

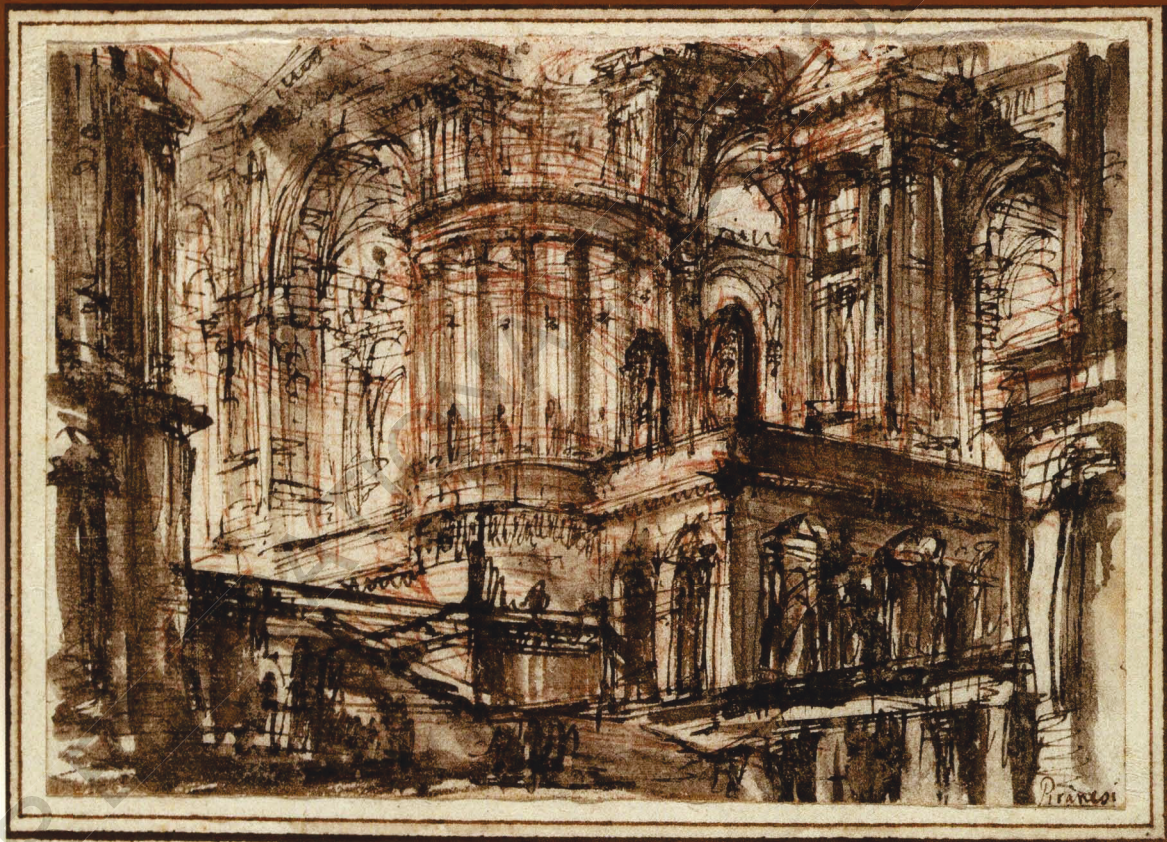
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Airborne Pollutants in Museums, Galleries, and Archives: Risk Assessment, Control Strategies, and Preservation Management

JEAN TÉTREAULT



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BY JEAN TÉTREAU



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DISCLAIMER

The information provided in this book is based on current scientific and technical understanding of the issues presented. Following the advice given in this book will not necessarily provide complete protection in all situations or against all adverse effects that may be caused by airborne pollutants.

COVER

A Fantastic Interior by Giovanni Battista Piranesi (c.1750 — 1759).
Pen and brown ink wash brown over red chalk on laid paper.
National Gallery of Canada, Ottawa.

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Note: Information supplementing this book can be found at
www.cci-icc.gc.ca/links/pollutants/index_e.shtml

PREFACE

Over the last few decades, many observations of the impact of airborne pollutants on materials in museums and laboratories have provided a better understanding of potential interactions and their kinetics. At the same time, the risk management field has developed new approaches for evaluating risk. The combination of these two sciences has provided valuable tools for preservation assessment and for the development of pragmatic strategies and policies to counter pollution in the context of museums, galleries, and archives. These tools can be used by museum directors, building and collection managers, conservation professionals, material scientists, exhibit designers, HVAC engineers, indoor air consultants, and architects to help them make decisions regarding the preservation of collections.

