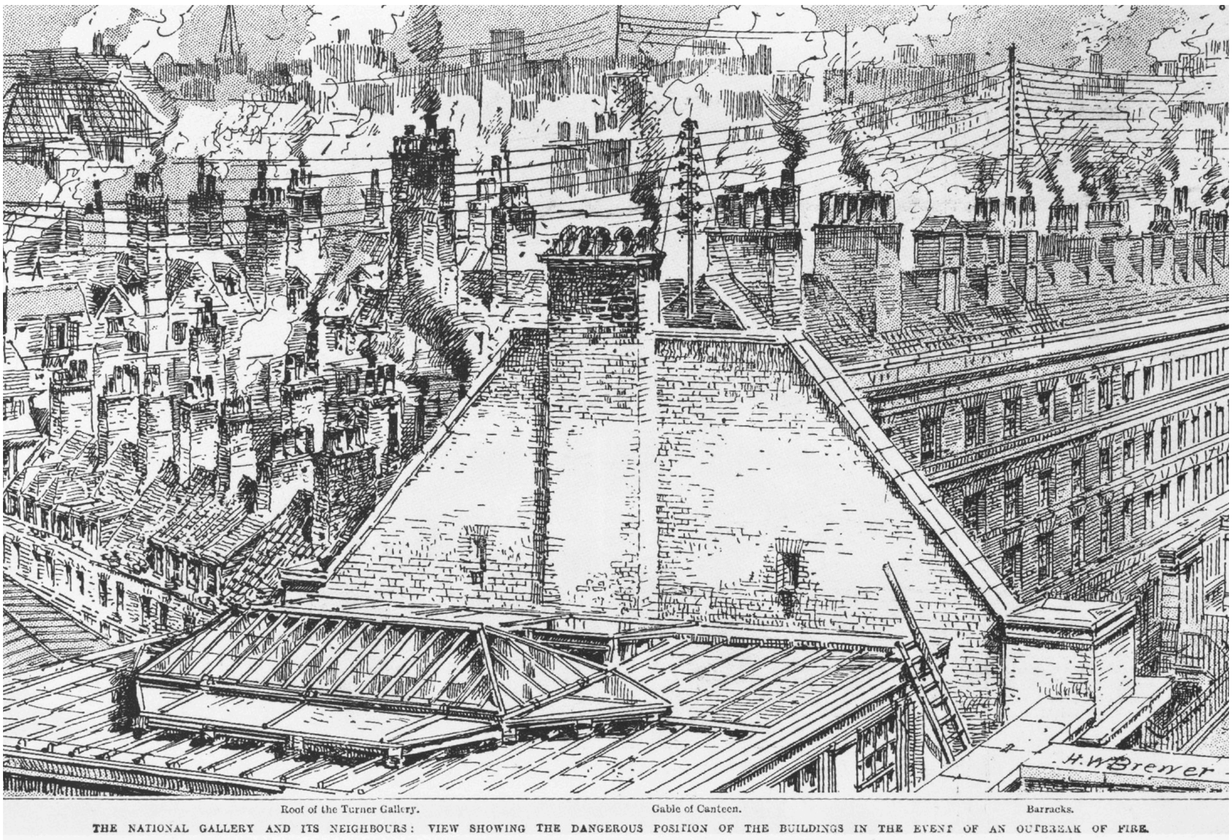

Fig. 3 Illustration of the Gallery roof from the *Daily Graphic*, 6 June 1895, p. 968.

By the turn of the century the Gallery had settled on a regime based on protecting the fronts and backs of paintings whenever possible, regular dusting[37] and improved ventilation.[38] Despite the unremitting emission of smoke in the vicinity of the Gallery (see Fig. 3) no attempts had been made to filter the air by, for example, 'passing [it] through a layer of loosely packed carded cotton' as recommended by Church in his book *The Chemistry of Paint and Paintings*, first published in 1890.[39]

The Effect of Pollution on Paintings

Smoke and dust (particles)

The soiling of buildings and their contents by smoke and dust has been known for many centuries. Evelyn described how 'this horrid Smoake . . . obscures our Churches . . . fouls our Clothes, and . . . spreads a Yellow upon our choycest Pictures and Hangings'.[40] The soiling of paintings can be much reduced by glazing or backing the frames, and varnished paintings can often be cleaned to remove the dirt accreted to, or absorbed by, the protective layer. It is far more difficult, however, to clean unvarnished paintings, or works on paper.[41] In the nineteenth century lack of any means of preventing dust and smoke from entering the Gallery meant that objects that would be irreversibly damaged were generally not displayed. In 1841, there was some discussion as to whether the Raphael cartoons should be transferred to the metropolis for display at the Gallery, an idea rejected by the Keeper, William Seguier, who stated that the cartoons would be 'destroyed in a very few years ... by the smoke of London' because 'they are water-colour, and of course when the smoke has fallen upon them there is no means of removing it'.[42] Ruskin later proposed that Turner drawings be stored in cases for their protection against dust and light and only exposed to the light infrequently,[43] a process that was taken one step further when the Victoria and Albert Museum placed a painting by Turner in a sealed case from which the air had been evacuated.[44]

Apart from soiling, particles can also instigate chemical reactions. Although smoke is primarily elemental carbon, unburnt residues of organic compounds can be present. Descriptions of smogs in nineteenth- and twentieth-century London describe them as containing oily or greasy particles and of various colours from chocolate brown to yellow; at the turn of the century, Church refers to 'the solid and liquid particles suspended in yellow fog'.[45]

