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# **Guidelines on pollution control in heritage buildings**

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## **Re:Source**

### **The Council for Museums, Archives and Libraries**

University College London

Emcel Filters Ltd

Horniman Museum and Gardens

The Manchester Museum

Museum of London

Victoria & Albert Museum

Department of the Environment, Transport and the Regions  
in association with *Museum Practice*

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## **Foreword**

Bruce Sharpe

Sustainable construction champion, DETR Construction Directorate

The Government expects the construction industry to contribute to the more sustainable development of our society. This means that the industry has to deliver buildings and structures which provide greater satisfaction, well-being and value to clients and users, while at the same time reducing the consumption of carbon-based energy and natural resources. To help, DETR sponsors an extensive research and innovation portfolio, intended to develop new, and exploit existing, knowledge.

This document is an output from one of our recent collaborative projects, *Energy Efficient Pollution Control in Museums and Galleries*, which involved a group of strong and committed partners. The project combined high-quality research, collaboration between designers, building services professionals and end-users, with effective management and a clear output. It is an excellent exemplar of how the three strands of sustainable development – social, economic and environmental – fit together. Using the guidelines in the document will improve indoor air quality, energy efficiency and the use of resources within buildings devoted to our cultural heritage. And they will enhance quality of life generally because they demonstrate that a sustainable balance between access and preservation can be achieved.

Furthermore, this research is capable of wider exploitation. It tells us more about the deposition of pollutants and the impact of ventilation rates on indoor air quality. There is plenty here to interest the wider construction and building management communities. I commend it to you.

## **Preface**

May Cassar,

Project Manager for 'Energy Efficient Pollution Control in Museums and Galleries'

These guidelines are intended to address the concerns of managers and designers of museums, galleries, libraries and archives over indoor air quality. These concerns are often due to ignorance of the extent to which urban pollution is a problem to collections in buildings. While science is still mapping out the full extent of this problem and its impact on heritage materials, this publication based on sound scientific building research is a pragmatic decision-making guide to dealing with pollution in buildings now. The information is presented in different forms: in boxes and tables, and as text, graphs and illustrations. This should enable a range of readers to tackle issues of varying complexity. Pollution as any other environmental problem is a shared responsibility. The research, carried out by a team of university researchers, industry and end-users, has produced a publication that will be of use to building designers, building services engineers and heritage managers. If you find these guidelines useful, please let others – and us – know about it. You will find contact details on the back cover. The wider this information is disseminated, the greater will be its benefit.

## **SCOPE**

These guidelines are written from a UK perspective, but are applicable to other countries with a temperate climate and similar pollution problems. Sections 1-5 of the guidelines provide background information from the scientific and conservation literature. Sections 6-8 are based on the above project results, with the emphasis on control of pollutants with outdoor sources. Some background information is provided on control of pollutants generated in showcases and enclosures, but the reader is advised to consult other publications in this area, beginning with those listed in Sections 9 and 10.

## **1. INTRODUCTION**

Air pollution can attack heritage materials. Museums, galleries, libraries and archives are all at risk. Deterioration is usually slow and progressive: prolonged exposure can cause severe damage to a wide range of objects.

Different materials are susceptible to different pollutants, so organisations will face their own set of pollution-related issues. These guidelines are intended to help:

- Museums, galleries, archives and libraries in making a rational assessment of the risks of pollution damage to their collections.
- Architects, building services engineers and others designing and installing pollution control measures.

The guidelines are not prescriptive. Instead they propose a step by step method to define problems and to develop and achieve appropriate solutions. It has three main stages:

- STAGE 1      Consider the types of heritage materials, and the pollutants . See Section 4.  
STAGE 2      Assess the pollution characteristics of the microenvironment of objects, the individual room or gallery; the building as a whole; and finally the external environment. See Section 5.  
STAGE 3      Determine the action required. See Section 6.

If hazards are identified, you may need to test for certain pollutants and to measure their concentrations. To determine the risk and to reach an appropriate solution you will need to compare pollution levels with published standards and damage threshold levels, where these are available. However, the current state of knowledge on acceptable levels is incomplete.

The main focus of this document is on the control of gaseous pollutants in typical UK buildings. Other issues are only touched upon as they are covered in detail elsewhere (see Sections 9 and 10). These include:

- Ventilation for human health and comfort.
- The control of particles.
- Location of air inlets.
- Detailed design of ventilation systems.
- Choice of filter materials.

## **2. WHICH ARE THE DAMAGING POLLUTANTS AND WHERE DO THEY COME FROM?**

Indoor pollutants have two principal origins:

- Outdoor pollutants, which are brought into the building by ventilation.
- Pollutants generated within the building, and needing removal, usually by ventilation, though chemical absorption is also possible.

Sources of indoor pollution include human and animal metabolism, combustion, cooking, introduced materials and chemicals, and not least outgassing from the buildings materials and contents, including items in the collection and their display and storage cases.

Table 1 lists damaging pollutants which are commonly found in museum, gallery, library and archive buildings.

Table 1. Air pollutants and their effect on materials. *This information is based on reviews published by Brimblecombe [1] and Baer and Banks [2].*

Species	Effects	Sources of indoor pollution
<b>Sulphur dioxide (SO<sub>2</sub>)</b>	tarnishes metals damages paints and dyes embrittles and discolours papers reduces strength of textiles attacks photographic materials	external environment few indoor sources today, but commonly from coal or oil burning in the past
<b>Nitrogen dioxide (NO<sub>2</sub>)</b>	induces fading in textile dyes reduces strength of textiles damages photographic film	external environment gas heating and cooking appliances decomposition of cellulose nitrate
<b>Ozone (O<sub>3</sub>)</b>	cracks rubber induces fading in dyes attacks photographic materials damages books	external environment photocopiers, laserprinters electrostatic particle filters insect electrocutors
<b>Hydrogen sulphide (H<sub>2</sub>S)</b>	tarnishes metals, especially silver	external environment human bioeffluents construction and decorative materials wool and textiles vulcanised rubber organic materials from waterlogged archaeological sites
<b>Carbonyl sulphide (OCS or sometimes written COS)</b>	tarnishes metals, especially silver	external environment, biochemical and geochemical processes in the oceans generally no indoor sources
<b>Formic acid (HCOOH)</b>	corrodes certain metals, especially lead, zinc, copper alloys (mostly those with high lead content) attacks calcareous materials, e.g. seashells attacks mineralogical specimens	drying paint, oxidation of formaldehyde some woods (but lower emissions than acetic acid)
<b>Acetic acid (CH<sub>3</sub>COOH)</b>	corrodes certain metals, especially lead, zinc, copper alloys (mostly those with high lead content) attacks calcareous materials, e.g. seashells attacks mineralogical specimens may attack paper, pigments and textiles	wood & wood products, adhesives and sealants, decomposition of cellulose acetate film
<b>Formaldehyde (HCHO)</b>	May be oxidised to formic acid	Wood particleboard products, resins, some thermosetting plastics.
<b>Particles</b>	soiling, discoloration deposition of reactive species such as acidic particles and alkaline particles	external environment, motor traffic people, abrasion, pollens, combustion, candles, biodeterioration, plaster surfaces, insects, carpets salt spray in marine environments and from road salt

### *Pollutants mainly from outdoors*

Nitrogen dioxide, sulphur dioxide, ozone, hydrogen sulphide and carbonyl sulphide are the main damage-causing gases present outdoors. They come mainly from fuel burning in transport, buildings and industry. The sulphides are also generated by biological processes, principally in the oceans and through the decay of organic matter. Much of the nitrogen dioxide and ozone is not formed directly, but in secondary reactions involving the action of sunlight on pollutants emitted largely from motor vehicles.

Some of these pollutants also have indoor sources: nitrogen dioxide from gas stoves, and hydrogen sulphide as a bioeffluent from people and from some interior decorative materials and museum objects themselves, e.g. zoological specimens and organic archaeological material, especially from waterlogged sites. Ozone can also be given off by photocopiers and laserprinters, particularly older models.

Outdoor pollution also includes small particles: dust and aerosols, which can remain suspended in the air for long periods. The most damaging tend to be small, black, sticky, acid particles from the incomplete combustion of oil, particularly in diesel engines.

### *Pollutants mainly generated indoors*

The organic compounds acetic acid, formic acid and formaldehyde tend to be the most common and damaging, causing corrosion of metals and calcareous materials, and sometimes attacking pigments, paper and textiles. These are often referred to as *carbonyl compounds* because their molecules all contain the carbonyl C=O bond structure and have similar types of reaction with objects. (Carbonyl sulphide is *not* usually grouped with these compounds, and is considered a *sulphide* in terms of its reaction with objects, e.g. tarnish of silver).

- Acetic acid is given off by wood, wood products and certain adhesives and sealants.
- Formic acid is emitted from some woods and when oil-based paint dries.
- Formaldehyde is emitted chiefly from glues and binders in particleboard and composite materials.

All these materials are frequently used in the construction and fitting out of museums, galleries, archives and libraries. Usually but not always, galleries and storerooms have sufficient ventilation to keep carbonyl concentrations at low levels in the rooms themselves. The big problems tend to arise in closed storage containers and display cases, where carbonyls from their construction materials, finishes, adhesives or contents can build up in concentration.

### *Know Your Enemy*

Before choosing a pollution control strategy one must assess the pollutants likely to affect items in the collection, where they will come from, and how they can be controlled. For instance, full air conditioning with carbon filtration will produce clean gallery air but will do nothing to help the lead object corroding in acetic acid vapour from its wooden showcase.

### *Know What is Not Your Enemy*



All the pollutants mentioned above have damaged objects in some way. Many other air pollutants, e.g. carbon dioxide, carbon monoxide, chlorofluorocarbons (CFCs) and volatile organic compounds (VOCs) have a high media profile because of their effect on health or on the environment, but do not normally damage heritage materials.

*How do you reduce pollutant levels?*

The main methods are outlined below. Details are discussed in later sections.

For pollutants brought in from outdoors:

- Many surfaces in a building themselves adsorb pollutants. This often
- makes indoor concentrations of outdoor pollutants significantly lower than
- those outside, particularly in naturally-ventilated buildings.
- Reduce natural and mechanical ventilation rates (but not below the
- appropriate levels for health, safety and comfort),
- Incorporate filters in the air handling plant that can absorb designated
- pollutants.

Note that many filters used are not good at trapping the very small dust particles which can stick to surfaces.

For pollutants generated indoors:

- Carefully specify building materials, furnishings and finishes for minimum emissions.
- Extract air from polluting activities (e.g. cookers, copiers, laboratories) at source.
- Add chemically adsorbent materials, normally in recirculatory air cleaners, but also in surface finishes.
- Increase ventilation rates (but levels of outdoor pollutants may then increase).
- Control ventilation rates in accordance with monitored pollutant concentrations.

**BOX 1. QUANTIFYING POLLUTANT LEVELS**

The concentration units used for air pollution are either the part per billion (ppb) or the microgram per cubic metre ( $\mu\text{g}/\text{m}^3$ ). They have different meanings, but are often used interchangeably and can readily be converted from one to another.