The goals of this book are to:

- define key airborne pollutants for indoor museum environments
- supply tools based on the exposure–effect relationship to assess the risk to collections exposed to pollutants
- establish guidelines for control strategies that give flexible, pragmatic solutions
- offer guidelines for assessing the degree of protection of collections
- provide a basic tool for cost–benefit analysis that fulfils the principles and the policy of the museum
- propose an investigative approach for evaluating the degree of preservation of collections in terms of the aggressiveness of pollutants and for identifying causes of damage

Even though the effect of pollutants on some materials remains equivocal and the effectiveness of some control strategies is not fully known, this book provides a basis for making judgments about a situation and better cost–benefit decisions.

This book does not cover the effects of pollutants on human health and on outdoor cultural property, the effects of non-airborne pollutants (such as pollutants transferred from one material to another at a contact point), or the degradation of objects through their own internal pollutants.

Jean Tétreault

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* Pages numbers in **bold** indicate colour photographs.

ACRONYMS AND ABBREVIATIONS

ACS	American Chemical Society	KCO ₃	Potassium carbonate
AE/h	Air exchange per hour	kg	Kilogram
Ag	Silver	KMnO ₄	Potassium permanganate
AHP	Analytical hierarchy process	KOH	Potassium hydroxide
AIC	American Institute for Conservation of Historic and Artistic Works	LOAED	Lowest observed adverse effect dose
AINC	Australian Network for Information on Cellulose Acetate	LOAEL	Lowest observed adverse effect level
Al	Aluminum	MERV	Minimum efficiency reporting value
APT	Association for Preservation Technology International	MOE	Ministry of the Environment, Ontario
ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning Engineers	MSDS	Material safety data sheet
ASTM	American Society for Testing and Materials	N	Air exchange rate
Avg.	Average	N ₂ O	Nitrous oxide
CAC	Canadian Association for Conservation of Cultural Property	NaHCO ₃	Sodium bicarbonate
CaCO ₃	Calcium carbonate	nd	No date
CAPC	Canadian Association of Professional Conservators	NFPA	National Fire Protection Association
CCI	Canadian Conservation Institute	NH ₃	Ammonia
CEN	European Committee for Standardisation	nm	Nanometre
CH ₂ O	Formaldehyde	NO	Nitric oxide
CH ₃ COOH	Acetic acid	NO ₂	Nitrogen dioxide
CIE	International Commission on Illumination (Commission Internationale d'Éclairage)	NO _x	Nitrogen oxides
Cl ₂	Chlorine	NOAEL	No observed adverse effect level
CO ₂	Carbon dioxide	NV	Natural ventilation
Cu	Copper	O ₂	Oxygen
DEAE	Diethylamino ethanol	O ₃	Ozone
EC	Environment Canada	OCS	Carbonyl sulphide
EEA	European Environment Agency	ODA	Octadecylamine
EPA	Environmental Protection Agency, United States	PAN	Peroxyacetyl nitrate
GC/FID	Gas chromatography coupled to a flame ionization detector	Pb	Lead
GC/MS	Gas chromatography coupled to a mass spectrometer	PLV	Pump large (air) volume
h	Hour	PM _{2.5}	Suspended particle matter of 2.5-μm diameter or less
H ₂ O	Water	PM ₁₀	Suspended particle matter of 10-μm diameter or less
H ₂ S	Hydrogen sulphide	ppb or ppbv	Particles per billion (volume/volume)
H ₂ SO ₄	Sulphuric acid	ppm or ppmv	Particles per million (volume/volume)
HC	Health Canada	PVAc	Poly(vinyl acetate)
HCOOH	Formic acid	PVC	Poly(vinyl chloride)
HEPA	High-efficiency particulate air	RH	Relative humidity
HNO ₃	Nitric acid	RTV	Room temperature vulcanization
HPLC	High-performance liquid chromatography	SO ₂	Sulphur dioxide
HVAC system	Heating, ventilating, and air-conditioning system	SO _x	Sulphur oxides
I/O	Indoor/outdoor ratio	SPME	Solid-phase microextraction
ISA	Instrument Society of America	Std	Standard deviation
ISO	International Organization for Standardization	TVOC	Total volatile organic compounds
		UK-IIC	United Kingdom, International Institute of Conservation of Historic and Artistic Works
		UV	Ultraviolet
		VAV	Variable air volume
		VOC	Volatile organic compound
		WRI	World Resources Institute
		yr	Year
		μg m ⁻³	Micrograms per cubic metre
		μg m ⁻³ yr	Micrograms per cubic metre multiplied by year (dose)
		μm	Micrometre