Some particles contain metals, for example iron or lead, although the latter is primarily a twentieth-century problem caused by lead additives to motor fuels, and its level has been much reduced by the introduction of unleaded petrol. Iron, however, is often present in particulate matter (see later section) and has been implicated in the catalytic oxidation of sulphur dioxide (SO_2) to the potentially much more damaging sulphur trioxide (SO_3). When SO_2 or SO_3 dissolve in moisture in the air or water on the surface of the object they produce sulphurous or sulphuric acid respectively, which can be extremely deleterious. Dust may also contain traces of other metals that, theoretically, have the ability to catalyse reactions on the surface of objects, particularly in the presence of water or water vapour, but there is little evidence that these processes play a significant role in deterioration of paintings. Alkaline particles, frequently associated with concrete or cement dust, have been identified as a potential hazard to dyes, silk and certain pigments.[46]

Gaseous pollutants

Reduced sulphur gases

Early reports of the effect of gaseous pollutants stress the effect of miasmata or organic emanations from people or animals, including those associated with poor public hygiene. Experiments with painting materials in the nineteenth century tended to concentrate on the effect of such vapours, so it is no surprise that Field's experiments during the first quarter of the century involved exposing a sample '*to the foul air* by suspending it beneath the seat of a privy'.[47] Although many of the pigments he examined were affected by light, only iodine scarlet (mercury iodide) and lead-containing pigments were changed by the 'foul air'; the latter were blackened by 'exposure to the mephitis of a jakes'.[48] The principal contaminant in these *emanations* was presumably hydrogen sulphide, although other reduced sulphur gases, such as carbonyl sulphide, may also have been present. These species react with certain metals or metal compounds to create black or dark-coloured sulphides; the darkening of paintings associated with the formation of lead sulphide was noted in a number of nineteenth-century sources.[49] Church cautioned that such pollution in galleries might arise because the air used to ventilate the rooms was taken from gratings 'on the level of the ground, in out-of-the-way and dirty corners, and certain depositories of uncertain rubbish. From such sources air laden with organic and inorganic impurities alone can come'.[50]

Sulphur dioxide

Until the introduction of clean air legislation in the second half of the twentieth century, the most common gaseous pollutant in London was undoubtedly sulphur dioxide. This arises from the burning of coal with a significant sulphur content; coal produced in Britain has an average sulphur content of about 1.6% but, historically, had a higher proportion of sulphur, as less care was taken to select good-quality fuel for mining. The sulphur is present both as organosulphur compounds and as inorganic sulphides, notably pyrites (FeS_2). Sulphur dioxide (SO_2) is readily soluble in water to give sulphurous acid (H_2SO_3) and, on oxidation, sulphuric acid (H_2SO_4); it is these acids that are largely responsible for the deleterious effects of SO_2.

Another concern in the late nineteenth century and early twentieth century was whether gas lighting ought to be introduced at the National Gallery. Quite apart from the fire risk, was the fear that the gas, or its combustion products, might be damaging. Church summarised the potential dangers: 'Gas, before and after burning, is bad for pictures. The evil effects of an occasional escape of unburnt gas are less to be dreaded than those caused by the products of gaseous combustion. These products are sulphuric acid, sulphurous acid, carbonic acid and the moisture, which is formed at the same time. Thence results a hot, moist atmosphere laden with these corrosive compounds.'[51]

Buildings are attacked by sulphur dioxide, particularly those that are constructed from limestone (calcium carbonate), which is converted to calcium sulphate by prolonged exposure to acidic conditions. The crust of calcium sulphate formed on damaged buildings is often black, as its formation is accompanied by smoke deposition (see Fig. 4). A similar problem affects wall paintings, many of which are executed on a chalk-based substrate. Conversion of the chalk (calcium carbonate) to calcium sulphate causes a change in volume, which can cause surface disruptions ranging from the appearance of small 'pustules' on the surface to severe delamination.

Metals can also be damaged by sulphur dioxide; by 1912, an iron girder in Charing Cross station (a few hundred metres distant from the National Gallery) was found to contain around 9% iron sulphate when

Fig. 4 The smoke-blackened façade of the National Gallery, *c.*1900.

it collapsed after long exposure to smoke from coal-fired railway engines.[52] As we have already seen, Faraday recognised the role of the sulphur acids generated by burning coal in the conversion of copper to copper sulphate.[53]

Faraday had also called attention to the deterioration of leather armchairs at the Athenaeum Club,[54] a process attributed to sulphur-containing gases by Church, who determined that the calf-leather binding of a damaged book contained the equivalent of 6% of free sulphuric acid.[55] Other organic materials such as wood, cotton, wool and silk are attacked by the acids formed from SO_2. Although acid gases attack paper, it is often difficult to distinguish between the effect of these gases and deterioration caused by acidic materials in the composition of certain types of paper, particularly those based on wood pulp rather than cotton rag. Acid-catalysed hydrolysis of cellulose- or protein-based textiles is responsible for weakening fabrics, including painting canvases, which yellow and embrittle.

Most pigments and dyes are relatively insensitive to sulphur dioxide, although some acid-sensitive pigments may be affected by the gas once it has been oxidised and hydrolysed to yield sulphuric acid. For example, a preliminary test on artificial ultramarine indicated that even at quite high SO_2 concentrations and at high RH there was little apparent damage, while as soon as drops of water condensed on the surface, decoloration was immediate.[56] Church, having noted that acidic gases dissolved in moisture were 'very injurious to paper, wood, canvas and pigments,' went on to recommend that galleries be coated with a distemper paint containing white lead to 'absorb the sulphuretted hydrogen as well as the sulphuric and sulphurous acid present in town air'.[57]

Nitrogen dioxide

Although oxides of nitrogen are present in the atmosphere from natural sources, the levels have increased in urban areas, particularly during the twentieth century, due to high-temperature combustion processes that oxidise atmospheric nitrogen to, for example, nitric oxide (NO) or nitrogen dioxide (NO_2). Of the oxides of nitrogen, nitrogen dioxide is of most concern to the conservator; it can dissolve in water to form nitrous acid, which, on aerial oxidation, yields nitric acid, a strong acid and oxidant.[58] As nitric acid is of a comparable strength to sulphuric acid, it might be expected to corrode metals, attack calcareous stone and damage textiles in the same manner, were it not for its volatility, which reduces its effect. There is little specific evidence to relate the presence of NO_2 to damage, as it is usually present alongside other potentially damaging gaseous pollutants, such as SO_2. Nitrogen dioxide has, however, been shown to affect iron gall inks, some synthetic dyestuffs, the arsenic sulphide pigments orpiment and realgar, and a few traditional organic colorants, both on silk and paper; these changes resulted from an exposure equivalent to five or six years in an urban museum with no chemical filtration.[59] Brimblecombe has reviewed the effect of NO_2 and other gaseous pollutants on various museum artefacts.[60]