The **part per billion** is a measure of the volume fraction of pollutant gas in air, i.e. what proportion of a given air volume is made up of pollutant gas. This fraction is directly proportional to the number of pollutant molecules present in the air. Thus 1 ppb means that 1 pollutant gas molecule is present for every billion (1 000 000 000) air molecules. This may seem like a tiny fraction, but it should be remembered that 1  $\text{m}^3$  of air contains over  $10^{25}$  molecules, so 1 ppb means that over  $10^{16}$  pollutant molecules are present. The part per million (ppm) and part per trillion (ppt) are used to express pollutant concentration on a similar basis.

One ppm is 1 part in 1 000 000 and 1 ppt is 1 part in 1 000 000 000 000.

1 ppm = 1000 ppb  
1 ppb = 1000 ppt

The **microgram per cubic metre ( $\mu\text{g}/\text{m}^3$ )** expresses pollutant concentration as mass per unit volume rather than as a volume fraction. This is most appropriate for particulate

pollution but is also commonly used for gaseous pollution. Because pollutants have different molecular masses a concentration in  $\mu\text{g}/\text{m}^3$  does not represent the same number of molecules for every gas.

1 000 000 micrograms = 1 gram

The **conversion factors** between the two systems are temperature- and pressure-dependent. Under normal ambient conditions (20°C and 1 atmosphere pressure) the following factors should be used:

	ppb	$\mu\text{g}/\text{m}^3$
Sulphur dioxide	1	2.6
Nitrogen dioxide	1	1.9
Ozone	1	2.0
Hydrogen sulphide	1	1.4
Carbonyl sulphide	1	2.5
Formic acid	1	1.9
Acetic acid	1	2.5
Formaldehyde	1	1.2

So, to convert from ppb to  $\mu\text{g}/\text{m}^3$  for example for nitrogen dioxide, multiply by 1.9; to convert from  $\mu\text{g}/\text{m}^3$  to ppb divide by 1.9.

**PM<sub>10</sub>** is a measure of particles less than 10  $\mu\text{m}$  in diameter (1 000 000 micrometres ( $\mu\text{m}$ ) = 1 m), which are the particles most likely to affect health. Particles both smaller and larger than 10  $\mu\text{m}$  will be important for soiling of museum objects, so this measure is not the most relevant for conservation but may be useful when making comparisons with data collected in the health field.

The **detection limit (DL)** is the lowest concentration of a compound that can be detected using a particular analytical method. When a measurement of a compound is made and nothing is found, it is more precise to say that the compound was 'below detection limit' (<DL), meaning that it may be present at a lower level than the detection limit, but the analytical technique used was not sensitive enough to find it.

For a more detailed discussion of units see Reference [3].

## BOX 2. HOW MUCH DAMAGE IS POLLUTION CAUSING?

In conservation science it is generally well understood which pollutants are most damaging to which materials, and which pollutants appear to be harmless. Less well understood is the concentrations at which pollutants start to cause damage.

Pollutant damage is analogous to light damage in that it broadly follows the **reciprocity principle** where the damage caused depends on the amount of pollution to which an object has been exposed, or the 'dose'.

**Dose** is defined as the pollutant concentration multiplied by time. Thus a concentration of 10 ppb for 10 years is the same dose as 1 ppb for 100 years. The units of dose are those of concentration multiplied by time. No standard unit has yet been established, but the most commonly used units are the **ppb.year**, often written ppb.yr.

Much of the damage we see now may be historic: UK urban environments in the 19th and much of the 20th century were much more polluted with coal smoke and sulphur dioxide than now. For example, a recent study of leather book bindings placed in the British Library in 1930 estimated that they had received 90% of their pollutant dose prior to 1971 and only 10% subsequently [4]. This estimate could be made because reliable measurements of sulphur dioxide – the main damage agent in this case - in London are available from the 1930s, when concentrations were very much higher than now.

This example illustrates one way in which concentration limits or **threshold values** can be deduced from damage that has already occurred and past pollution exposure. In many cases this information is lacking, making it difficult to relate the damage we see to the current concentration levels.

*By **threshold value**, we mean a pollutant dose or concentration above which measurable object damage will eventually occur and below which the object should be reasonably safe.* In practice, pollutants will react with objects at concentrations far lower than those normally found in the atmosphere, so to specify threshold values at the point at which reaction begins would be so low as to be unachievable. Instead by setting pollution exposure limits that are realistic and achievable we are in effect specifying an acceptable rate of damage for the object: for instance, that damage does not become visible for at least 100 years exposure.

Factors such as relative humidity can affect pollution damage: for instance, most reactions with pollutants are much faster at higher humidities, leading to greater damage. This is called a **synergistic effect**, where the combined effect of two (or more) factors is greater than the sum of their effects on their own.

In addition, it may be hard to separate pollution-related damage from that caused by other environmental factors, e.g. light, humidity and biodeterioration. For instance, textile dyes are decolourised by nitrogen dioxide, but for a historic object it may be hard to separate this effect from fading due to light exposure.

Another way to determine pollution damage is to expose materials to artificially high pollutant concentrations in a test chamber and to measure the damage that results. Using the reciprocity principle (equal dose causes equal damage) this can be extrapolated to normal atmospheric concentrations and an exposure limit recommended.

In fact only a few pollution limits have been derived using the above methods. Most published values are based on what is technologically achievable - for example using carbon filtration in an air conditioning system - or on a subjective assessment of empirical observations. Table 2 lists the pollutant levels commonly found inside and outside heritage buildings in the UK, together with some of the recommended exposure values that have been published in recent years. The *exposure value* is not necessarily the *threshold value* as it may be tempered (upwards or downwards) by what normally occurs or what is practically possible in normal circumstances. Future research will improve levels of understanding, but in the meantime we should use these values with caution and prudence.

*Guidelines on efficient pollution control in heritage buildings*

Table 2. Pollutant levels likely to occur outside and inside heritage buildings in the UK and Recommended Exposure Values for various materials and museum, gallery, library and archive interiors. For most of the gases, there is considerable variation in the exposure values recommended by different sources. This reflects the fact that detailed knowledge in this area is lacking, and a consensus has yet to be reached.

Species (sources)	Typical pollutant level in various environments (month-long average data)			Recommended Exposure Values		
	UK Urban Environment [5]	Building Interior [6], [1], [2]	Enclosure [7],[8] (measured in showcases and cupboards)	Item	Recommendation	Basis
Sulphur dioxide (outdoor)	3-20 ppb	< 1 ppb (with chemical filtration) 0-15 ppb otherwise	negligible	Paper-based records	0 ppb	British Museum Libraries [9]
				Leather book bindings	< 0.1 ppb	Larsen et al [4] Epidemiological study
				Paper-based records	< 0.4 ppb	US National Bureau of Standards [9]
				General museum interiors	< 4 ppb	G Thomson 'The Museum Environment' [10] Best available technology
Nitrogen dioxide (mainly outdoor)	10-40 ppb	< 1 ppb (with chemical filtration) 1-20 ppb otherwise	negligible	Paper-based records	0 ppb	British Museum Libraries [9]
				Paper-based records	< 2.5 ppb	US National Bureau of Standards [9]
				General museum interiors	< 5 ppb	G Thomson 'The Museum Environment' [10] Best available technology

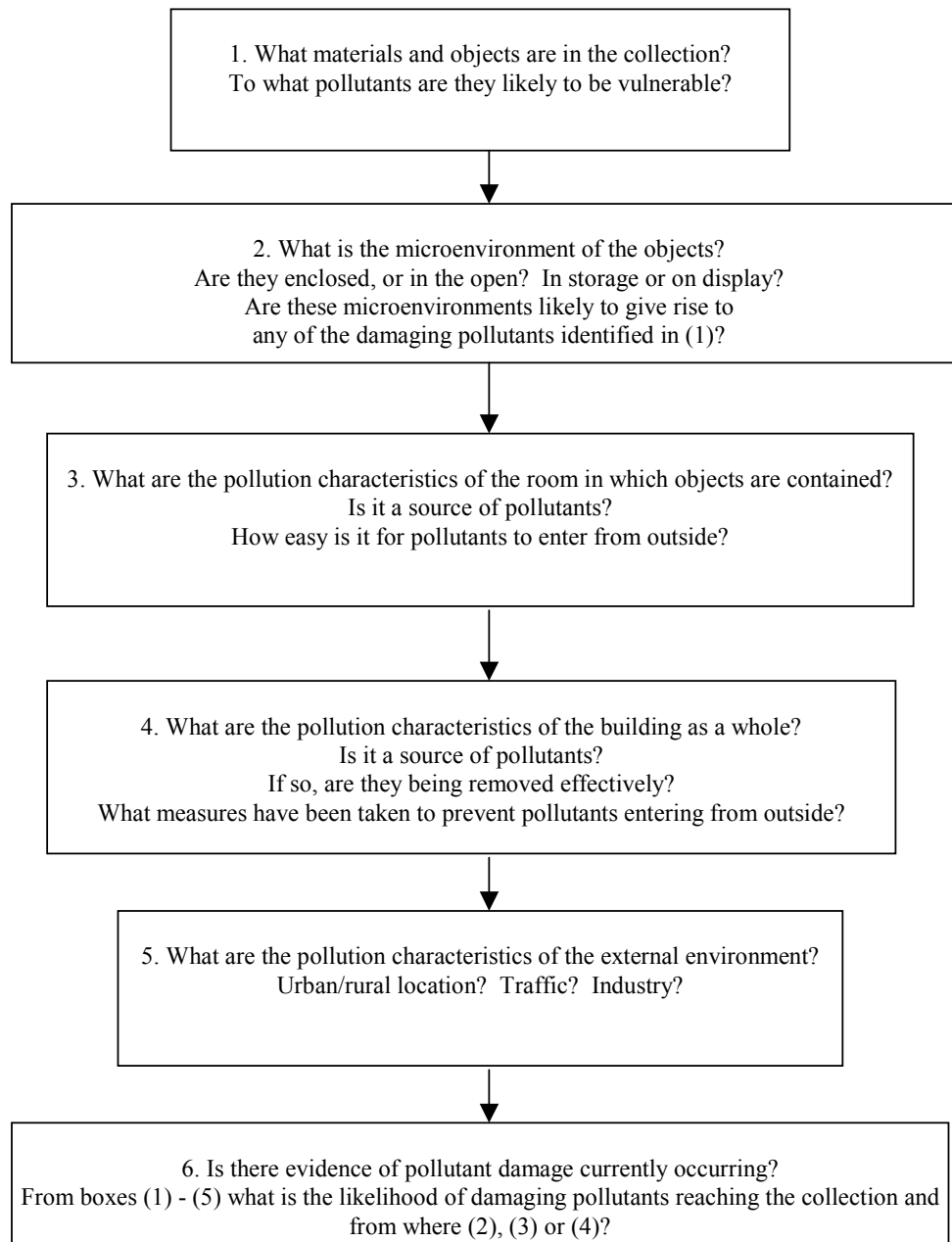
*Guidelines on efficient pollution control in heritage buildings*