KEY AIRBORNE POLLUTANTS

Many airborne pollutants*¹ cause adverse effects* on collections in an indoor environment. These pollutants have been arranged into eight distinct chemical groups; particles (dust) form a ninth group. Table 1 shows the sources and effects of these different groups of pollutants on objects. Pollutants originate both from outside and inside a building. Indoors, pollutants are typically from products, indoor activities (such as cleaning), visitors, and even objects in the collection. Outdoors, pollutants are mainly related to human activities such as industrial processes and vehicular traffic. Table 2 shows the effects of pollutants on objects in an indoor environment or in model experimental conditions. Different objects are susceptible to different airborne pollutants and deteriorate at varying rates depending on the parameters involved. In some cases, damage is caused by more than one pollutant. For example, the analysis of corrosion compounds on a metal often confirms the presence of more than one pollutant.

From a management point of view, airborne pollutants (most of which are listed in Table 1) can rarely be controlled and monitored individually. Doing so would require far too much time and too many resources. One way to narrow down the number of pollutants is to use the 80-20 Rule (Pareto's principle*) whereby 80% of pollutants can be controlled in museums by controlling the 20% of pollutants known to be the most significant. Based on this principle, seven pollutants have been designated as key pollutants for museums. The remaining airborne pollutants do not require the same close level of control because their sources, reactivities, and permissible concentrations are equal to or less than those of the key pollutants of the same chemical group. Consideration of a limited number of pollutants also simplifies the risk assessment* of the adverse effects of pollutants on the collection. The seven key airborne pollutants — acetic acid, hydrogen sulphide, nitrogen dioxide, ozone, fine particles, sulphur dioxide, and water vapour — are described below.

In this book, the level or concentration of pollutants is expressed in $\mu\text{g m}^{-3}$. For information on the conversion of concentration units, consult Box 1.

BOX 1. CONCENTRATION UNITS

The terms "level" and "concentration" are used as synonyms in this book, although the term "level" can also be used in a more general sense, e.g. the level of protection or the level of risk. In risk assessment, the level is normalized and has the same meaning as concentration.

Two different units can be used to quantify the concentration of most airborne pollutants:

- parts per billion (ppb or ppbv) is a measure of the volume fraction of pollutants in the ambient air; 1 ppb means there is 1 pollutant molecule present in a group of 1 billion air molecules (equivalent to 1×10^{-9})
- micrograms per cubic metre ($\mu\text{g m}^{-3}$) represents the quantity of a pollutant per unit volume

The two units are related in the following way (21°C and atmospheric pressure of 101.3 kPa):

$$\text{ppb} = \mu\text{g m}^{-3} \times 24.04 \div (\text{molecular weight})$$

For example, to convert $2.5 \mu\text{g m}^{-3}$ acetic acid into ppb, multiply 2.5 by 24.04 (the molar volume of a perfect gas) and divide by 60.05 g/mol (the molecular weight of acetic acid). The result is 1 ppb (or 0.000001%).

As a general rule of thumb, for most pollutants 1 ppb is equivalent to $2 \mu\text{g m}^{-3}$. The exact conversions for some key pollutants are provided below.

Key pollutants	Conversion factor
Acetic acid	1 ppb = $2.50 \mu\text{g m}^{-3}$
Hydrogen sulphide	1 ppb = $1.42 \mu\text{g m}^{-3}$
Nitrogen dioxide	1 ppb = $1.91 \mu\text{g m}^{-3}$
Ozone	1 ppb = $2.00 \mu\text{g m}^{-3}$
Particles ^a PM _{2.5}	
Sulphur dioxide	1 ppb = $2.67 \mu\text{g m}^{-3}$
Water vapour ^b	1 ppb = $0.75 \mu\text{g m}^{-3}$

a: The concentration of particles cannot easily be converted to ppb due to the different molecular weights of the fine particles.

b: The level of water is usually reported in relative humidity (RH) as a percentage.