Changes in Air Pollution in the Twentieth Century

The air in London, as in most major cities, is now considerably less smoky that at the turn of the century, despite a considerable growth in population. A number of factors have contributed to this decline, including a dilution effect as populations have spread over a greater area, changes in fuel use patterns away from high-sulphur, sooty fuels, increased use of electricity which is generated away from city centres and clean air legislation.[61] In London, smogs, a term for dense smoky/sooty fogs, continued to affect the city during periods when certain meteorological conditions prevailed until the 1950s. A particularly severe smog settled upon London in 1952, which has been estimated to have caused four thousand additional deaths,[62] and which was one of the factors leading to the passing of the 1956 Clean Air Act. Although the Act focused on reducing smoke pollution, by creating smokeless zones and promoting the use of smokeless fuels, SO_2 levels were reduced in tandem, as smokeless coals and oils generally have a lower sulphur content. The continuing move from coal to gas and electricity, combined with the relocation of electricity generating stations and heavy industry away from city centres, has further reduced the SO_2 and smoke levels in urban areas.

Tall chimneys, stipulated in the 1968 Clean Air Act, were intended to reduce SO_2 concentrations at ground level by providing better dispersal. More recently, systems have been introduced that remove SO_2, either during combustion or from flue gases, often by reaction with calcium carbonate, as limestone chips or as a slurry; the calcium carbonate

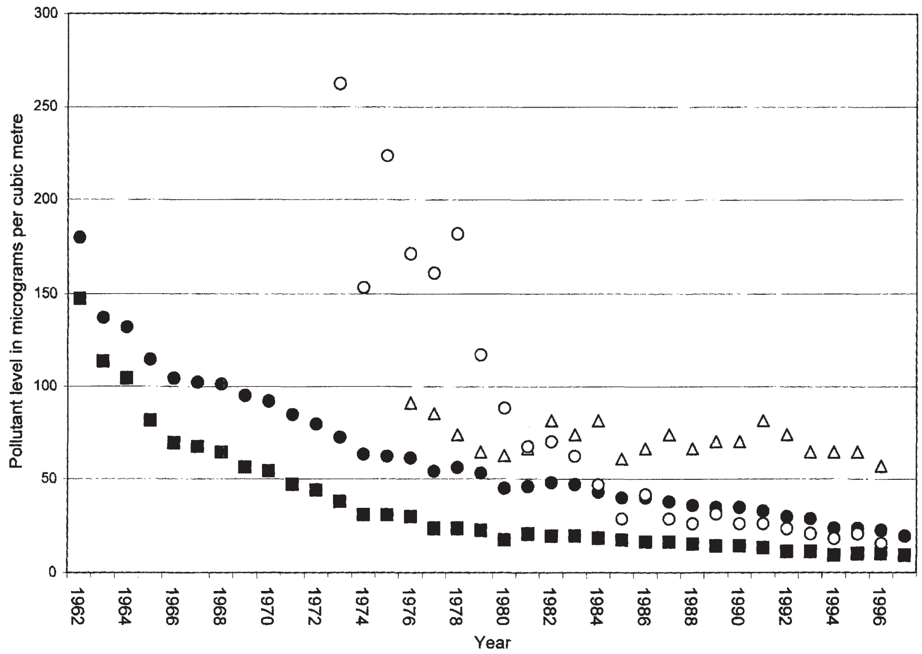

Fig. 5 Yearly average UK and London pollutant levels over the last four decades in micrograms per cubic metre: UK average smoke level ■ ; UK average SO_2 level ●; London average SO_2 level ○; London average NO_2 level △.

reacts with SO_2 to give calcium sulphate and carbon dioxide. The effect of such measures can be seen in Fig. 5. Over the period 1962–97, average smoke levels for the UK have fallen from around 150 to less than 10μg.m^{-3}, while SO_2 levels have dropped from nearly 200 to 20–30μg.m^{-3}. In London, the levels of SO_2 have declined more markedly still, from 200–250μg.m^{-3} in the mid-1970s (at a time when the national average was around 60μg.m^{-3}) to around 20μg.m^{-3} in the late 1990s, somewhat lower than the national average.[63]

Unfortunately, the decline in pollution from coal burning has coincided with the rapid expansion in the use of motor vehicles which, by 1997, had become responsible for around 50% of the total emissions of smoke and oxides of nitrogen in the UK (see Fig. 6). As the primary pollutant generated by combustion is NO, the level of NO_2 will not necessarily rise or fall in tandem; the rate of oxidation of NO to NO_2 may be limited by the availability of oxidants such as atmospheric ozone.

As in the nineteenth century, the Gallery's position in central London makes the building susceptible to high levels of pollution, currently from motor vehicles in general and buses in particular. The latter are typically powered by diesel engines which, although more fuel efficient, produce higher levels of particles and nitrogen oxides than the petrol engines found in most cars; indeed, particles from diesel engines are one of the major pollutant problems for the Gallery at present. As a result, the levels of NO_2 in the air surrounding museums are now often of more concern than those of SO_2. Although the number of motor vehicles has continued to increase, there has been some reduction in the levels of certain pollutants over the last few years; for example in Figs. 5 and 6 it can be seen that NO_2 levels began to drop slightly in the period 1990–7. Pollution control has been driven by a number of air-quality directives produced by the European Community and UK governments, and since 1993 all new cars sold within the European Union have been fitted with catalytic converters. These reduce pollutant emissions by passing the exhaust gases through a honeycomb structure coated with platinum group metals; the large surface area of the catalyst ensures efficient (up to 90%) conversion of carbon monoxide and hydrocarbons to carbon dioxide and water and the reduction nitrogen oxides to nitrogen. While reducing the levels of harmful pollutants, catalytic converters do not help to reduce levels of carbon dioxide, the increase in the levels of which has been identified as a major cause of 'global warming'.

