PAS 198:2012

Specification for managing environmental conditions for cultural collections

Collections Trust

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Foreword

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This PAS is not to be regarded as a British Standard. It will be withdrawn upon publication of its content in, or as, a British Standard.

The PAS process enables a specification to be rapidly developed in order to fulfil an immediate need in industry. A PAS may be considered for further development as a British Standard, or constitute part of the UK input into the development of a European or International Standard.

Relationship with other publications

This PAS can be used in conjunction with the following additional publications for the cultural sector:

- PAS 197:2009, *Code of practice for cultural collections management*

  PAS 198 is set within the cultural collections management framework given in PAS 197:2009, in particular with respect to collections care and conservation.
- PD 5454:2012, *Guide for the storage and exhibition of archival materials*

  PD 5454:2012 references PAS 198 as a specification for managing environmental conditions for cultural collections that can be used by those managing archives. PD 5454:2012 superseded BS 5454:2000, *Recommendations for the storage and exhibition of archival documents* and PD 0024:2001, *Archival documents – Guide to the interpretation of BS 5454:2000 – Storage and exhibition of archival documents*.
- European standard on sites and buildings intended for the storage and use of cultural collections

  The European Committee for Standardization has started work on a new European Standard on sites and buildings intended for the storage and use of cultural collections. The work is being conducted through a working group of the European technical committee, CEN/TC/346, Conservation of cultural property. PAS 198 is expected to form part of the UK's contribution to the environmental aspects of this new European Standard.

Use of this document

It has been assumed in the preparation of this PAS that the execution of its provisions will be entrusted to competent people who are appropriately qualified and experienced in the care and management of cultural collections for whose use it has been produced.

Presentational conventions

The provisions of this standard are presented in roman (i.e. upright) type. Its requirements are expressed in sentences in which the principal auxiliary verb is "shall".

Commentary, explanation and general informative material is presented in italic type, and does not constitute a normative element. The word "should" is used to express recommendations, the word "may" is used to express permissibility and the word "can" is used to express possibility, e.g. a consequence of an action or an event.

Spelling conforms to *The Shorter Oxford English Dictionary*. If a word has more than one spelling, the first spelling in the dictionary is used.

Contractual and legal considerations

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

Compliance with a PAS cannot confer immunity from legal obligations.

0 Introduction

0.1 General

PAS 198 has been developed to help collecting organizations meet their responsibility to establish and maintain environmental conditions that preserve the cultural collections in their care for future use and enjoyment. It is a specification for managing environmental conditions for collections and covers temperature, relative humidity, light and pollution. The starting point for users of this PAS is to develop an understanding of the sensitivity of collection items to these agents of deterioration.

This PAS aims to help users make their own judgements about specifying beneficial environmental conditions appropriate to local circumstances. The emphasis is on providing conditions for the materials and structures of collection items that will help prevent rapid deterioration or irreversible damage. Although deterioration cannot be arrested altogether, it can be significantly slowed down. Good management of environmental conditions can extend the lifetime of even sensitive materials.

This PAS also takes account of a move in the UK towards energy restraint, prompted by the international drive to reduce the use of fossil fuels. Annex A explains the thinking that underlies the requirements of this PAS on the relationship between energy economy and environmental conditions. Architectural or engineering aspects of environmental control are beyond the scope of this specification, however, and guidance on building options is therefore not included.

0.2 Background

The development of PAS 198 is in part a response to the statement issued by the UK National Museum Directors' Conference (2009) that "museums need to approach long-term collections care in a way that does not require excessive use of energy, whilst recognising their duty of care to collections. There is general agreement that it is time to shift museums' policies for environmental control, loan conditions and the guidance given to architects and engineers from the prescription of close control of ambient conditions throughout buildings and exhibition galleries to a more mutual understanding of the real conservation needs of different categories of object, which have widely different requirements and may have been exposed to very different environmental conditions in the past."