A program to convert concentration units can be found on the Internet
<iaq.dk/papers/conc_calc.htm> (Ryhl-Svendsen 2001).

1. All terms marked with an asterisk are defined in the Glossary.

TABLE 1. SOURCES OF AIRBORNE POLLUTANTS

Airborne pollutants	Indoor and outdoor sources ^a
Amines (RNR)^b	Ammonia (NH₃): alkaline-type silicone sealants, concrete, emulsion adhesives and paints, household cleaning products, visitors, animal excrement, fertilizer and inorganic process industries, underground bacterial activities. Cyclohexylamine (CHA), diethylamino ethanol (DEAE), and octadecylamine (ODA): corrosion inhibitor in humidification systems, some vapour corrosion inhibitors. Aliphatic amines: epoxy adhesives.
Aldehydes (RCOH) and carboxylic acids (RCOOH)	Aldehydes: Acetaldehyde (CH₃HCO): some poly(vinyl acetate) adhesives, wood products. Formaldehyde (CH₂O): carpet finishing components, fungicide in emulsion paints, fabric-finishing components, gas ovens and gas burners, natural history wet collections, ozone-generating air purifiers, urea formaldehyde-based adhesive products, tobacco smoke, vehicle exhaust, other combustion. Carboxylic acids: Acetic acid (CH₃COOH): acid-type silicone sealants, degradation of organic materials (general) and objects such as cellulose acetate-based objects (vinegar syndrome) and wood products, many emulsion paints, flooring adhesives, human metabolism, linoleum, microbiological contamination of air-conditioning filters, oil-based paints, photographic developing products, some "green" type cleaning solutions. Formic acid (HCOOH): degradation of organic materials (general), oil-based paints, wood products. Fatty acids* (RCOOH): burning candles, cooking, flooring adhesives, human metabolism, linoleum, lubricant in HVAC systems, microbiological activities from air-conditioning or on objects, objects made of animal parts (including skins, furs, taxidermy specimens, insect collections), oil-based paints, papers, skins, paper and wood products, vehicle exhaust.
Nitrogen oxide compounds (NO_x)	Nitric oxide (NO): agricultural fertilizers, fuel combustion from vehicle exhaust and thermal power plants, gas heaters, lightning, photochemical smog. Nitrogen dioxide (NO₂): degradation of cellulose nitrate and same sources as for NO but mainly from oxidation of NO in the atmosphere. Nitric acid (HNO₃) and nitrous acid (HNO₂): oxidation of NO₂ in the atmosphere or on a material's surface, possibly the degradation of cellulose nitrate.
Oxidized sulphur gases* (SO_x or S⁺)	Sulphur dioxide (SO₂): degradation of sulphur-containing materials and objects such as proteinaceous fibres, pure pyrite or mineral specimens containing pyrite sulphur dyes, sulphur vulcanized rubbers, petroleum refineries, pulp-and-paper industries, combustion of sulphur-containing fossil fuels. Sulphuric acid (H₂SO₄): oxidation of SO₂ in the atmosphere or on a material's surface.
Oxygen (O₂) and ozone (O₃)	Oxygen: 21% of the atmosphere. Ozone: electronic arcing, electronic air cleaners, electrostatic filtered systems, insect electrocuters, laser printers, photocopy machines, UV light sources, lightning, photochemical smog.
Particles (fine and coarse)	General: aerosol humidifier, burning candles, concrete, cooking, laser printers, renovations, spray cans, shedding from clothing, carpets, packing crates, etc. (due to abrasion, vibration, or wear), industrial activities, outdoor building construction, ozone-generating air purifiers, soil. Ammonium salts: ammonium sulphate and nitrate: reaction of ammonia with SO₂ or NO₂ in indoor or outdoor environments or on solid surfaces. Biological and organic compounds: micro-organisms, degradation of materials and objects, visitor and animal danders, construction activities. Chlorides: sea salt aerosol, fossil combustion. Soot (organic carbon): burning candles, fires, coal combustion, vehicle exhaust.
Peroxides (ROOR)	Hydrogen peroxide (HOOH): degradation of organic materials such as rubber floor tiles, wood products, micro-organism activities, oil-based paints. Peroxyacetyl nitrate (PAN): automobile exhaust particularly from alcohol-based fuels, photochemical smog.
Reduced sulphur gases* (S⁻)	Carbon disulphide (CS₂): polysulphide-based sealants, fungal growth, rotting organic matter in the oceans, soils, and marshes. Carbonyl sulphide (OCS): degradation of wool, coal combustion, coastal ocean, soils, and wetlands, oxidation of carbonyl disulphide. Hydrogen sulphide (H₂S): arc-welding activities, mineral specimens containing pyrite, sulphate-reducing bacteria in impregnated objects excavated from waterlogged site, visitors, fuel and coal combustion, marshes, ocean, petroleum and pulp industries (kraft process), vehicle exhaust, volcanoes.
Water vapour (H₂O)	Visitors, water-based paints and adhesives, wet cleaning activities, outdoor environment.