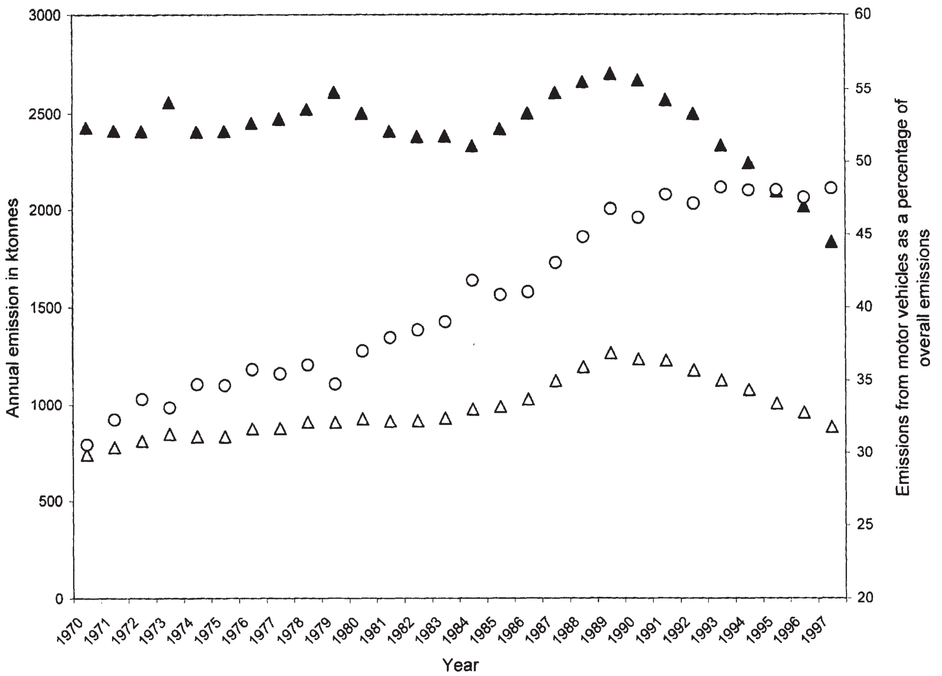

Fig. 6 Emissions of nitrogen oxides in the UK over the last three decades in kilotonnes: left axis, total emissions ▲, emissions from motor vehicles △; right axis, emissions from motor vehicles as a percentage of total emissions ○.

London remains a polluted city, not least because of motor traffic, but is not often subject to the modern phenomenon of 'photochemical smog' that affects the atmosphere in cities such as Los Angeles, where high levels of ozone, nitrogen oxides and other potentially damaging species (associated with high vehicle use and local meteorological conditions) present particular problems for museum collections.

Pollutant Control and Monitoring in London Museums

The first study of pollution in the National Gallery was conducted by Rawlins in 1936, in an era when none of the rooms at Trafalgar Square had air-conditioning or filtration. He began by examining paintings that had been framed and backed to protect them against dust, reporting that the 'experience is not very cheering ... the amount of dust, both on the inside of the glass and on the picture itself, was extraordinarily large'.[64] Rawlins used syphon recorders, which periodically drew two litres of air through a filter paper. The device used to measure levels outside the Gallery was partially automatic, so that a semi-continuous record was available against which to compare the measurements made inside the building. The amount of 'smoke' was determined by comparing the spots on the filter paper with a graduated shade chart. This comparative method was not capable of producing very accurate results, but external measurements revealed an average level of about 1000$\mu g.m^{-3}$, with peaks of 3200$\mu g.m^{-3}$.[65] The indoor to outdoor ratio was around 70%, with a 'lag' of an hour between peaks in the exterior level affecting the dust concentrations in the rooms. Finally, a jet method was used to collect particles for microscopic examination. The carbonaceous particles in the smoke were described as 'thin, buckled plates, greasy-looking and quite soft',[66] and it was suggested that this might cause them to adhere more easily to the painting surface.

By the time Thomson conducted further studies of pollution in the 1960s, some of the rooms had been equipped with air-conditioning systems that incorporated particle filters, which over a two-month period in 1959 had been found to remove over 90% by weight of dust; recirculating the air raised the efficiency.[67] Thomson observed that because 'clean air' legislation was taking effect, leading to a reduction in particles, SO_2 had become the primary pollutant.[68] Levels of SO_2 in towns varied seasonally and were typically 300 to 400$\mu g.m^{-3}$ (as expected, higher than the national average shown in Fig. 5), while the level of NO_2 in London was in the range 10 to 30$\mu g.m^{-3}$.[69]