Species <i>(sources)</i>	Typical pollutant levels in various environments (month-long average data)			Recommended Exposure Values		
	UK Urban Environment [5]	Building Interior [6], [1], [2]	Enclosure [7],[8] <i>(measured in showcases and cupboards)</i>	Item	Recommendation	Basis
Ozone <i>(mainly outdoor)</i>	5-25 ppb	< 1 ppb (with chemical filtration) 0-10 ppb otherwise	negligible	General museum interiors	0 ppb	G Thomson 'The Museum Environment' [10] Best available technology
				Paper-based records	< 13 ppb	US National Bureau of Standards [9]
Hydrogen sulphide <i>(indoor &amp; outdoor)</i>	100-200 ppt	0-500 ppt; may have indoor sources	0-700 ppt; may have internal sources			NOT CURRENTLY SPECIFIED Measurements of these pollutants have been rare until recent years. Only now is a database of measurements being built up, and research being done to ascertain their threshold values.
Carbonyl sulphide <i>(outdoor)</i>	500 ppt	500 ppt	0-500 ppt			
Formic and Acetic acid <i>(indoor)</i>	negligible	< 30 ppb	100s-10,000s ppb in cases with internal sources			
Formalde- hyde <i>(indoor sources)</i>	negligible	< 30 ppb	100s-1,000s ppb in cases with internal sources			
Airborne Particles (PM <sub>10</sub> ) <i>(indoor &amp; outdoor)</i>	20-30 µg/m <sup>3</sup>	20-100 µg/m <sup>3</sup> (busy entrance hall or gallery) < 10 µg/m <sup>3</sup> (store or archive)	negligible	General museum interiors	< 75 µg/m <sup>3</sup>	US National Bureau of Standards [9]

### **3. A COLLECTIONS-CENTRED METHODOLOGY FOR DEALING WITH POLLUTION ISSUES IN HERITAGE BUILDINGS**

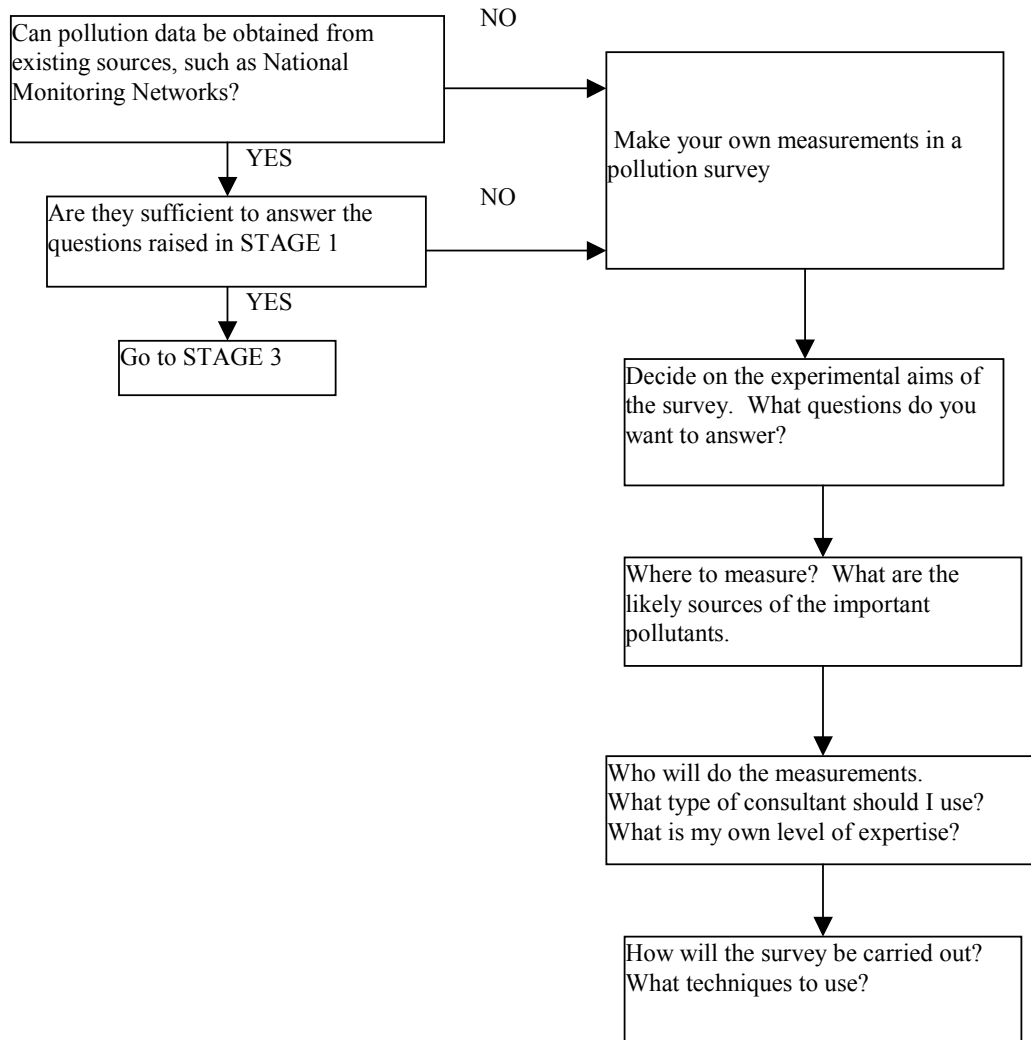
The assessment is in three stages, each of which is in several steps.

STAGE 1 Assess the degree of risk to a collection from pollution. This is outlined in the flowchart below. See Section 4 for full details.



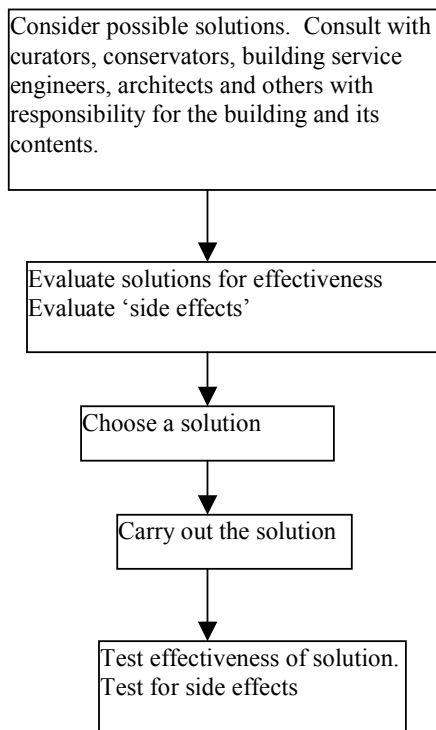
If the answer from STAGE 1 is that pollution damage is occurring, or is likely to occur, then the next stage is:

STAGE 2      Make measurements of the concentrations of the important pollutants, or obtain data from existing sources. See Section 5.



STAGES 1 & 2 have identified whether there is a pollution threat to the collection and the environment(s) in which this occurs. The next step is deciding how to deal with the threat.

STAGE 3 Choose an appropriate solution. See Section 6, which also includes case studies of the application of the method.





## 4. METHODOLOGY STAGE 1: RISK ASSESSMENT

The risk assessment needs to consider:

- the types of object and materials in the collection and the pollutants that might affect them
- whether there is evidence of current damage
- the existing storage or display conditions, e.g. temperature and relative humidity, light levels, particulate and gaseous pollution, biodeterioration;
- the nature of the building in which they are housed; its environmental control systems; and shelving, container, case or cupboard materials; and
- the local outdoor environment and the pollutants likely to be present.

You should start by considering the problem from the collection's point of view, working out from:

- the types of object and the pollution hazards to the materials they contain; to
- the immediate microenvironment of the objects; to
- the environment in the surrounding room; to
- the building as a whole; and lastly to
- the external environment.

This may seem obvious, but museums, galleries, libraries and archives often seem to start at the other end: they embark on measuring pollutant levels in the building without thinking what is most likely to threaten objects in their collection. The outcome may ultimately be the same, but the process can cost a lot more time and money. Consultants may analyse for irrelevant compounds, or look in the wrong places.

*The elements of the risk assessment:*

### 4.1 Step 1. Identify material or object types and the associated pollution hazards

Table 3 will help you to identify which materials in your collection are potentially at risk, the damage which may occur, and the pollutants which are often involved. For the likely sources of these pollutants, see Table 1.

Table 3. Indoor air pollution damage to materials, from Baer and Banks [2]. Note that the types of damage here listed can also be caused or made worse by other environmental factors such as light, and high temperature and relative humidity.

<b>Material</b>	<b>Type of Impact</b>	<b>Main air pollutants</b>
<b>Metals</b>	Corrosion, tarnishing	Sulphur dioxide, hydrogen sulphide, carbonyl sulphide, formic acid, acetic acid and formaldehyde
<b>Paintings and organic coatings</b>	Discolouration, soiling	Sulphur dioxide, hydrogen sulphide, alkaline dust particles
<b>Paper</b>	Embrittlement, discolouration	Sulphur dioxide
<b>Photographic materials</b>	microblemishes, 'sulphiding'	sulphur dioxide and hydrogen sulphide

<b>Textiles</b>	Reduce tensile strength, soiling	Sulphur dioxide and nitrogen oxides
<b>Textile dyes</b>	Fading, colour change	Ozone, nitrogen oxides
<b>Leather</b>	Weakening, powdered surface	Sulphur dioxide
<b>Rubber</b>	Cracking	Ozone

#### **4.2 Step 2. Review pollution characteristics of the microenvironment**

The microenvironment is the immediate environment around the object, created by a showcase, cupboard, cardboard box or plastic bag; or in the room for objects on open display or storage.

##### *Wooden display cases, drawers and cupboards*

Overall a case – even a leaky one – will reduce damage by pollutants from outside:

- Entry of pollutants from the room will be restricted by the low rate of air exchange.
- Some of the pollutants that do get in will be removed by surface reaction around the door seals and onto display materials.
- Inevitably, some pollutants will reach the objects themselves, but in much smaller quantities than if there were no case at all.

On the other hand, case materials and finishes, such as wood and wood products, papers, fabrics, hessian, paint and sealants, generate their own pollutants. Carbonyl compounds are the main offenders:

- Acetic acid is emitted from all woods, but the amount varies with type and age. Commonly used woods, oak, beech, birch and Douglas fir are particularly high in free acetic acid. Even old wood (over 100 years) can still generate considerable amounts of acetic acid.
- New or recently applied paint may emit formic acid, which is corrosive and is also found in composite wood products and in some timbers (e.g. oak).
- If composite wood products such as particleboard, medium density fibreboard (MDF), plywood and hardboard are present, then formaldehyde is also emitted.

In addition, MDF, textiles, rubbers and composites may also give off sulphide gases.

In the enclosed environment of a drawer or display case, these pollutants can build up to high and very damaging concentrations, typically several hundred to several thousand ppb for carbonyl compounds and several hundred ppt for hydrogen sulphide.