This PAS also reflects a debate initiated in 2009 by the UK Arts and Humanities Research Council (AHRC) and UK Engineering and Physical Sciences Research Council (EPSRC) Science and Heritage Programme research cluster "Environmental Guidelines: Opportunities and Risks" (EGOR). One of the outcomes of the EGOR initiative was a recommendation that new environmental standards based on recent scientific evidence should be developed for cultural collections in the UK. These should apply to the range of materials commonly found in archives, libraries and museums, thus going beyond the scope of BS 5454:2000, *Recommendations for the storage and exhibition of archival documents*, which has been superseded by PD 5454:2012, *Guide for the storage and exhibition of archival materials*.

0.3 Approach

Users of this PAS are required to evaluate the sensitivity of their collection items to temperature, relative humidity, light and pollution, recognizing that materials react in different ways to different agents of deterioration, and that collection items are often composite objects with a structure combining a number of different materials. Collecting organizations often need to find ways of dealing with a wide range of material sensitivities. Collection items also often have a history of repair and conservation treatments, which can be relevant when specifying beneficial environmental conditions.

This approach reflects the increasing use of the results of research over the past century into the effects of temperature, RH, light exposure and pollution on the rates of change of collection materials, to determine specific environmental conditions for specific aims, rather than highly prescriptive limits for environmental conditions for all collections.

Users are required to make decisions about suitable preservation environments on the basis of information about a collection, including any available data on its current and past storage and display environment, the materials and structures of collection items and their current condition. Other key factors include the significance of particular collection items in the context of the collection, and the impetus to reduce energy consumption. Decisions need to be made in the context of local priorities, and compromises might be necessary.

On the basis of this information, organizations are required to develop an environmental management strategy appropriate to the collection. The strategy will set out an agreed understanding of the “expected collection lifetime”, that is, the length of time over which the usable life of collection items can be prolonged by means of preservation measures. The expected collection lifetime depends on the resources the organization decides to invest in its collection items for preservation purposes, taking into account their significance, planned use and display, and the rate at which their constituent material or materials would be expected to deteriorate if no preservation measures were taken. The expected collection lifetime could range from a few years for an ephemeral collection to many centuries.

Against the background of the strategy, organizations are required to set an environmental specification for the collection. Guidance on suitable environments is given in Annexes B to G. The aim of these annexes is to help users estimate the likely impact of environmental conditions on the lifetime over which collection items can be preserved, with the focus on those which because of their component materials or complex structure are recognized as sensitive to temperature, relative humidity, light and pollution. Collecting organizations are required to monitor environmental conditions and take measures to mitigate damage caused by these four agents of deterioration.

In implementing this PAS, a balance needs to be struck between the often conflicting demands of the care of the collection, the use and display of collection items and energy economy. While there are many factors that influence the environmental conditions in which collection items are stored, displayed or transported, PAS 198 aims to provide an effective framework for managing the preservation of collections over the expected collection lifetime as the highest priority.

An illustration of the different parameters to consider when setting environmental conditions for a cultural collection is given in Figure 1.