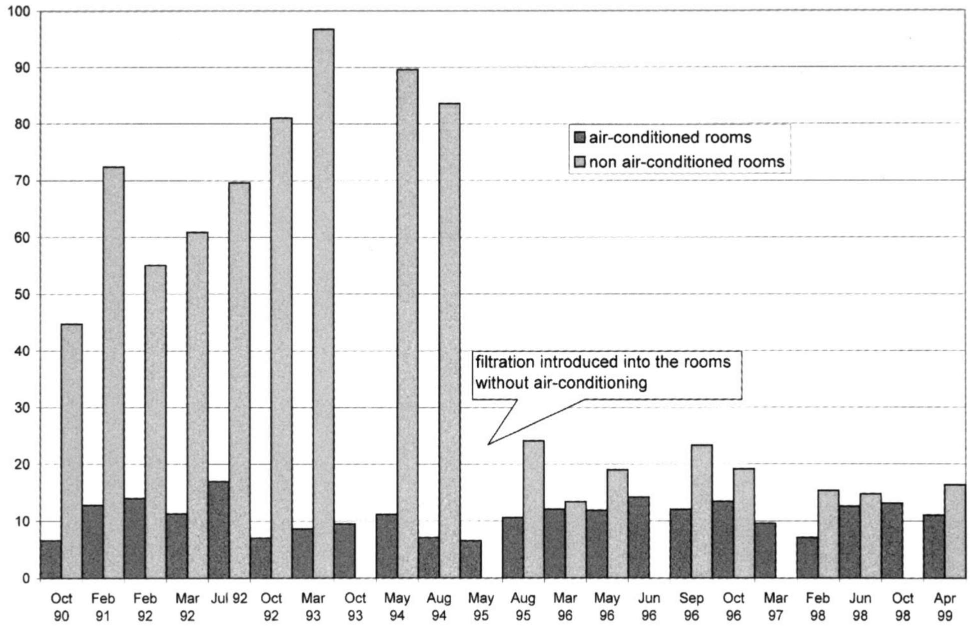

Fig. 7 NO_2 levels in air-conditioned and non air-conditioned rooms during 1990–9, expressed as a percentage of the exterior level.

In the air-conditioned rooms at the National Gallery, 95 to 97% of the SO_2 was removed when the air was passed through the water spray used in humidification.[70] At the same time similar levels of SO_2 (200 to 600μg.m^{-3}) were recorded by Padfield at the Victoria and Albert Museum. He noted that even without chemical filtration the inside levels were only 50% of those outside, perhaps due to absorption of gas by, or reaction with, walls and fabrics.[71]

An extensive study of SO_2 levels at the Tate Gallery was conducted by Hackney between 1978 and 1983.[72] Outside SO_2 levels, measured on seventeen days during this period, ranged from 31 to 208μg.m^{-3}. Within the building, the level was reduced, particularly in air-conditioned rooms fitted with chemical filters, where, except on days with very high external SO_2 levels, the pollutant level was below the detection limit of the gas analyser.[73] Measurements of NO_2, made in 1977, ranged from 44μg.m^{-3}, at the main entrance to the Tate Gallery, to <5μg.m^{-3} in a display case. As a result of this survey, the use of activated carbon filters to remove gaseous pollutants, and their regular replacement, were recommended. Lower levels were also found behind canvases when paintings were fitted with backboards, or surrounding objects stored in enclosures.[74]

In the last decade there have been a number of investigations of pollutants in museums in London, including a recent study of gaseous pollutants and suspended particles in two London museums, the National Museum of Childhood and the Museum of London. At the former, the average outdoor levels were 51μg.m^{-3} (NO_2) and 60μg.m^{-3} (SO_2), while at the Museum of London average levels of 58μg.m^{-3} (NO_2) and 20μg.m^{-3} (SO_2) were recorded.[75] Inside the naturally ventilated Museum of Childhood, the NO_2 concentration was 84% of the external level while the SO_2 level was only 16% of that outside. In the air-conditioned Museum of London, the levels of both NO_2 and SO_2 were much reduced, to 19 and 14% respectively,[76] suggesting that for SO_2 reduction in these museums, full air-conditioning did not confer significant extra benefit.

Current Programmes of Monitoring at the National Gallery

Unlike many other museums, the National Gallery is fortunate to have a collection that is, from a material standpoint, quite homogeneous. A single climate suffices for the long-term preservation of the Collection, obviating the need for individually conditioned, sealed display cases with their attendant problems associated with the accumulation of pollutants, for example carbonyl species or reduced sulphur gases. The principal pollutants of concern are, therefore, those generated by visitors, and those entering from outside the building and described in earlier sections detailing London's pollution. Following the recommendations given by Thomson, the National Gallery attempts to limit the concentration of both NO_2 and SO_2 to less than 10µg.m^{-3},[77] and to reduce particle concentrations by using efficient filters on the intake and recirculation air systems. As rooms at the Gallery have gradually been equipped with air-conditioning over the last five decades, particle and chemical filters based on activated carbon have been fitted. For the last five years, the air supplied to those galleries without air-conditioning has also been passed through particle and chemical filters prior to entering the room.

Gaseous pollutants

In order to assess the success of pollutant control at the Gallery, routine gaseous pollution measurements have been made in the Gallery since 1990, using diffusion tube techniques.[78] Tubes sensitive either to NO_2 or SO_2 have been exposed for two-week periods in both air-conditioned and non-air- conditioned rooms. During each survey one tube is exposed on a roof at the north of the Gallery and another left unopened in a refrigerator to act as a control. The NO_2 diffusion tubes measure the cumulative dose absorbed by tris-(2-hydroxyethyl)amine (triethanolamine, TEA) coated on a stainless steel mesh at the closed end of the tube. After exposure, the tube is sealed and sent for analysis; the quantity of NO_2 absorbed by the TEA as nitrite is determined spectrophotometrically after conversion to a diazonium compound.[79] The SO_2 sampler works on a similar principle; the quantity of SO_2 converted to sulphate is measured by ion chromatography. We have had no great success with diffusion tubes designed to measure ozone levels, perhaps because the levels of this gas inside the Gallery are at, or below, the detection limit of the tubes.

SO_2 levels outside the Gallery in the period since 1992 have been in the range 7.5 to 27µg.m^{-3}, in broad agreement with the levels shown in Fig. 5. In the air-conditioned rooms, SO_2 levels were between 1.2 and 9.4µg.m^{-3}, equating to indoor to outdoor ratios of between 5 and 41%; the highest reading (41%) corresponded to a level of 3.1µg.m^{-3} in a gallery over a period when the exterior level averaged only 7.5µg.m^{-3}. In the rooms without air-conditioning levels of up to 50 to 75% of the outdoor concentration were measured.