Formaldehyde, formic and acetic acid have their own characteristic smells, as in new oak furniture and in ‘vinegar syndrome’, when acetic acid produced by decaying acetate film is sufficiently concentrated to smell of vinegar. However, no smell does not mean no risk: these pollutants cause object damage at concentrations well below their odour thresholds.

Many display cases also have a characteristic chemical odour, especially when new. This is usually due to volatile organic compounds with low odour thresholds, such as alcohols,

esters, ketones and aromatics, used in the manufacture and finishing of the case. These compounds do not react with most objects, so smell does not necessarily indicate a pollution problem.

### ***Metal and glass cases***

Metal and glass do not emit pollutants, and cases of these materials are usually, but not always, designed to seal tightly, keeping out external pollution. However, the metal and glass surfaces will be less able to adsorb the external pollution that does get in.

While metal and glass cases are themselves inert, they may contain polluting materials, e.g. back and baseboards of wood or MDF, display and backing materials, sealants used for glass-glass and glass-metal joins, and museum objects. In a well-sealed case, this may lead to high concentrations of carbonyl and sulphide compounds, similar to those in wooden cases.

### ***Plastic bags and boxes***

Thermoplastic bags and boxes - if well sealed - can work well in excluding external pollutants. They may emit some organic compounds, but these are seldom harmful as they do not normally include the organic acids or formaldehyde (but PVC may contain free hydrochloric acid). However, reference [11] describes how a plastic box used to store wood adsorbed acetic acid vapours, and caused corrosion when it was re-used to store lead objects. Hence boxes and bags used to store vulnerable metals, shells etc. should either be new or have previously only contained inert materials. Take care also if putting composite items (e.g. wood and metal) in such sealed containers, emissions from one component will not be able to disperse and may damage another.

### ***Cardboard storage boxes***

Cardboard is a good absorber of external air pollutants, but a cardboard box is not air tight. Cardboard may also be acidic and emit organic acid vapours. Ensure that acid-free archival quality boxes are specified for vulnerable materials.

## **4.3 Step 3. Review pollution characteristics of rooms and galleries**

The design of a building and the materials used in construction and finishing can greatly affect the indoor concentrations of both externally and internally generated pollutants.

- Materials and finishes can add pollutants, outgassing in the same way materials in enclosed cases, see Section 4.2. The consequences are usually less severe, because:
  - rooms have a much higher air volume in relation to their enclosing surfaced area than a cabinet or drawer,
  - air change rates are also much higher, even in most well-sealed rooms.However problems have been known, for example, in buildings which contain a lot of oak or plywood, for example in flooring, panelling and structural elements.
- Interior surfaces can also remove pollutants. Chemicals that damage objects are by definition reactive, so they also react with interior surfaces. This “pollutant removal by surface deposition” is an important mechanism by which the indoor concentrations of outdoor pollutants can be reduced without recourse to air conditioning and carbon filtration; and has been found to be effective in many naturally-ventilated buildings.

## HOW MUCH CAN SURFACE DEPOSITION REDUCE POLLUTANT LEVELS?

This depends on:

- The ventilation rate – the lower the rate the less mass of pollutants will be brought in and the more chance they will have to be adsorbed.
- The chemistry of the gases. Pollutant-surface reactivity generally decreases in the order: ozone, sulphur dioxide, nitrogen dioxide, hydrogen sulphide, carbonyls.
- The nature of the surfaces. In general:
  - Metal and glass are relatively unreactive.
  - Plaster, porous brick, tile, wood and carpet are more reactive and more effective at removing pollutants such as nitrogen dioxide, sulphur dioxide and ozone.
  - Paints tend to be in the middle of the scale, with porous and alkaline paints more reactive, and impermeable and gloss paints less reactive.
- The surface area. The larger this is in relation to the volume of the room, the more the chance that the pollutant will be adsorbed.

Pollutant entering a room will deposit onto all available surfaces, so the amount that reaches object surfaces can be reduced by ensuring that room surfaces are large in area and made of reactive materials, such as concrete, brick, stone, plaster and wood, preferably with no or porous surface finishes. The process of deposition may cause some deterioration of these ‘sacrificial’ surfaces. However, this has been going on since air pollution first became a problem and seldom has gaseous pollution damage been identified to wall and flooring materials in normal use and with normal cleaning and maintenance cycles. On the other hand, culturally significant surfaces of buildings which need to remain untouched are just as susceptible to pollution hazards as movable heritage.

### **BOX 3. SURFACE DEPOSITION - POLLUTANT REMOVAL BY THE BUILDING FABRIC**

For highly reactive pollutants such as sulphur dioxide, ozone and to a lesser extent nitrogen dioxide, the concentration in a building is normally lower than outside, even when no filtration is installed. Similarly, concentrations of these pollutants inside cases and cupboards are lower than those in the rooms themselves. This is because when these pollutants come into contact with surfaces such as floors, walls and ceilings they react and are converted into inert forms.

How effective this process is at removing pollutants from the air can be modelled in a mathematical mass balance equation:

$$I/O = \text{ach} / (V_{\text{dep}} (S/V) + \text{ach}) \quad [12]$$

where I = indoor concentration

O = outdoor concentration

ach = air exchange rate ( $\text{hr}^{-1}$ )

$V_{\text{dep}}$  = deposition velocity of the pollutant gas ( $\text{m hr}^{-1}$ )

S = surface area of interior ( $\text{m}^2$ )

V = interior volume ( $\text{m}^3$ )

Thus an I/O ratio of 1 means that the concentration inside is the same as outside and a value of 0.2 means that the indoor concentration was 20% of the outdoor.

From the equation the three factors that determine the indoor/outdoor pollutant ratio in a naturally ventilated room or building are:

(i) Air exchange rate. This typically varies between 0.1 air changes per hour (written as ac/h or ach) in tightly-sealed rooms and 10 ach in very crowded public areas; or with windows wide open in summer. Average ventilation rates in houses with the windows closed tend to be between 0.5 and 1 ach.

(ii) Deposition velocity ( $V_{dep}$ ), which is a property of the pollutant gas and its interaction with surface materials in a room, i.e. how readily they will react with the pollutant.  $V_{dep}$  has units of  $m\ hr^{-1}$ . The table below shows some typical values.

(iii) Surface area to volume ratio (S/V), which depends on the room dimensions and layout. For a small store room such as those at the Horniman Museum Study Collections Centre (case study 1) values between 1 and 10 are typical, whereas large open plan galleries such as those at the V&A and Manchester Museum may have values much less than 1. The added surface area due to room furnishings may also be significant.

Thus, pollutant removal by deposition can be enhanced by reducing air exchange rate, using materials with a high deposition velocity, or increasing the surface/volume ratio, by introducing extra surface into a room for example by adding screens or profiled surface finishes.

Deposition velocities vary considerably depending on the gas and surface materials: for instance, from the table below wallpaper removes sulphur dioxide over a hundred times faster than plate glass adsorbs ozone.

Species	$V_{dep}$ ( $m\ hr^{-1}$ )	Notes
Sulphur dioxide	57.6–90.0	on various cements [13]
	25.2	on activated carbon [14]
	6.1–14.8	on various wall papers [15]
	4.7	on emulsion paint [16]
	1.2	on gloss paint [16]
	1.8	typical interior value [17]
Ozone	0.02–0.04	on plate glass or aluminium [18]
	1.3	estimated average value for interior [12]
Nitrogen dioxide	0.01–4.3	on various indoor surface materials [19]

Figure 0, based on the above equation developed by Weschler et al [12] and data from the case study museums, predicts the behaviour of nitrogen dioxide in naturally ventilated museums of different size and interior layout. It can be clearly seen that smaller rooms, with reactive surfaces such as brick and plasterboard are better at removing pollutants than large rooms with unreactive metal and glass surfaces, such as are found in some museums of modern design. Note that the low levels of ventilation required to achieve good pollutant control may not be adequate for some habitable rooms: where higher ventilation rates are required active filtration may be necessary.

*Occasionally you may need to measure air exchange rates. Techniques are outlined in Box 4.*

The air exchange or 'fresh air' ventilation rate is an important parameter in determining the pollution concentration within a building. Three factors determine the air exchange rate of a building:

1. **Air Infiltration.** This is uncontrolled leakage of air through cracks and small openings (e.g. for services such as water, gas and electricity) in the building fabric.
2. **Controlled natural ventilation,** by opening windows and doors and stacks.
3. **Mechanical ventilation,** through the use of fans to blow air into and around a building. The air exchange between inside and outside (i.e. the 'fresh air exchange rate') may only be a small proportion of the air being circulated around the building.

#### **BOX 4. MEASURING AIR EXCHANGE RATES**

Often you will not need to measure air exchange rates to come up with a pollution control strategy. However, sometimes there will be concerns that there is not enough ventilation. Conversely, the fabric of many buildings – both new and old – can be leaky and let in too much outside air – typically at joints between construction materials, around the outsides as well as the insides of window and door frames, and through cracks, holes and cable, pipe and duct runs. These are not always easily spotted, although the use of smoke pencils can be very useful.

There are two main methods of measuring air exchange rates. Both are usually undertaken by specialists.

- **TRACER GAS METHODS**

These can determine the air exchange in both naturally and mechanically ventilated buildings.

**1. Passive method.** Two sets of tubes are put in the space and opened – one set (the emitters) give out a small quantity of a chemical, usually an inert perfluorocarbon, the others (diffusion samplers) absorb it. A few weeks later, the absorber tubes are sealed and sent away for analysis. The amount of chemical absorbed is a function of the volume of the room, the number of emitters, and the average air exchange rate during the exposure period.

**2. Active method.** A gas such as sulphur hexafluoride, is released into the room to be measured and allowed to mix thoroughly with the air. Its concentration is then measured over a period of several hours. How quickly this decays is a function of the air exchange rate

- **THE PRESSURE TEST METHOD**

This only determines the leakiness of the construction, i.e. the air infiltration, and as such is only suitable for naturally ventilated buildings.

The space is pressurised by a fan and the air flow through the fan measured. From the relationship between pressure and air flow volume, the air leakage rate can be deduced. The pressures involved are very, very small: they will not blow windows out or pictures off the wall, as some people fear!

- For individual rooms or domestic-scale buildings, a small unit which can be inserted into a door opening ("a blower door") is used.
- For large buildings, a fan towed by a vehicle which also provides its power is used.

Sometimes, a building's own ventilation plant can be used to provide the pressure, but in practice independent, calibrated equipment normally proves more reliable and cost-effective.

Pressure tests can be combined with small (e.g. smoke pencil) and large-scale smoke tests to determine the air leakage paths.

Note the air exchange rate between inside and outside will vary with time in most buildings. In naturally ventilated buildings door and window opening may increase in summer. Air infiltration will increase during windy episodes or when it is very cold outside. In mechanically ventilated buildings most of the air may be recirculated when they are unoccupied.

For more information on measuring air exchange rates see reference [20].

[Picture 1. Ventilation Measurement at the Manchester Museum...]