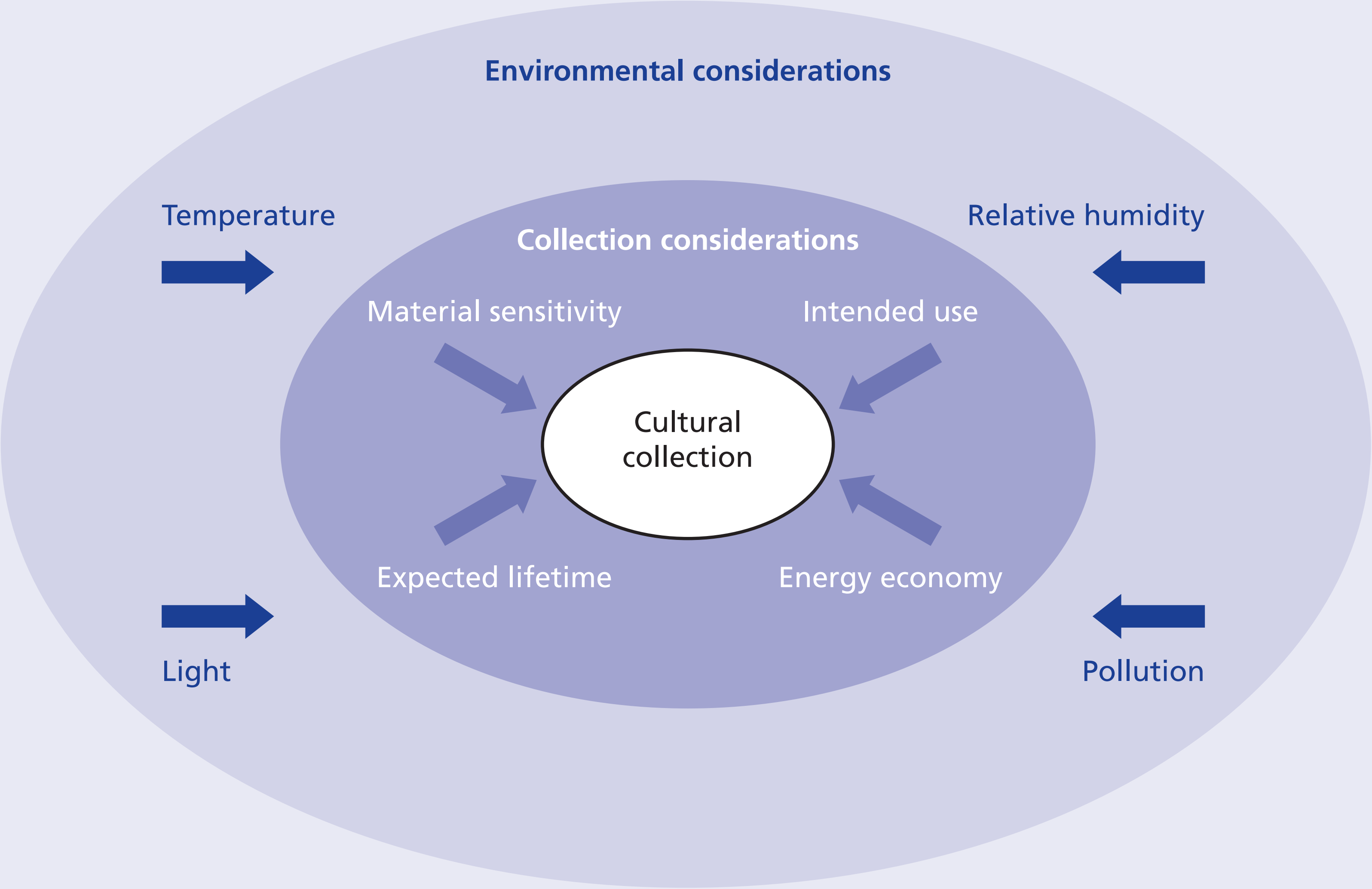
0.4 Research

The body of published research relating to the collection environment has grown over the last 10 years. Where possible, PAS 198 refers to research publications with the aim of promoting understanding of the risks to collections arising from decisions on environmental conditions. Heritage science research is sometimes limited since experimental work cannot be carried out on original objects. As scientific research is therefore often reliant on material models or simulated conditions to measure and predict material change, it might not reflect accurately the behaviour of the actual object being modelled or simulated. Therefore, alongside this empirical research, it continues to be important to take account of the experience of, and data collected by, conservation professionals who witness first-hand the changes to objects over time.

It is recognized that research evidence is lacking in some areas, and where this is the case, accumulated professional experience forms the basis for the requirements. Inclusion of a reference recognizes that it reflects the best available scientific evidence at the time of developing this PAS. In view of the gaps in the evidence currently available, it is clear that further research is needed into the response of a variety of materials commonly found in collections to a broad range of environmental factors and the full range of conditions.

Full details of research publications referenced in this PAS can be found in the bibliography, which has been compiled with contributions from experts including members of the PAS 198 Steering Group and Review Panel and members of TNA PAS 198 Working Group.

Figure 1 – Parameters to consider when setting environmental conditions for a cultural collection



1 Scope

This PAS specifies requirements for managing the setting of environmental conditions for collection items held in cultural collections in the UK, whether in storage, on display or in transit.

It sets out a framework within which environmental conditions can be specified and methods of achieving them can be determined. It also provides guidance in the form of notes and informative annexes to support collecting organizations in complying with the requirements of this PAS. Such informative material, however, does not constitute a normative element of this PAS.