Over the period 1990 to 1999 NO_2 levels have been measured on at least twenty occasions. Exterior levels (on the roof of the Gallery) have been in the range 34 to 76µg.m^{-3}. Again, these are of the same order as the average data for London shown in Fig. 5. In the air-conditioned rooms the average levels were found to be 2.9 to 9.8µg.m^{-3}, which equates to between 6 and 17% of the outside level, see Fig. 7. Although the average was always below the Gallery's target of 10µg.m^{-3}, the level in some rooms was occasionally greater than this value. On investigation, the principal cause was found to be that the chemical filters for these rooms were coming to the end of their useful life and were in need of replacement. In other instances, the high level could be attributed to the proximity to unconditioned spaces, particularly the entrance vestibules at the Trafalgar Square entrance.

Fig. 7 also shows the indoor to outdoor ratio of NO_2 in the rooms without air-conditioning. Two distinct periods can be seen. Before 1995, the average level in these rooms was always more than 40% of the outside concentration, while after this time the level was always less than 25%. This clearly shows the value of the introduction of chemical filters in the air supply to rooms without air-conditioning, although full air-conditioning gives more efficient NO_2 removal, presumably because the gas is also removed as it dissolves in the water spray in the humidifier unit.

Dust

To assess the levels of dust in the Gallery, several surveys of suspended particles have been undertaken. These studies have two purposes: first to indicate the success of dust removal methods by mapping

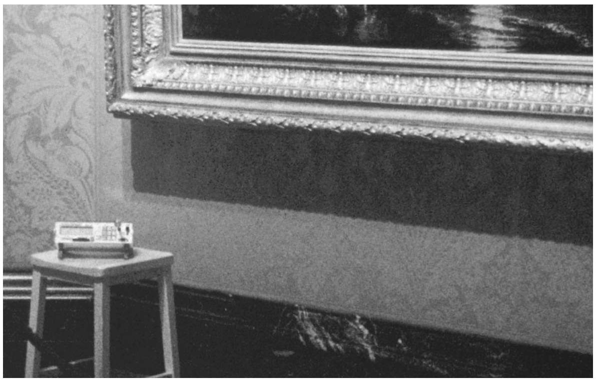

Fig. 8 Grimm dust monitor in use in Room 15.

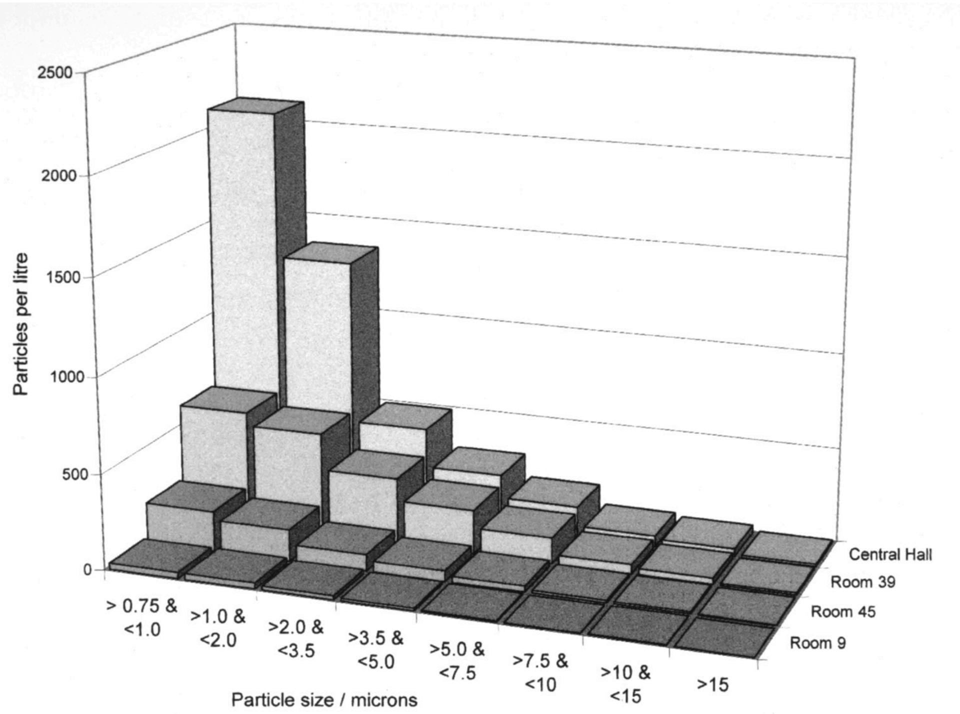

Fig. 9 Particle size distribution in Rooms 9, 45, 39, and Central Hall.

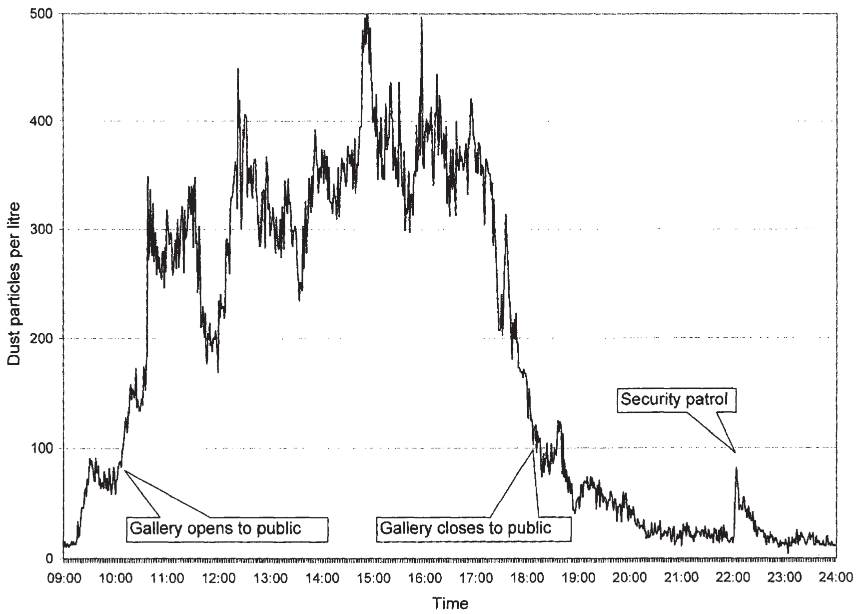

Fig. 10 Dust levels in Room 45 (particles > 0.75μm), showing the relation between level and visitor occupation.