#### MAXIMISING THE EFFECTIVENESS OF SURFACE DEPOSITION

To achieve the greatest reductions in the levels of pollutants from outdoors:

- Reduce the rate at which polluted outside air enters the building, for example by improving fabric airtightness, sealing doors and windows, and examining mechanical ventilation rates.
- Have a large surface area. Hence small rooms, or larger ones with many screens or partitions will adsorb more pollutants than those that are open-plan.
- Choose adsorbent surfaces, and do not paint over those which are already absorbent..

In stores and archives occupied by small numbers of people, minimising ventilation rates can be an effective strategy, as is shown by some of the case studies in Section 6.

#### DON'T OVERDO IT!

Although there is often the opportunity to reduce unnecessary ventilation and the associated transfer of outdoor pollutants, there still needs to be adequate ventilation for visitors and staff and to remove internally generated pollutants (see Section 6.4). If ventilation rates become too low, internally generated tarnish-causing gases such as hydrogen sulphide can occasionally become a problem. Other internally generated pollutants such as carbonyls seldom attain damaging concentrations in rooms and galleries, unless totally inappropriate building materials have been used. *If you do reduce room ventilation rates, it is therefore important to check the resultant levels of critical pollutants to be sure that there have been no unintended consequences.*

#### 4.4 Step 4. Review pollution geography within the building

It is important to consider how pollutants are distributed about the whole building, not just the display and store rooms. In particular:

- Are pollutants being generated in public, office and ancillary areas which subsequently migrate into display and storage areas. In particular:
  - **Nitrogen dioxide** emitted by cooking appliances, which should not be located in or near the collections space and preferably be equipped with air extraction to outdoors.
  - **Combustion fumes** from unflued or open-flued heating appliances.
  - **Moisture and other chemicals** emitted by cooking, cleaning and conservation laboratory activities.
  - **Ozone** may also be emitted by photocopiers and laser printers, which also need care in siting and ventilation. The manufacturer's specification may give

information on ozone emission, which is likely to be a greater problem with older equipment.

- Ventilation and air-conditioning systems can be effective at providing filtered air and removing polluted air, but they may also introduce unwanted pollution:
  - **From outside.** This can be exacerbated if air intakes are poorly-located, for example at low level beside a busy road, rather than at higher level at the back of a building; or just from windows being opened or air infiltrating in the wrong places.
  - **By short-circuiting** or recirculation between mechanical extract outlets, flue terminals etc. and “fresh air” intakes.
  - **By poor maintenance** of plant and their distribution ductwork, for example filter failure, or an accumulation of dust, pollutants and biological activity internally.
  - **By aerosols** generated by humidifiers and spray washers, which can be carried in the airstream and cause their own pollution problems. There are also reported instances of the hygroscopic lithium bromide from desiccant dehumidifiers being carried over and causing corrosion of metals: inert desiccants are preferable.

Check how all the plant is configured and where all intakes and exhausts are located.
- The building’s internal layout can also help to isolate storage and display areas from pollutants. For example, surface deposition in corridors and public areas can significantly reduce outdoor pollutant levels in inner rooms, as discussed in Section 6.

#### **4.5 Step 5. Assess pollution characteristics of external environments**

The main sources of outdoor pollution in urban areas are transport, industry and to a lesser extent buildings.

##### **SULPHUR DIOXIDE**

This comes chiefly from burning fossil fuels - particularly coal - in industry, power stations and for heating. With coal’s decline in the UK, sulphur dioxide levels have fallen dramatically (figure 1 is for central London, data for other UK towns and cities are similar). This is very welcome, as sulphur dioxide has probably caused more damage to cultural property than any other single pollutant. However, it is still important to consider the need to control it, especially if sensitive objects are on open display.

##### **NITROGEN DIOXIDE**

Oxides of nitrogen (NO<sub>x</sub>) originate mainly from motor vehicles, but also from combustion in boilers, cookers and industrial processes. Some nitrogen dioxide is emitted directly, and more is created – particularly on sunny days - when other NO<sub>x</sub>s react with air in the presence of sunlight. A declining trend in NO<sub>x</sub> emissions from UK industry has coincided with increased emissions from road transport. Consequently UK urban background nitrogen dioxide concentrations have been fairly steady over the last 30 years (figure 1 is for central London, data for other UK towns and cities are similar). However, busy urban streets have particularly high concentrations of this pollutant; and this has implications for the location of air intakes in mechanically controlled buildings, and ventilation strategies in older and historic buildings.



## OZONE

Outside, this is principally formed by a reaction involving volatile organic compounds from petroleum fuel and nitrogen dioxide from motor exhausts. These pollutants are chiefly generated in urban areas and react together in the presence of strong sunlight. Since the reaction is quite slow, maximum ozone pollution is often found well away from where the primary pollutants were first emitted, and often in rural locations. In recent decades, urban ozone concentrations have not varied much (figure 2 is for central London, data for other UK towns and cities are similar), but there has been an increase in concentrations in rural sites, particularly those in the south and east of the UK, where hours of sunshine tend to be longest.

## SULPHIDE GASES

Hydrogen sulphide and carbonyl sulphide originate from natural biological and geochemical processes that can take place well away from urban areas, so they tend to be present at very low background concentrations everywhere. In urban areas, hydrogen sulphide is also emitted by motor vehicles with catalytic converters, particularly when new or when cold in the first five minutes or so of a drive. Hydrogen sulphide is also emitted by some industrial and combustion processes.

### **4.6 Step 6. Is damage occurring or likely to occur?**

Evaluation of steps 1 to 5 should enable you to assess where there is the possibility of damage occurring and to what objects. It is important to think specifically about pollution problems and to identify interactions between pollutant and objects that are likely to occur. If there is already evidence of pollution damage in a collection then this usually indicates what is the most pressing priority. An assessment must be made of the degree of risk posed from pollutants overall and this compared with other damage factors such as temperature, relative humidity, light and biodeterioration, so that resources can be allocated sensibly. Reference [21] discusses how this might be done.

## **5 METHODOLOGY STAGE 2: OBTAINING POLLUTION DATA**

For externally-generated pollutants, a considerable amount of data can be obtained from government monitoring networks, so you may not need to make your own measurements. For pollutants with mainly internal sources, you will often have to measure concentrations.

### *Data normally available free of charge*

The UK national monitoring network is run by AEA Harwell on behalf of the Department, Environment, Transport and Regions. Many local authorities also carry out their own monitoring. Although they only measure pollutants which have health effects, these include important ones for heritage materials, especially nitrogen dioxide, sulphur dioxide and ozone.

The UK National Network covers the entire country at intervals of a few kilometres. Data are collected at 15 minute intervals and are freely available through the Internet [5]. Sometimes, these published external levels may themselves furnish enough information to assess the

pollutant risk to a collection. For instance, in areas of low concentrations the risk will be small and the threat of damage from outdoor pollution could be ranked below other environmental factors. However, you must take care to match the proximity and type of monitoring site with that of the museum, archive or library site. For example, nitrogen dioxide concentrations at the kerbside can be much higher than even a few metres away [3], so data from an urban background site may underestimate the pollution directly outside a museum on a busy street.

### *Preparing for a pollution survey*

Where significant risks are identified you may need to investigate further. Measurements can be used to determine the ‘pollution geography’ of the building, and to answer questions like:

- How well does the building fabric exclude externally-generated pollutants?
- Are there any internal sources?
- Is there a gradient of pollution within the building?
- What side of the building is the most/least polluted? This is useful in deciding from where to ventilate the building.

If you decide to carry out a survey of the pollutants in and around a building, you need to plan to ensure that measurements answer the right questions. In doing so, consider the points A, B, C and D below.

#### **A. Define the aims of the survey.**

Starting from a collection’s needs:

- To what pollutants is the collection susceptible?
- Is it on display or in storage?
- In what environments are these likely to occur?
- Are any modifications or improvements to the building being planned or in progress?
- Can the survey be designed to test where modifications would be most effective, e.g.
  - Which galleries may need better environmental control;
  - In a renovation programme, which display cases should we replace first?

#### **B. Choose the sample sites.**

- What information is needed to meet the aims and answer the questions considered in A?
- How many external sites are appropriate?
- What type of sampling do we want? See Box 5 for an outline of the techniques widely used.
- For which gases?

#### **C. Who will do the work?**

Several UK universities (see list at the end of this document) specialise in the study of pollutants in heritage buildings. They will be able to advise on both measurement and data interpretation. Organisations with little expertise in the preventive conservation field will benefit from this level of advice. Alternatively, an organisation with in-house expertise

capable of planning a survey and interpreting the results may require a measurement-only contractor.

*WARNING: some consultants do not specialise in pollution damage to cultural heritage. Those whose expertise is in the health or environment field may not always be able to offer appropriate advice to heritage organisations. Sometimes they may also be unable to monitor down to the low concentrations that are critical for some pollutants in conservation.*

#### **D. How will the survey be carried out?**

The number of sites to be monitored depends on the aims of the survey and the size of the building. Monitoring should be for the pollutants that the previous steps have shown to be the greatest hazards at these locations. In the case of externally generated pollutants this should include at least two, preferably three, external sites on different sides of the building so that the external pollution can be fully characterised. Inside the building, the monitoring sites should include corridors and entrance halls as well as the collections space, to assess the pollution geography. If passive diffusion tubes are used (see Box 5), their measurements are only approximate: it is therefore recommended that they are exposed in duplicate or triplicate at each position and the average taken to obtain the most reliable result.

#### **BOX 5. TECHNIQUES OF POLLUTION MEASUREMENT**

There are two distinct approaches: active and passive sampling.

##### **ACTIVE SAMPLING**

This uses a pump to draw air through a collection or measurement device, which may even give an instantaneous reading. Current equipment that can measure down to the low concentrations of interest to conservation is often bulky, expensive (thousands of pounds at 2000 prices), needs mains electricity and is inconvenient for monitoring simultaneously at many locations inside and outside a building.

Active sampling over a short time period can give a valuable snapshot. In addition, a series of readings can show, for example, daily cycles in pollutant concentrations: this can help identify pollutant sources. However, such spot checks may not reflect long-term exposure conditions. To do this, regular measurements must be taken either manually or automatically, and this can be expensive.

##### **PASSIVE SAMPLING**

Here there is no pump. Instead, air is allowed to diffuse slowly down a small tube or onto a badge. A chemical inside the device, specific to the pollutant of interest, then reacts with it. Subsequent laboratory analysis reveals the amount of pollutant which has reacted over the exposure period, which is typically between a few days and a few weeks.

After analysis, each sampler provides a single value which represents the average concentration to which it was exposed. Peaks and troughs and cycles in concentration that occur over the sampling period are not recorded. The slow, progressive way in which the sampler takes up pollutant mirrors the way objects react with pollutants and therefore gives a more realistic estimate of the long-term exposure of objects to air pollution.

Diffusion samplers are small and unobtrusive, making them easy to deploy in rooms and cases. The cost of individual samplers is low (£4-8 as a contract service at 2000 prices) so monitoring can be carried out fairly cheaply. By deploying many samplers throughout a building at the same time (externally, in various rooms, in some display cases, etc) one can determine the 'pollution geography' of the site.