a: Refer to Appendix 1 for quantified data and references.

b: Expressions in parentheses are either the chemical symbol or a common acronym. R represents either a hydrogen bond (H) or a radical such as CH₃(CH₂)_x (or even more complex).

TABLE 2. ADVERSE EFFECTS OF AIRBORNE POLLUTANTS

Airborne pollutants	Effects on materials ^a
Amines	Ammonia: blemishes on ebonite, corrosion of metal by an ammonium salt, efflorescence on cellulose nitrate. If combined with sulphate or nitrate compounds, it can form a white deposit on the surface of objects. Other amines: thought to be responsible for the blemishes on paintings, corrosion of bronze, copper, and silver.
Aldehydes and carboxylic acids	Acetaldehyde and formaldehyde: possible oxidation of the aldehyde to carboxylic acids in high RH and/or in presence of strong oxidants. Acetic and formic acids: corrosion of copper alloys, cadmium, lead, magnesium, and zinc, efflorescence on calcareous materials such as seashells, corals, limestones, and rich calcium-based fossils, efflorescence on rich soda glass objects, lowering of the degree of polymerization of cellulose. Fatty acids: blemishes on paintings, corrosion of bronze, cadmium, and lead, ghost images on glass, yellowing of papers and photographic documents.
Nitrogen oxide compounds	Corrosion of copper-rich silver, deterioration of leather and paper, fading of some artists' colorants.
Oxidized sulphur gases*	Acidification of paper, corrosion of copper, fading of some artists' colorants, weakening of leather.
Oxygen and ozone	Oxygen with (UV, visible) radiation: brittleness and cracking of organic objects, fading of colorants. Ozone: fading of some artists' colorants, dyes, and pigments, oxidation of organic objects with conjugated double bonds such as rubber, oxidation of volatile compounds into aldehydes and carboxylic acids.
Particles	General: abrasion of surfaces (critical for magnetic media), discoloration of objects (especially critical for those with surfaces with interstices that entrap dust, e.g. with pores, cracks, or often micro-irregularities), may initiate or increase corrosion processes due to their hygroscopic nature, or may initiate catalysis forming reactive gases. Ammonium salts: corrosion of copper, nickel, silver, and zinc, blemishes on furniture varnished with natural resins and on ebonite. Chlorine compounds: increase of rate of metal corrosion. Soot: discoloration of porous surfaces (painting, frescoes, statues, books, textiles, etc.), increase of rate of metal corrosion.
Peroxides	Discoloration of photographic prints, fading of some artists' colorants, oxidation of organic objects and pollutant gases.
Reduced sulphur gases*	Corrosion of bronze, copper, and silver, darkening of lead white pigment, discoloration of silver photographic images.
Water vapour	Hydrolysis reaction on organic objects such as cellulose acetate- and nitrate-based objects, some dyes in colour photographs, polyurethane-based magnetic tape or polyurethane foam, photographic gelatine, many type of papers, natural varnishes, flexible (plasticized) PVC. It also increases the rate of other deterioration such as corrosion of metals, efflorescence on calcium-based materials, and photo-oxidation of artists' colorants.

a: Refer to Appendix 2 for quantified data and references.