The areas specifically covered by this PAS include:

a) the general management of environmental conditions (Clause **3**, Annex A and Annex B);

b) temperature (see Clause **4**, Annex C and Annex E);

c) relative humidity (see Clause **5**, Annex D and Annex E);

d) light (see Clause **6** and Annex F); and

e) pollution (see Clause **7** and Annex G).

This PAS is applicable to all types and sizes of cultural collections held by individual collectors and all types of collecting organizations such as archives, historic houses, libraries and museums, whether public or private.

It covers the materials and physical structures of collection items but does not cover born-digital material.

It does not cover the architectural or engineering aspects of environmental control.

It is for use by collecting organizations with a responsibility for the environmental management of their cultural collections. It can be used by collection owners, collection and building managers, architects and engineers, archivists, conservators, curators, librarians, registrars, scientists and others concerned with collections care and conservation.

It is also of use to sponsoring and funding bodies and others who need to understand the environmental requirements of collections.

It focuses on climatic conditions prevailing in the UK and therefore is aimed primarily at UK users. However, it does take account of an international readership.

2 Terms and definitions

For the purposes of this PAS, the following terms and definitions apply.

***NOTE** Attention is also drawn to general terms and definitions for the conservation of cultural property given in BS EN 15898.*

2.1 agent of deterioration

factor, whether occurring naturally or through human actions, that has the potential to cause harm to a collection item

***NOTE** For example, temperature, relative humidity, light and pollution.*

2.2 anoxic

oxygen-free

2.3 cold storage

storage at temperatures below 0 °C

2.4 collecting organization

organization that collects, cares for and provides access to collection items for education, learning, enjoyment, legal or evidential purposes

***NOTE 1** For example, archives, historic houses, libraries or museums.*

***NOTE 2** Organization includes individuals such as owners of private collections.*

[derived from PAS 197:2009, **2.6**]

2.5 collection

total body of collection items, or part thereof, held by a collecting organization

[PAS 197:2009, **2.8**]

2.6 collection item

object forming part of a collection

***NOTE** For example, an artefact, book, digital or physical document (including a record), journal, specimen or work of art.*

[derived from PAS 197:2009, **2.22**]

2.7 collection space

area or enclosure in which collection items are held, all sharing the same body of air

***NOTE** For example, a building, room, storage cabinet, display case or transit crate.*

2.8 collections care

range of activities intended to safeguard a collection

***NOTE** These activities can include organizational policies, security, storage, cleaning, maintenance, handling, scientific investigation, environmental monitoring and control, exhibitions and loans, conservation, provision of surrogates and emergency planning.*

[PAS 197:2009, **2.10**]

2.9 collections management

strategies, policies, processes and procedures relating to a collection's development, information, access and care

[PAS 197:2009, **2.14**]

2.10 competent person

someone who has the necessary and sufficient training, knowledge, experience, expertise, skills and/or other qualities to complete their allotted task safely and effectively

[PAS 197:2009, **2.16**]

2.11 conservation

interventive techniques applied to a collection item to achieve chemical and physical stabilization for the purpose of extending the useful life of the collection item to ensure its continued availability

***NOTE** Also known as interventive conservation and remedial conservation.*

[derived from PAS 197:2009, **2.17**]

2.12 cooled storage

storage at temperatures below the average annual temperature of the location, but not below 0 °C

2.13 cultural collection

collection containing evidence of human activity and the natural environment, accompanied by associated information

[PAS 197:2009, **2.19**]

2.14 damage function

quantitative expression of cause and effect relationships between agents of deterioration and material change

2.15 deliquescence

reaction between a solid and atmospheric water vapour causing dissolution to form an aqueous solution on the surface of the solid

2.16 digital ink

ink formulated for use with digital printers

2.17 dust

dry particulate composed mainly of lightweight organic and inorganic materials from a variety of sources

NOTE *Chemical and biological sources include buildings, people, traffic and textiles.*

2.18 expected collection lifetime

length of time over which the usable life of collection items can be prolonged by means of preservation measures

NOTE *The expected collection lifetime depends on the resources an organization decides to invest in its collection items for preservation purposes, taking into account their significance, planned use and display, and the rate at which their constituent material or materials would be expected to deteriorate if no preservation measures were taken.*