The advantages of passive sampling have made it the method of first choice for most pollution measurements in heritage buildings. Validated methods are available for most of the gases of interest to museums, galleries, libraries and archives [22-25].

[Picture 2. Instrumental monitoring equipment...]

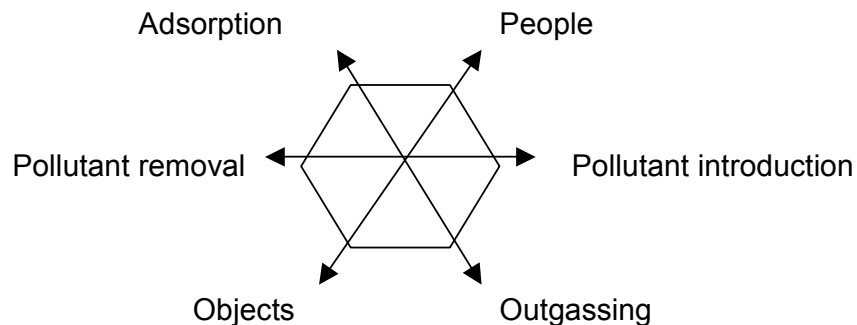
[Picture 3. Diffusion tubes...]

## **6. METHODOLOGY STAGE 3: CHOOSING AN APPROPRIATE SOLUTION**

The results of a survey will inform the decision on what needs to be done to control pollution. It is vital to choose appropriate solutions, which will vary for different locations and objects.

Table 4 summarises the various measures which can be adopted for control of gaseous pollution. The list is not exhaustive, for example it does not specifically include normal good practice items for building professionals (e.g. air extraction at source from polluting activities); or predominantly curatorial activities like the control of pollutants generated inside display cases. This issue is outside the scope of this document and the reader should consult references [8, 26-31] for further information. The measures are presented, in ascending order of the level of control, complexity and expense. In practice, measures are often combined, so we illustrate their application by using case studies of different strategies, again in ascending order of complexity and cost.

When choosing a solution it is important to consult with all those it is likely to affect. This may include curators, conservators, archivists, building service engineers and architects. Arriving at a solution may involve balancing the following factors:



*Guidelines on efficient pollution control in heritage buildings*

Table 4. Summary of pollution control measures, with advantages and disadvantages.

<b>Measure</b>	<b>Advantages</b>	<b>Disadvantages</b>
<b>Reduce air infiltration</b> <ul style="list-style-type: none"> <li>– seal doors and windows</li> <li>– introduce draft lobbies</li> <li>– place objects in enclosures such as display cases and cupboards</li> </ul>	Relatively easy and cheap to seal doors, windows and cracks in the building fabric from outside, and introduce internal doors, which are kept closed. Passive, low maintenance solution. Suitable for air conditioned and naturally ventilated buildings.	Not suitable if the ventilation rate necessary to achieve effective control of outdoor pollutants proves to be less than that required for human occupancy or the dispersal of internally-generated pollution. New internal doors may disrupt movement through the building and may then be propped open.
<b>Appropriate location of air inlets</b> <ul style="list-style-type: none"> <li>– with air conditioning and mechanical ventilation, site inlets away from busy roads, car parks, and loading bays.</li> <li>– in naturally ventilated buildings, try to seal windows/doors on busy roadside against air infiltration</li> </ul>	Low cost, low maintenance solution. Can be applied to both naturally ventilated and air conditioned buildings.	May prevent cross-ventilation in naturally ventilated buildings. With existing air conditioning and mechanical ventilation systems, it may be difficult to modify inlet locations.
<b>Intelligent control of ventilation</b> <ul style="list-style-type: none"> <li>– automatic CO<sub>2</sub> sensor or timer control of ventilation</li> <li>– Occupant control of natural ventilation</li> </ul>	Ventilation kept to minimum necessary for comfortable human occupancy. Can lead to good energy savings.	When human occupancy is high, more pollution is brought in to the building. May be ineffective if installed in a leaky building. Needs effective commissioning, regular checking and calibration.
<b>Increase surface area</b> <ul style="list-style-type: none"> <li>– Store or display in smaller rooms</li> <li>– Change building layout to include more smaller rooms or add screens etc.</li> </ul>	Passive, low maintenance solution.	Change in room plan could be difficult and expensive. Introduction of many small rooms instead of larger open spaces may be inconvenient for display purposes and space use efficiency.
<b>Introduce more absorbent surface finishes</b>	Passive, low maintenance solution. Can be made to work with existing building layout. Brick and plaster commonly used as indoor surfaces. Other wall coverings, such as carbon-impregnated cloth can be introduced relatively cheaply. This approach could be designed in to new buildings.	Materials needed may not fit in with gallery design and 'look'. Changing existing wall surfaces in historic buildings may be difficult or unacceptable.
<b>Portable filtration unit</b>	Highly effective for small spaces such as temporary exhibition galleries, storerooms.	Equipment must be physically present in the gallery or storeroom; check size and noise in operation
<b>Local gallery filtration</b>	Cost-effective way of providing air conditioning and filtration for the most vulnerable objects in a collection. May be easier to install in an older building than a full system. Less capital, maintenance and energy costs than a full system.	Requires objects of same type to be displayed/stored together – may not be best context in which to display them. Conditioned gallery will need to be zoned off from the rest of the building.
<b>Full air conditioning with carbon filtration</b>	If correctly installed and maintained, enables close control of all zones in a building.	Very expensive in terms of capital, maintenance and energy costs.

## **6.1 STRATEGY 1 PASSIVE POLLUTION CONTROL AND NATURAL VENTILATION**

The natural process of deposition onto surfaces (see Section 4.3) can be utilised to reduce pollutant concentrations inside rooms and whole buildings. Under ideal conditions, the resulting levels can be comparable to those with full air conditioning and carbon filtration.

As discussed in section 4.3, the following measures will enhance passive pollution control.

1. Additional surface area can be introduced.
2. The reactivity of existing surfaces could be increased using different decorative finishes. In principle, adsorbent surfaces could also be used to control internally generated pollutants such as carbonyls and hydrogen sulphide. However, these gases are not as reactive as the externally generated pollutants, and would need specific materials to trap them, e.g. activated carbon for carbonyl compounds and zinc oxide, for hydrogen sulphide.
3. There may be scope to reduce the ventilation rate by sealing holes, cracks, windows and doors; and fitting external lobby doors and extra interior doors. The limiting factor with this approach is the provision of sufficient fresh air for the comfort of the building occupants. In storerooms and archives with little or no occupancy, ventilation can be at a very low level, provided moisture and indoor pollution are still controlled. However, this would not be possible in a well-visited gallery during the occupied period.
4. Putting objects in display cases will greatly reduce the amount of outdoor pollution that reaches them, but may increase their exposure to damaging internally generated pollutants, such as the carbonyls.

### **Box 6. Case Study 1: Passive pollution control at the Horniman Museum**

The Horniman's Study Collections Centre is a converted Victorian School in part of South-East London with considerable industrial and traffic pollution. The building has a cellular room layout with many interior doors. The internal surfaces are mostly wood and painted brick and plaster. The store rooms were quite densely packed with objects in cardboard boxes, plastic bags or covered in sheeting. In the study, the outside air ventilation rate was substantially reduced by sealing windows with mastic and fitting lobbies to all exterior doors. This gave it close to optimal characteristics for pollution control by passive deposition: low occupancy, low ventilation rate, high surface:volume ratio, and relatively highly adsorbent surfaces.

Pollution measurements in winter and summer revealed very low nitrogen dioxide concentrations in the storerooms, with sulphur dioxide below the detection limit. The rooms at the core of the building had the lowest pollution concentrations because the air getting into them had followed a tortuous path from the outside, with much opportunity for pollutant deposition. Figure 3 confirms the progressive decrease in nitrogen dioxide concentration, going from the exterior environment to the entrance lobby, interior corridor and storeroom.

Concentrations of nitrogen dioxide, sulphur dioxide and ozone in the storerooms were as low as those achieved in the air conditioned fully-filtered museums, demonstrating the how effective passive measures can be, particularly in stores and archives with small rooms and low ventilation rates.

*NOTE: the ventilation rate in these stores averaged 0.3-0.4 air changes per hour. This is satisfactory for domestic levels of occupancy, but not of course for situations in which there are large numbers of staff or visitors [32].*

[Picture 4. Horniman Museum Study Collections Centre, taken from the roadside]

[Picture 5. Exterior door lobbies]

**Box 7. Case Study 2: Passive pollution control at the Manchester Museum Mummy Store**

The Mummy Store is a ground-floor room in a late 19<sup>th</sup> century university building. The interior surfaces are a mixture of painted brick and plaster, metal and linoleum. Inside the store an recirculatory air conditioning unit maintains close control over temperature and relative humidity; but has no fresh air supply and no pollution filtration, either gaseous or particulate. Natural ventilation was the only way in which outside air could enter the store. In the study, all the windows were sealed up. So was the entrance door, which leads to a corridor and almost immediately to outside. Good pollution control by passive means was evident (see figure 4), with a measured concentration of nitrogen dioxide in winter and summer of about 1 ppb, compared with an outdoor concentration of around 20 ppb. The air exchange rate was 0.2 ach, a very low value achieved only by an excellent level of sealing.

[Picture 6. Manchester Museum]

**BOX 8. POTENTIAL UK SAVINGS POTENTIAL ADOPTING PASSIVE POLLUTION CONTROL MEASURES WHERE APPROPRIATE**

*Energy consumption by UK museums costs about £140 million per year and is responsible for producing about 1.7 million tonnes of CO<sub>2</sub> [33]. 43% of these museums have some mechanical form of environmental control (including air conditioning) and consume, on average, twice as much energy as comparable naturally-ventilated museums. Air conditioning itself accounts for 12% of UK museums' total energy consumption, costing about £17 million per year. Say one-fifth of these museums have air conditioning installed principally to control air pollution, a change to passive methods of control could save £3.4 million in energy costs and cut CO<sub>2</sub> emissions by 41,000 tonnes per year. The savings in libraries and archives are comparable. There is particular scope for savings in new-build or refurbishment projects, in which air conditioning is often specified because it is thought by designers or their clients to be the only means of providing satisfactory protection from air pollution.*

**6.2 STRATEGY 2. PORTABLE OR TEMPORARY FILTRATION UNITS**

Portable filtration can produce as clean an environment as permanently installed equipment, provided the space to be controlled is not too large or too leaky. Such units are useful for temporary exhibitions, for instance to meet the conditions demanded for loan of material. The equipment must be physically present in the gallery or storeroom, although it can be made quite small and quiet in operation. They can also help to 'mop up' pollutants from newly refurbished spaces or newly installed display cases.