ACETIC ACID

Acetic acid vapour is a common and reactive indoor-generated pollutant often classified in the chemical group of carbonyls*. It can be released by various products, such as paints, varnishes, poly(vinyl acetate) adhesives, acid-cured silicone, wood products (especially oak and cedar), and some cleaning products. Acetic acid (CH_3COOH) can even be released by some organic objects*. Many lead objects have been damaged when displayed or stored in an enclosure* in the presence of products emitting acetic acid, such as wood products and paints. Visible corrosion on lead can happen in a new display case made of products that emit acetic acid after only 1–3 months of exposure. An example is shown in Figure 1. White powder on the lead coin was caused by acetic acid released by an oak display case. In extreme cases, lead objects can be completely destroyed after a few years, leaving only a white powder. Lead is commonly found as seals on historic documents, small figurines, medals, coins, bullets, modern sculptures, part of composite objects, solder in metal objects, and in metal alloys. In some cases, bronze objects have also deteriorated due to acetic

acid (Tennent and Baird 1992). Where objects are not in a small enclosure, but are in an open room (except where there are very large surfaces of acid emissive products and inadequate ventilation), there have been very few reported problems caused by acetic acid. The two main strategies to protect acetic acid-sensitive objects are to select non- or low-acid-emissive enclosure products and avoid mixing acid-sensitive objects with acid-emissive objects in the same enclosure.

It is worth mentioning the “vinegar syndrome.” This is a typical problem of internal pollutant generation by an object; acetic acid is released by cellulose acetate films (negatives or soundtrack movies) or three-dimensional cellulose acetate objects, especially after reaching a critical phase of hydrolysis* degradation (Reilly 1993).

Formic acid and formaldehyde are two other common indoor pollutants considered harmful by the conservation community. However, they do not have the same wide spectrum of reactivities as acetic acid. The adverse effects of these two compounds can be minimized by avoiding their major sources, such as oil or alkyd paints, and unsealed urea formaldehyde-based glue on wood products in enclosures. Paints formed by oxidative polymerization, such as oil-based, alkyd, and oil-modified urethanes, release both formaldehyde and peroxide vapours during the curing process. A certain amount of the formaldehyde can become oxidized by the peroxide during the first few days after the paint application. Formaldehyde is discussed in the section “Other Pollutants.”

HYDROGEN SULPHIDE

Hydrogen sulphide (H_2S), a reduced-sulphur gas with a characteristic “rotten egg” odour, is a key pollutant due to its great capacity to tarnish silver and copper within a year, even in remote areas and at levels far below the human olfactive threshold ($1\text{--}10\ \mu\text{g m}^{-3}$). Figure 2 shows the typical tarnishing effect of H_2S . It is also known to darken lead white pigment on paintings. The main anthropogenic* sources of H_2S are the pulp-and-paper and petroleum industries. Outside the urban environment, H_2S is emitted by oceans, volcanic and geothermal activities, marshes, and vegetation (Watts 2000). Inside buildings, elevated levels of H_2S can be found when many people are present. It has been found that a person in a classroom releases about $100\ \mu\text{g}$ of H_2S per hour (Wang 1975).



Figure 1. Corroded lead medals in an oak display case. Courtesy of the Musée du séminaire de Sherbrooke. [A colour version of Figure 1 is available on p. 91.]



Figure 2. Tarnished silver-plated copper key ring. Continued cleaning of tarnish compounds will eventually remove the thin silver layer.

[A colour version of Figure 2 is available on p. 91.]

Silver objects can tarnish quickly when displayed with waterlogged archaeological objects contaminated by sulphate-reducing bacteria (Little et al. 1998; Green 1992). Carbonyl sulphide (OCS), another common reduced-sulphur compound, is generated mainly in the countryside. It has a lower reactivity on metals than H_2S .

There is a common notion that wool is harmful to silver, and some people have reported fast tarnishing of their silver collection in a room with a wool carpet. On the other hand, silver medals exhibited in display cases with military wool costumes have shown little tarnish after many years. A similar observation was made at the Canadian Conservation Institute (CCI) where silver coupons did not tarnish in a test chamber with a wool sample at about 50% relative humidity* (RH) for more than 8 yrs. In fact, wool does not release significant levels of reduced-sulphur compounds at room temperature. To the contrary, it is rather good at adsorbing sulphur compounds (Crawshaw 1978), which explains the low tarnishing rate of silver in airtight enclosures in the presence of wool. However, the scenario is different with a wool carpet in a room. Wool does tend to release reduced-sulphur compounds when strongly illuminated (Brimblecombe et al. 1992). These compounds, combined with dust and salt with which the carpet may be contaminated and with reduced-sulphur compounds originating from the outside air and visitors, may cause accelerated tarnishing of a silver collection in a carpeted room exposed to direct sunlight.