2.19 general storage

storage of materials at temperatures near the average annual temperature of the location or near human comfort temperatures

2.20 glass transition temperature (T_g)

temperature at which amorphous materials change from hard and brittle to viscous and rubbery

2.21 hydrolysis

chemical reaction in which a compound reacts with water to produce other compounds

2.22 hygroscopic material

material that adsorbs moisture when the environmental relative humidity rises and loses moisture when relative humidity drops

[BS EN 15757:2010, **3.6**]

2.23 hypoxic

low-oxygen

2.24 illuminance

quantity of luminous flux falling on a surface

NOTE 1 *Also known as light level, light intensity and lux level.*

NOTE 2 *Illuminance is measured in lux, which is lumen/m^2.*

NOTE 3 *A more detailed definition is given in BS ISO 80000-7.*

2.25 light exposure

total illuminance over a period of time

NOTE *Light exposure is measured in lux-hours.*

2.26 luminous flux

amount of light emitted from a light source per second

NOTE 1 *Luminous flux is measured in lumens.*

NOTE 2 *A more detailed definition is given in BS ISO 80000-7.*

2.27 thermal response time

time taken to re-establish thermal equilibrium throughout a collection item following a change in ambient temperature

3 General

A collecting organization is expected to determine the environmental conditions for its collection within the context of a documented collections care and conservation policy, recommendations for which are given in PAS 197.

This clause specifies an overall framework for developing an environmental management strategy and setting an environmental specification for a collection. Clauses **4** to **7** specify in detail the approach to be adopted in setting parameters for temperature, relative humidity, light and pollution.

3.1 Assigning responsibility

The organization shall designate competent persons with the responsibility for:

a) developing and updating an environmental management strategy for the collection in accordance with **3.2**;

b) collecting environmental data relating to the collection in accordance with **3.3**;

c) carrying out an environmental risk assessment in accordance with **3.4**;

d) setting an environmental specification for the collection in accordance with **3.5**;

e) monitoring environmental conditions in accordance with **3.6**; and

f) taking action to mitigate damage and deterioration caused by temperature, relative humidity (RH), light and pollution.

3.2 Developing a strategy

The organization shall develop an environmental management strategy for the collection. The strategy shall include a statement of the expected collection lifetime and the energy demand arising from the environmental conditions needed to achieve this, taking into account the sensitivity, significance and use of individual collection items.

***NOTE** The strategy should make clear the balance the organization intends to aim for between preservation requirements, usage and display and energy economy.*

3.3 Collecting data

The organization shall collect data relating to the collection, including as a minimum data on:

a) the significance of the collection or collection items therein;

***NOTE** Conducting a significance assessment should form part of a collecting organization's collections development policy and procedures. Recommendations for conducting a significance assessment are given in PAS 197:2009, **4.3**. Attention is also drawn to Russell and Winkworth (2009).*

b) the current and expected usage of collection items, including display, handling, transit and loan;

c) the condition of the collection;

d) the past environment of the collection as detailed in any existing records, noting in particular changes over time;

e) the current external and internal environment of the collection space in order to measure performance over time, including:

    1) the temperature and RH inside and outside the collection space in accordance with **4.10** and **5.10**;

    2) the illuminance or duration of exposure of light falling on collection items in accordance with **6.7**;

    3) pollutants in accordance with **7.4**, any pollution-related damage identified during an inspection conducted at predetermined intervals and, where a problem is identified, the effects of pollutants on collection items;

f) changes made to environmental control systems; and

g) energy use, recorded in such a way that energy used for different purposes, for example lighting, heating and ventilation, storage or display, can be measured separately.

3.4 Assessing the risks

The organization shall conduct an environmental risk assessment of collection items, including an assessment of:

a) the structure and component materials of the collection items, including their history of conservation and repair; and

b) the sensitivity of the collection items to temperature, RH, light and pollution.

NOTE 1 The effects of known interactions between one or more agents of deterioration should also be assessed. Examples of known interactions are given in Annex B.

NOTE 2 Recommendations for conducting an overall risk assessment of a cultural collection are given in PAS 197. In addition to environmental risks, the overall risk assessment also takes into account risks from other factors such as fire, flood and theft, which are outside the scope of this PAS.