**Box 9. Case Study 3: A Portable Filtration Unit at the Horniman Museum, London**

The fumigation room in the Horniman Museum Study Collections Centre has a leaky metal roller-shutter door to enable large objects to be brought in. This room was the most polluted in the building, with significant concentrations of nitrogen dioxide and some sulphur dioxide. A portable recirculatory carbon filter unit, manufactured by Emcel Filters Ltd was installed and the pollution levels monitored over several weeks, with the unit operating at different filtration flow rates. The unit was highly effective at reducing all the main pollutants down to low concentration, or below detection limit (<DL). Figure 5 shows the nitrogen dioxide concentrations in the Storeroom before and after the filter was installed. The vertical axis shows internal concentration compared to average external concentration (I/O ratio).

[Picture 7. Portable filtration unit...]

### **6.3 STRATEGY 3. LOCAL GALLERY FILTRATION**

A cost-effective pollution control solution is to group all vulnerable objects together in one or more galleries with local recirculatory filtration or air conditioning. This has the obvious advantage of requiring smaller plant with lower capital, maintenance and energy costs. This solution is often adopted in older buildings, where it is difficult to install extensive plant and ductwork without causing expensive and unacceptable disruption to the building fabric.

The main disadvantage is the constraint on the display of a collection. Objects of similar material (e.g. tapestries or watercolours) have to be located together, while it may be more meaningful to display them in other contexts. Care should also be taken to ensure that vulnerable objects stored or displayed together do not damage one another, for instance by the spread of insect pests. Close-fitting closed doors to contain pollution-controlled galleries may also interrupt freedom of movement through a building; but if propped open the benefits will be undermined.

#### **Box 10. Case Study 4: Victoria & Albert Museum, London**

Gallery 94 (the Devonshire Hunting Room) is fully air conditioned with filtration for both particles and gaseous pollutants. The plant is mounted on the roof, with only a short run of ductwork to the room below. The gallery is sealed off from the rest of the naturally ventilated museum by pairs of doors at the three entry points.

Pollution measurements in summer and winter (figure 6) showed a similar pattern to the fully air conditioned Museum of London (see case study 6), with sulphur dioxide undetected and nitrogen dioxide at a very low level.

The efficacy of filtration was tested by removing the carbon filters. Nitrogen dioxide then approached the very high outdoor levels; and were slightly above those in the adjacent naturally ventilated gallery, in which a lower air change rate provided more opportunity for pollutant removal by deposition. Sulphur dioxide was also detected: this was not found in the Museum of London, even with the filters removed. This was probably because the short run of duct work here did not provide as much opportunity for removal by deposition as the much longer ducts at the Museum of London.

[Picture 8. V&A Exterior]

[Picture 9. V&A Gallery 94]

#### **Box 11. Case Study 5: Theatre Museum, Covent Garden, London**

The Theatre Museum is air conditioned with four separate systems, each serving different zones. The Picture Gallery zone has particle but not gaseous filtration; the other three zones have both.

Figure 6 shows high nitrogen dioxide concentrations in the unfiltered Picture Gallery, similar to those at the V&A Gallery 94 when the filters were removed. The connecting corridor from the Picture Gallery to the other zones, including the Archive Store had separating glass doors that were normally left open for ease of access. The nitrogen dioxide concentrations measured in the Archive Store were much higher than normal for a filtered zone, due to the entry of unfiltered air via the corridor from the Picture Gallery. Consequently the purpose of having carbon filtration in this, and the other zones was being undermined. This highlights the need, not only to install appropriate control measures but to ensure that they are correctly managed, operated and maintained by staff.



#### **6.4 STRATEGY 4. INTELLIGENT CONTROL OF VENTILATION**

Selecting the appropriate rate of outside air ventilation is a balance between:

- increasing the rate to disperse internally generated pollutants (and heat in naturally ventilated buildings); and
- reducing the rate to prevent introducing too much polluted air into the building.

There is also a need to avoid unnecessary ventilation in order to minimise a building's fuel and maintenance bills.

In most buildings the minimum ventilation rate is set to disperse the odour and moisture generated by the building occupants (CIBSE recommend 8 litres of outside air per second per person [32]). Most heritage buildings have a highly variable occupancy rate and so it is efficient to vary the ventilation rate appropriately.

In naturally ventilated buildings this is often achieved by air infiltration plus manual control of windows and doors. In mechanically ventilated buildings with regular occupancy, a simple time switch may be appropriate, turning the mechanical ventilation on when the building is occupied. In galleries with highly variable occupancy (i.e. only a few visitors during opening hours, but larger numbers such as school parties at unpredictable times) – or where the ventilation needs to recirculate constantly in order to maintain temperature, humidity and air quality conditions - a more sophisticated system using carbon dioxide sensors and variable speed fans may be appropriate. If this approach is adopted, care should be taken to ensure that it does not lead to large fluctuations in temperature and relative humidity. Note, carbon dioxide sensors typically cost about £600 and require regular calibration, so they are most appropriate for the larger systems and spaces.

Humans breathe out carbon dioxide (CO<sub>2</sub>) and are the main source of added CO<sub>2</sub> in most heritage buildings. Therefore, the concentration of CO<sub>2</sub> is a measure of the ventilation rate required per person. At steady state, a concentration of 1000 ppm is equivalent to approximately 8 l/s/person; but in intermittently-occupied buildings of large volumes, peaks and troughs will level out, making it often necessary to supply this amount of air instantaneously. A CO<sub>2</sub> sensor can be used to avoid over-ventilation. In terms of pollution control this means that the amount of outside air - and hence external pollution brought in - can be reduced at times of low occupancy, and taken down to a minimal level when the building is closed. This can result in only one third of the polluted outside air being brought into the building.

#### **6.5 STRATEGY 5. FULL AIR-CONDITIONING WITH CARBON FILTRATION**

This - the most costly method of pollution control - was once thought to be the ideal solution for museum climate control. However, current conservation thinking has moved away from recommending tight control of relative humidity and temperature in rooms - at least for museums and galleries - as conditions can often be kept within acceptable limits by natural ventilation.

**Box 12**

BS5454 *Recommendations for the storage and exhibition of archival documents* [34] specifies tight control of relative humidity and temperature. However, there is evidence that even the requirements of BS5454 can sometimes be met using passive natural ventilation techniques, as at the York Minster Library Archives (refurbished 1998) and the newly built Jersey Archive Store (opened 2000, see Twinn [35] for an explanation of the building design). If acceptable environmental control can be achieved with natural ventilation, then it is possible that pollutants too can be controlled using passive techniques, as outlined above.

With full air conditioning, all display (and possibly some storage areas) are provided with conditioned and filtered air from one or more central plants. Note that most fully air conditioned buildings do *not* have carbon filtration, but are designed primarily to provide comfort cooling. Carbon filtration is a feature of systems designed for specialist applications, of which museums, galleries and archives are one example. Therefore do not assume that because your building has air conditioning it is necessarily carbon filtered.

Full air conditioning is best designed at the same time as the building, and is most common in museums built or refurbished in the last 30 years. Inserting a full system in older buildings can be problematic owing to space requirements for plant and ductwork and the impact it has on a historic fabric. The average energy cost of an air-conditioned museum is twice that of a naturally ventilated one per unit of floor area. Maintenance costs can also be high. Over its lifetime the energy and maintenance costs of an air conditioning system far exceed its capital costs [33].

A typical fully-filtered installation has several banks of filters, to remove both particulate and gaseous pollution. First there are coarse particle filters, then secondary particle filters which remove finer material (and protect any carbon filters from particle clogging). Thirdly, carbon filters to remove gaseous pollution (some older setups may instead use an alkaline wash to clean the air). The carbon is often treated with a metal impregnation, such as copper or manganese to catalyse the chemical breakdown of the trapped pollutants. This prevents the re-emission of trapped gases which could otherwise occur from a saturated filter.

In urban areas, particle filters may need renewing three or four times a year. Carbon filters usually last much longer, typically for four years in urban areas and more elsewhere. Towards the end of their life they become progressively less effective rather than fail suddenly. The cost of replacing carbon filters serving a central plant supplying an entire museum could be £6–10 per m<sup>2</sup> of treated gallery floor area (2000 prices).

The lifetime of carbon filters depends on the amount of pollution they are required to remove. One way of extending filter life is to minimise the fresh air ventilation rate by using a high proportion of recirculated air. This reduces the amount of highly polluted air that is brought in from outside and hence the amount of pollution the filters have to remove, because recirculated air has already been filtered. Recirculating air can also minimise the energy costs of conditioning the air. Of course, sufficient fresh air must be introduced for the comfort of the occupants, but this can be ensured by the use of carbon dioxide sensors (see Section 6.4). For gaseous filtration to be effective it is important to ensure that all the air coming into the building passes through the carbon filters. Air leaks around the filters and infiltration through the building fabric itself will undermine the effectiveness of gaseous filtration. Although infiltration can be partially remedied by positive pressurisation, this can make it difficult to open doors in galleries.

Historically, carbon filters in UK museums were primarily used to remove sulphur dioxide, which until recent times was the most damaging urban pollutant. However, such filters should also be effective against ozone, nitrogen dioxide and hydrogen sulphide, though this last pollutant can come from indoors as well as outdoors, so centralised filtration on the outside air intake will not necessarily provide full protection.

**Box 13. Case Study 6: Museum of London**

The Museum of London is on London Wall, which carries heavy vehicle traffic. Its galleries and one storage area (the costume store) are fully air-conditioned with carbon filtration. All other offices, laboratories and stores are not air-conditioned or chemically-filtered.

The air-conditioning plant in the basement includes a coarse particle prefilter (effective for particles down to 5 µm) and a high efficiency particle arrestance (HEPA) filter for smaller particles, down to below 1 µm. The gaseous pollutant filters consist of 50 mm deep bonded carbon filter panels, effective against sulphur dioxide, nitrogen dioxide and ozone. In this environment the carbon filters last about four years.

Pollution measurements in the winter of 1998/99 and in the summer of 1999, showed a heavily polluted atmosphere outside, but internally sulphur dioxide and ozone were below detection limits. Nitrogen dioxide was very much reduced in concentration (see figure 7).

We asked how much of this reduction was directly attributable to the filtration system, and how much to other factors such as surface deposition. To find out, the carbon filters were removed and the unfiltered gallery atmosphere monitored for a month. Nitrogen dioxide levels were much higher, but sulphur dioxide remained below the detection level (<1ppb). Partly this was because monitored sulphur dioxide levels outside were already less than 3 ppb. In addition, it appears that this reactive pollutant was consumed by surface deposition on the long run of duct work between the central plant and the galleries. Nitrogen dioxide levels were reduced too, but by not as much as the more reactive sulphur dioxide.

[Picture 10. Museum of London Exterior] [Picture 11. Museum of London interior]

## 7. WORKED EXAMPLES OF THE METHODOLOGY

Figures 8 and 9 give two examples of its application to museum-related problems.

Figure 8. Example of assessing the risk of tarnish to silver collection.