NITROGEN DIOXIDE

Nitrogen dioxide (NO_2) is the most common compound of the nitrogen oxides group (NO_x) in the atmosphere. NO_2 is responsible for the reddish brown colour above cities, especially during a period of photochemical smog*. It is an important precursor of ozone. NO_2 is rapidly formed in the atmosphere by the action of ozone on nitric oxide (NO). Nitric oxide is the major NO_x emitted by fuel combustion in vehicles (about 50% of emissions), power plants, and industrial activities. Direct emission of NO_2 in the atmosphere accounts for a small fraction of total NO_x emissions. Since the beginning of the industrial age, the emission of NO_x has seriously increased. The national trend of NO_x emission in the United States during the 20th century is shown in Figure 3, which also shows the long-term trends of other pollutants in the United States and a few short-term trends of pollutant levels in Canada and Europe. However, in the last few years in the United States and Europe, there has been a slight decrease in NO_x emissions. Usually, the emission and concentration of outdoor pollutants follow a similar trend for a specific location. This is borne out in some cities in the United States and Canada, where extensive monitoring programs that were begun in the 1980s show a slight decline in the levels of NO_2 . Knowing the levels and trends of outdoor pollutants is important because these pollutants infiltrate museums at a fraction of the outdoor levels.

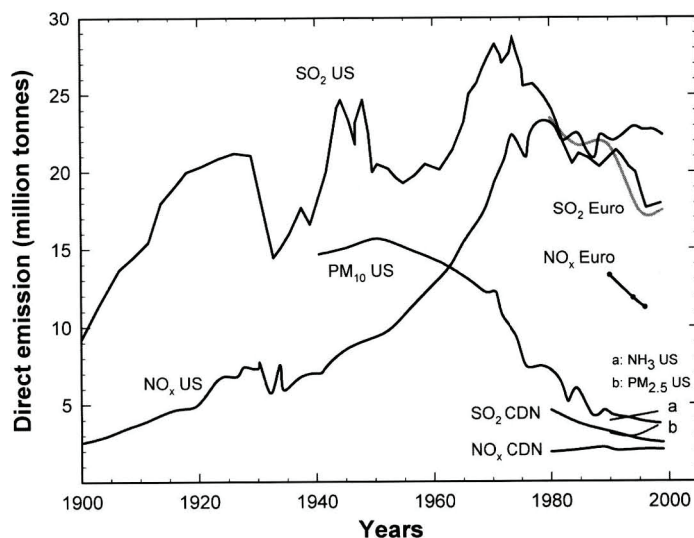


Figure 3. Pollutant emission trends in the United States, Europe, and Canada (EPA 2001c, 2000, 1996; EMEP nd).

Box 2.

ACID DEPOSITION

The term "acid rain" was initially used to refer to abnormal acidity found in precipitation. Eventually, to allow for a more global comprehension of the problem of acid compounds falling out of the atmosphere, the term "acid deposition" became more appropriate.

The acid compounds originate mainly from sulphur dioxide (SO_2) and nitric oxide (NO) gases that are emitted as a result of combustion of coal and fossil fuel and smelting activities. In the atmosphere, these gases react with water, oxygen, and other chemicals to form gases and aerosols* (acids, salts, and radicals) of SO_x and NO_x compounds (see Figure 4). They are also frequently adsorbed on other particles. Some reactions will be dominant under solar radiation or in the presence of water droplets (clouds, fog) (Harrison 1996), while others will be dominant at night with the oxidation of NO_2 by ozone.

The sulphate and nitrate aerosol compounds reduce visibility in urban as well as rural areas while they

remain in suspension. Eventually they will be deposited on earth in dry or liquid form. About half the compounds in the atmosphere fall back to earth through dry deposition as gases or particles in areas of high pollution close to the sources of emission. It is in this dry form that most airborne pollutants infiltrate the openings or ventilation system of a museum. The other half will fall as wet deposition in the form of acid rain, fog, or snow precipitation. Depending on weather conditions, compounds can be carried hundreds of kilometres before falling through precipitation. During the rain, dry deposited compounds are washed from trees and other surfaces. When that happens, the run-off water adds the acids to the acid rain, making the combination more acidic than the falling rain alone.