Table 1 **Results from dust surveys during 1998–9**

Room	Surroundings	Survey 1	Survey 2
Not air-conditioned		31–81%	36–72%
Air-conditioned	Not air-conditioned	18–64%	16–74%
Air-conditioned	Air-conditioned	1–12%	3–12%

the distribution of dust through the air-conditioned and ventilated rooms in the Gallery, and second, at a time of much building work, to look at the impact of construction on adjacent areas. Both types of survey are designed to highlight strengths and weaknesses of present arrangements and to suggest improvements to practice.

The dust surveys have been conducted using a Grimm 1.105 dust monitor (see Fig. 8) similar to that used recently by Cassar et al.[80] The instrument operates by drawing air into a sampling chamber at a constant, known rate. In the chamber, a light beam emitted by a laser diode is scattered by the dust particles. The light scattered at an angle of 90° is collected and particles quantified by analysing the signal from a photo-diode detector. The dust monitor can be set to measure either particles per litre or micrograms per cubic metre and is able to differentiate between particles of different sizes (>0.75µm, >1.0µm, >2.0µm, >3.5µm, >5.0µm, >7.5µm, >10µm and >15µm). The inlet filter on the monitor excludes very large particles, so textile fibres (confirmed as one of the major sources of particles in the Gallery by examination of dust samples under the microscope) are excluded from the measurements. The drawback of this method is that the larger particles (>20µm), thought to be responsible for loss of gloss and for soiling, are not measured by this meter,[81] which is optimised to monitor the smaller particles associated with health hazards.

To obtain an average level, the monitor was left in each room for one hour. At the beginning and end of each measurement period, the level of dust outside the Gallery was measured for comparison. Fig. 9 shows the number of particles in each size range for a number of different rooms at the National Gallery. Rooms 9 and 45 are fully air-conditioned, but Room 45 is adjacent to the main vestibule, which has no air filtration and is connected to Trafalgar Square by single doors. The Central Hall leads off the vestibule and has no air filtration, while Room 39 is supplied with filtered, but not conditioned, air.

The results of two recent surveys (during 1998–9) are summarised in Table 1. The rooms have been divided into those that are air-conditioned and those that are not. The air-conditioned rooms have been further subdivided into rooms that are adjacent to areas that are not air-conditioned and those that are surrounded by other air-conditioned spaces. All the figures are for particles >0.75µm in diameter, expressed as a percentage of the exterior dust level at the time.

It can be seen that the non air-conditioned rooms and those rooms that were adjacent to unconditioned areas, particularly those near the public entrances, had higher levels. For example, the level of 74% recorded for an air-conditioned room in the second survey was for a special exhibition in Room 1,

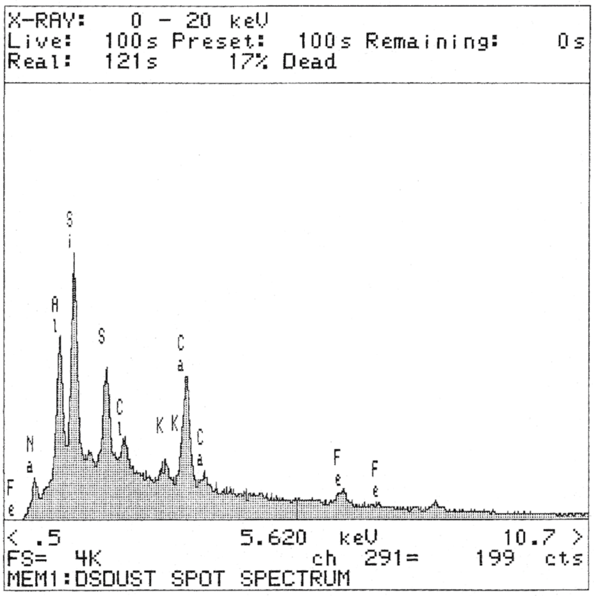

Fig. 11 EDX spectrum of a dust sample taken during a routine survey.

which is close to the main entrance from Trafalgar Square. The exhibition was extremely popular; the room was crowded and the door to the unconditioned vestibule opened and closed continually.

During these surveys it became clear that, as might be expected, the level in a room varied with occupancy; a much higher level of dust was present in a particular room in the middle of the day than when the Gallery opened. The dust monitor was placed in several rooms for a whole day; the results confirmed that the level rose during public hours and decreased once the Gallery closed (see Fig.10). The variation of dust levels with visitor numbers may be one of the reasons that the dust levels measured in air-conditioned rooms cover such a wide range (1 to 12%).[82]

The low level of dust at night indicates that the air-filtration systems are operating efficiently, restricting the amount of dust penetrating from outside the building. There are two possible fates for the dust present in the rooms during the day. First it may settle on the walls, floors and paintings during the night when there are no visitors to 'stir' the air in the room; in these surveys no measurements of precipitated dust have been made. The second possibility is that some or all the dust is removed from the air by recirculation through filters during the night. In the former case, much of the dust in the rooms will be present continually, but only airborne during the day, while the latter option implies that 'new' dust builds up in the rooms during each day, only to be removed at night. That the frames of paintings still require periodic dusting, despite good air filtration, suggests that some dust precipitates during the night. It seems likely, however, that a considerable percentage of the dust present in the building is generated by visitors, or brought in with them, rather than entering from outside in the air used to ventilate the rooms.