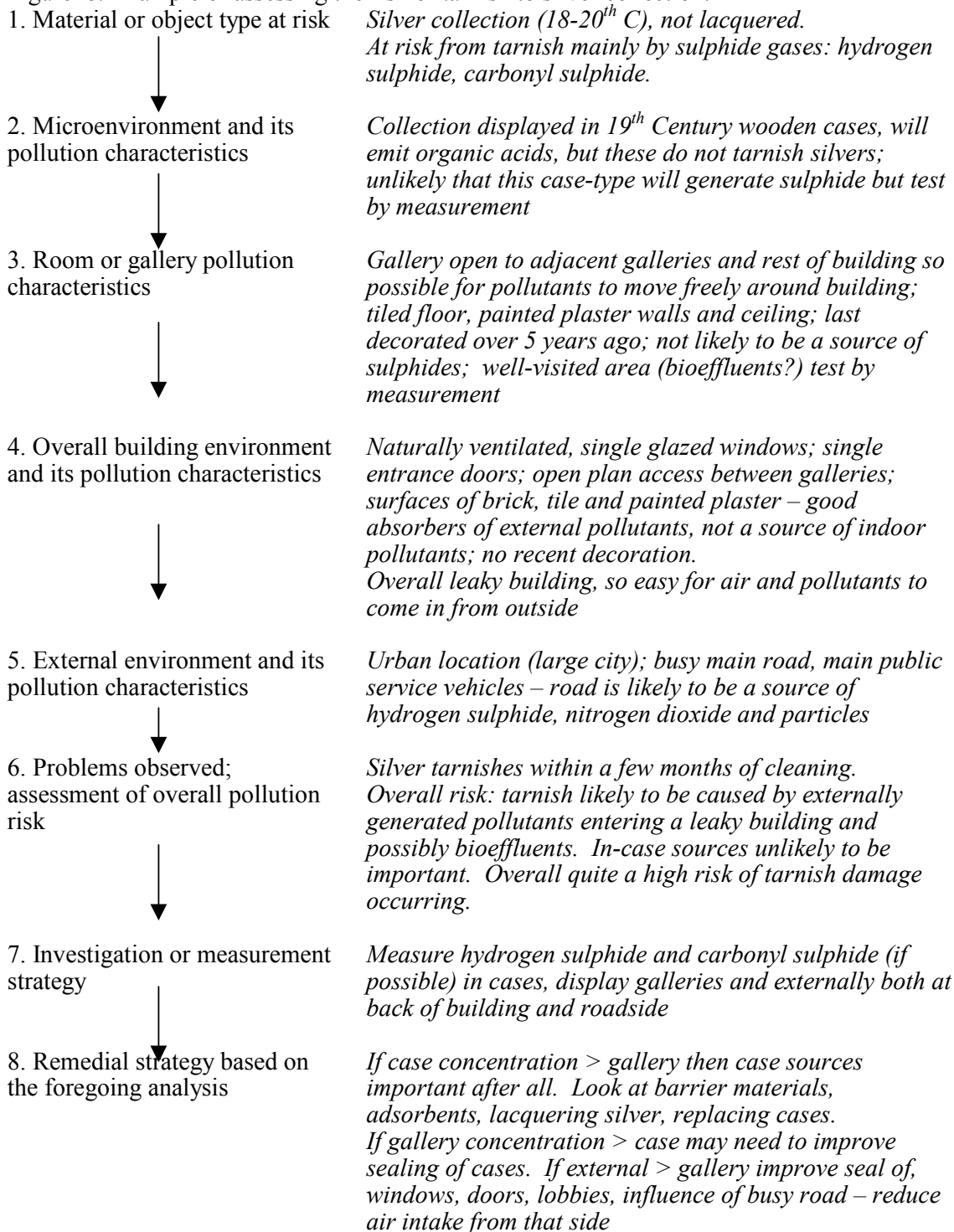
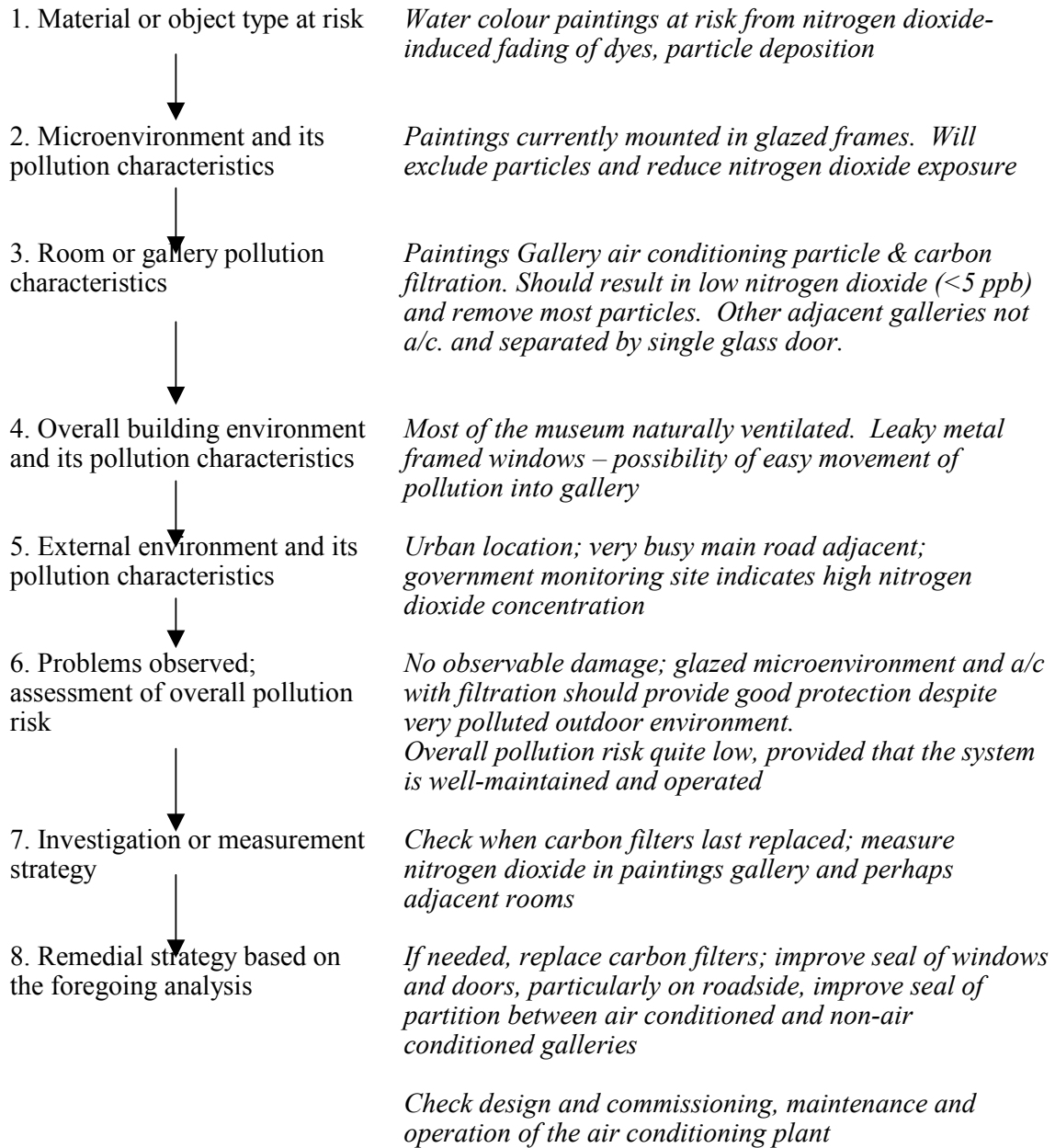


Figure 9. Example of assessing the risk of pollutant fading of watercolour dyes

*Guidelines on efficient pollution control in heritage buildings*



## **8. CHECKLIST**

In summary, by proceeding methodically a rational solution to the problem of pollution can be arrived at:

- ✓ Think specifically about the pollution threat to a collection.
- ✓ What pollutants interact with what materials?
- ✓ How well is the collection protected by its current environment?
- ✓ Effect of showcases, cupboards, building layout, building services?
- ✓ Will objects themselves emit pollutants that damage other objects?
- ✓ From an evaluation of the above, what risk is pollution likely to represent?
- ✓ If it is likely that there is a significant risk:
- ✓ Obtain pollution data –outdoor data from monitoring networks
- ✓ Make or commission pollution measurements (choose appropriate consultant)
- ✓ Consult with curators, conservators, archivists, building service engineers and architects
- ✓ Select an appropriate solution
- ✓ Consider less complicated and less expensive solutions first
- ✓ Do not attempt solutions which you will not be able to maintain in the long term

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## **10. SOURCES OF FURTHER INFORMATION**

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### **Organisations**

The UK National Museums and Galleries, English Heritage and the National Trust have specialists who can advise on pollution related issues.

*Some UK-based pollution consultants with experience in the cultural heritage field:*

AEA Technology Environment, Culham, Abingdon, Oxfordshire OX14 3DB. Tel 01235 463391, fax 01235 463050, email [environment-help1@aeat.co.uk](mailto:environment-help1@aeat.co.uk).

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## **Illustration Captions**

### Graphs

Figure 0. Effect of air exchange rate on indoor/outdoor nitrogen dioxide ratio for different museum building configurations predicted using steady state model.

Figure 1. Central London sulphur dioxide and nitrogen dioxide trends (source: UK National Air Quality Archive).

Figure 2. Central London Ozone Trends (source: UK National Air Quality Archive).

Figure 3. Winter and Summer Nitrogen Dioxide at the Horniman Museum Study Collections Centre.

Figure 4. Winter and Summer Nitrogen Dioxide at The Manchester Museum.

Figure 5. Indoor/outdoor pollutant ratios in the Horniman Museum Study Collections Centre fumigation room before and after installation of the portable filtration unit.

Figure 6. Nitrogen Dioxide Concentrations at the V&A Gallery 94 and Theatre Museum Picture Gallery.

Figure 7. Nitrogen Dioxide Concentrations at the Museum of London.

### Pictures:

(Numbers on yellow spots)

*Guidelines on efficient pollution control in heritage buildings*

1. Ventilation measurement at the Manchester Museum Mummy Store. A Blower Door consisting of a fan and an air-tight curtain is fixed in the doorway so that the room can be pressurised and depressurised and its ventilation rate determined.
2. Instrumental monitoring equipment for sulphur dioxide and nitrogen oxides, deployed in a museum store.
3. Diffusion tubes can be discretely deployed in museum interiors.
4. The Horniman Museum Study Collections Centre (building in the centre background with white-painted sealed panels in place of windows).
5. At the Horniman Museum Study Collections Centre the exterior doors have been fitted with lobbies to help exclude pollution.
6. The Manchester Museum is on a main road close to the centre of Manchester.
7. Portable filtration unit in the Horniman Museum Study Collections Centre Fumigation Room.
8. The Victoria & Albert Museum is located on the busy Cromwell Road.
9. The Victoria & Albert Museum Gallery 94 (Devonshire Hunting Room)
10. The Museum of London
11. The Museum of London Medieval Gallery, showing the open-plan interior of the Museum.

*Picture Credits: Victoria & Albert Museum Picture Library, Museum of London Picture Library.*

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