Other compounds such as ammonia, carboxylic acids, hydrogen sulphide, hydrogen chloride, and hydrogen fluoride can contribute to the acidity of the atmosphere. These compounds may be from either anthropogenic or natural sources and play a secondary role.

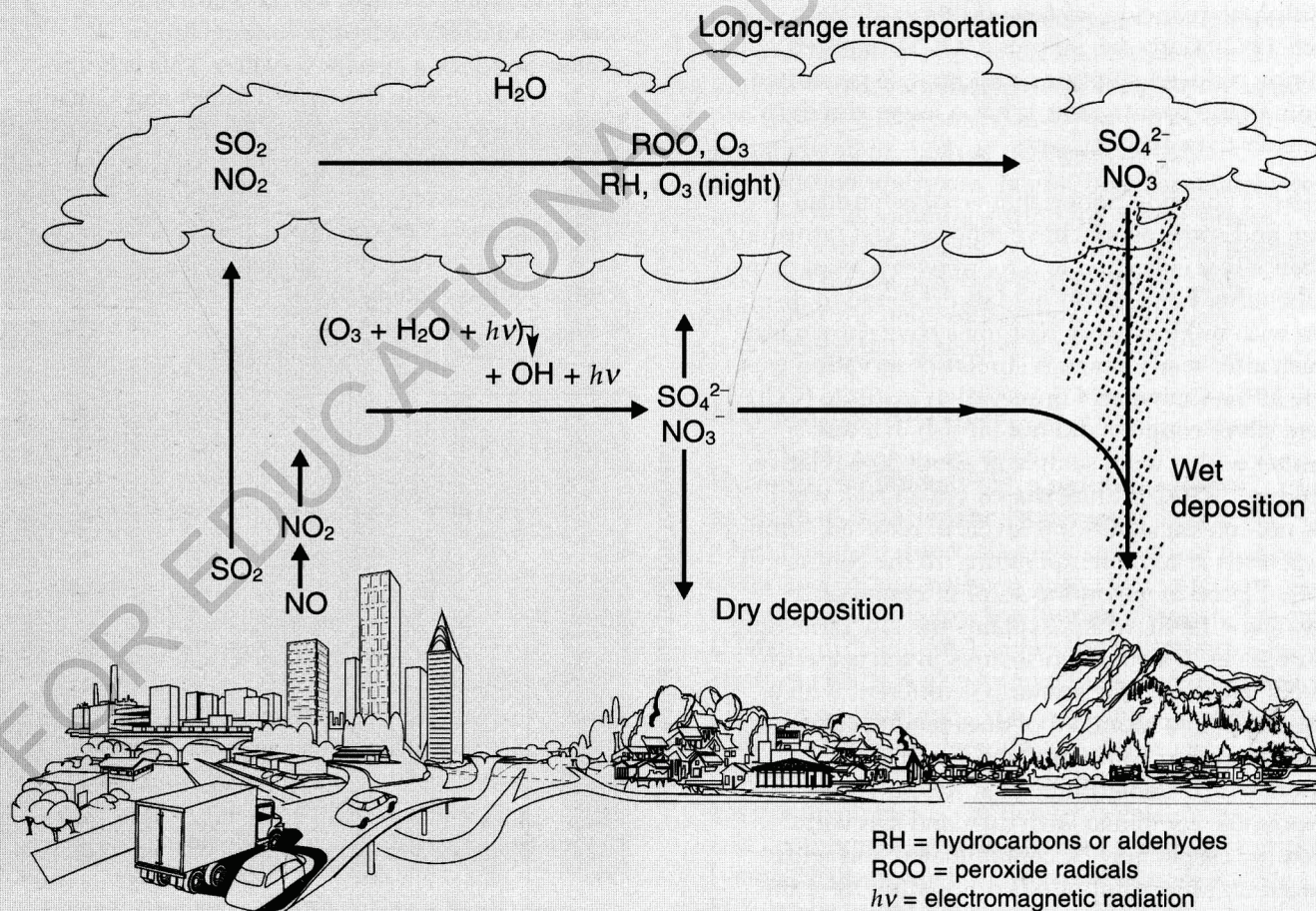


Figure 4. Main anthropogenic origins of SO_x and NO_x deposition.