Analysis by energy dispersive X-ray fluorescence (EDX) of a sample of the dust collected during the survey showed significant peaks for silicon, aluminium, calcium, potassium, sulphur, phosphorus, iron and copper (see Fig. 11). These elements suggest that minerals, including silicates, aluminates, sulphates and phosphates, are present. The EDX technique used was not able to detect carbon, the principal element present in smoke. In addition, conspicuous peaks for sodium and chlorine were observed, suggesting that a significant component of the dust might be exfoliated skin cells. A subsequent analysis of the organic components by gas chromatography/mass spectrometry (GC–MS) revealed the presence of squalene, a marker compound for skin cells.[83]

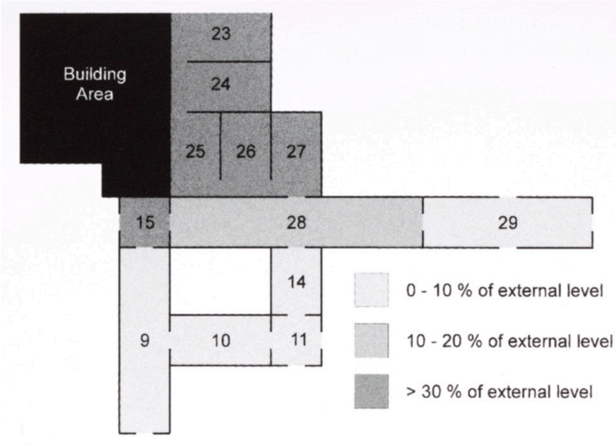

Fig. 12 Dust levels, as a percentage of the exterior level, in the rooms surrounding an area in which building work was occurring.

A survey conducted in a series of air-conditioned rooms during construction work revealed that, as might be expected, the dust levels in the rooms next to the building site were higher than those further away (see Fig. 12). The levels close to the area in which very dusty construction work was being undertaken were not, however, greatly different to the levels in air-conditioned rooms near entrance vestibules, suggesting that the measures taken to isolate the building area from the galleries were working reasonably well.

Conclusions

In the 175 years since the Gallery's foundation, the character of pollution in Central London has changed; particles and NO_2 emitted by vehicles have replaced smoke and SO_2 from coal burning as the major pollutants in urban areas. It is not, however, clear whether the greater concentration of NO_2 poses a more serious threat to museum collections, as the relative damage caused by SO_2 and NO_2 has not been quantified.

The Gallery no longer faces such an acute dilemma in ventilating the building without admitting noxious vapours and smoke, as the air supply to all exhibition rooms is filtered. But this supply air is drawn from outside the building in the midst of

London traffic and, as shown by the surveys described above, infiltrates some rooms from the public entrances. Visitors also bring pollution with them, on their clothing and feet, although not to the same extent as in the nineteenth century when the pavements around the Gallery were reduced to mud in wet weather. When asked by the 1850 Select Committee if 'the time of year make any difference in the accumulation of dirt', the Keeper, Thomas Uwins, responded that 'Wet weather will necessarily make a great difference, because it is brought in in the shape of mud on the feet, and that very soon crumbles into an impalpable powder, and becomes diffused through the rooms'.[84] A recent study has confirmed that wet weather greatly increases the quantity of material brought into a gallery on visitors' shoes.[85]

The surveys of pollutants have shown that the particle and chemical filtration provided by air-conditioning gives very high standards of pollution control in rooms surrounded by others of similar standard. The influence of the surrounding rooms is most obvious in the dust measurements, particularly if the adjacent area is unconditioned and connected directly to one of the public entrances. Moves which (rightly) give greater access to the Gallery for disabled visitors have led to the removal of revolving doors, which provide increased protection from pollution.[86] The doormats and air-curtains that have replaced revolving doors do not provide adequate protection and there is a tendency to wedge the doors open in warm weather. Once in the building, there is perhaps a greater expectation that visitors will behave with decorum than might have prevailed in the last century. Thomas Uwins described an impromptu picnic he had witnessed at the Gallery: 'On another occasion, I saw some people, who seemed to be country people, who had a basket of provisions, and who drew their chairs round and sat down, and seemed to make themselves very comfortable, they had meat and drink; and when I suggested to them the impropriety of such a proceeding in such a place, they were very good-humoured, and a lady offered me a glass of gin, and wished me to partake of what they had provided.'[87]

Following a recent study, during which the results from diffusion tube analysis were compared with measurements made with a gas analyser in the inlet ducts and air supplies to conditioned rooms,[88] the NO_2 and SO_2 surveys are being used to monitor the performance of chemical filters to indicate when these need replacement. Early indications are that this type of monitoring may reduce the frequency with which filters need to be replaced.

Finally, increased public awareness of environmental issues and the problems associated with pollution may encourage further legislation to reduce pollutant levels in cities. For the National Gallery, the proposed pedestrianisation of Trafalgar Square may prove to be a significant factor in reducing pollution in the immediate vicinity of the building.

Acknowledgements

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methyl esters, the gas chromatogram of this sample showed evidence of a component whose mass spectrum consisted of a base peak (the most stable fragment ion) with a molecular mass (Da/z) of 69. Other peaks in the spectrum were at 81 (93% of base peak ion intensity), 137 (42%), 341 (2%) and 410 Da (3%, molecular ion). A base peak with a mass of 69 Da is typical of a number of (generally) open chain isoprene-based components. Overall, the spectrum may be interpreted as that of squalene ($C_{30}H_{50}$), or (all E) 2, 6, 10, 15, 19, 23-hexamethyl-2, 6, 10, 14, 18, 22-tetracosahexaene, which has a molecular mass of 410. Squalene is a characteristic component of skin dust, of which it may constitute some 1–2% by weight. A blank analysis, carried out on the reagents alone, was run immediately prior to the dust sample, as inadvertent handling of syringe needles or deposition of fingerprint grease and dead skin particles on glassware can also give rise to the appearance of squalene. No squalene was detected in the control chromatogram.

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