NOTE 3 Further guidance on conducting risk assessments is given in BS ISO 31000, Ashley-Smith (1999), Waller (1995) and Waller (2003).

3.5 Setting an environmental specification

3.5.1 The organization shall set an environmental specification for the collection with the aim of preserving the collection for its expected collection lifetime.

3.5.2 The organization shall set the environmental specification after a review of:

a) the expected collection lifetime and associated energy demand, as specified in the environmental management strategy in **3.2**;

b) data collected in **3.3**; and

c) the environmental risk assessment conducted in **3.4**.

3.5.3 The organization shall include in the environmental specification:

a) the permissible upper and lower limits, rate of change and fluctuations for temperature (see Clause **4**);

b) the permissible upper and lower limits, rate of change and fluctuations for RH (see Clause **5**);

c) the permissible upper limit for light exposure, upper limit for illuminance and upper limit for UV to light ratio (see Clause **6**); and

d) gaseous pollutants expected to cause unacceptable risk, and any pollution control measures adopted with the intention of enabling the expected collection lifetime to be achieved (see Clause **7**).

3.5.4 The organization shall set the environmental specification in **3.5.3** for general storage, cooled storage, cold storage, display and transit.

3.5.5 The organization shall set separate environmental specifications for any microclimates provided for sensitive collection items.

3.5.6 The organization shall conduct a review of environmental conditions at predetermined intervals, taking into account the results of monitoring environmental conditions and inspection of collection items.

NOTE Further guidance on environmental management is given in ASHRAE (2007), Cassar (1995), Michalski (2007) and Michalski (2009).

3.6 Monitoring environmental conditions

3.6.1 The organization shall check all monitoring equipment in accordance with the manufacturer's instructions at predetermined intervals to determine that it is fully functional.

3.6.2 The organization shall calibrate all monitoring equipment in accordance with the manufacturer's instructions.

3.6.3 The organization shall conduct a review of the data collected in **3.3** to analyse the environmental conditions of the collection space and identify the need for any improvements.

*NOTE The monitoring of temperature, RH, light and pollution is covered in more detail in **4.10**, **5.10**, **6.7** and **7.4**, respectively. Monitoring should include visual inspection to identify damage and deterioration as well as the use of monitoring equipment.*

3.7 Achieving energy economy

The organization shall include in the environmental specification in **3.5** the measures taken to minimize energy demand.

NOTE Energy demand can be minimized through, for example, the use of climate and lighting control systems that are highly automated or limited to screening windows and opening doors. Further guidance on energy economy is given in Annex A.

3.8 Documenting and retaining data

The organization shall document all evidence of having complied with **3.1** to **3.7**. The documentation shall be retained in a retrievable form and for a predetermined period of time.

NOTE Data should be retained in accordance with good practice associated with the formats in which they are kept (for example, paper documents, electronic documents and data sets). Further guidance on records management is given in BS ISO 15489-1.

4 Temperature

The rates of many deterioration mechanisms (chemical, biological and physical) increase as temperature increases. Changes in temperature within a collection space can also cause deterioration. Given the different dependencies on temperature of these mechanisms, and their differing impact on collection items, a universal temperature range and permissible fluctuations for collections cannot be specified. Attempts to establish a universal safe zone for all collection items by providing conditions required only by sensitive collection items can result in unsafe conditions for atypical collections, as well as leading to unjustifiably increased use of energy.

4.1 Parameters

The environmental specification in **3.5** shall include parameters for temperature that will enable the expected collection lifetime to be achieved, taking into account the materials and structures of collection items and their sensitivity to temperature and changes in temperature. These parameters shall include:

a) the permissible upper limit for temperature;

b) the permissible lower limit for temperature;

c) the permissible rate of change for temperature; and

d) the permissible fluctuations for temperature.

NOTE 1 *A visual representation of the relative risk of damage and deterioration due to temperature is given in Figure C.1 alongside the relative energy demand associated with maintaining a particular temperature.*

NOTE 2 *More detailed guidance on the material damage and deterioration and risks associated with temperature and RH is given in Annex E for a representative selection of materials found in collections.*

NOTE 3 *Further temperature and RH requirements for limiting climate-induced mechanical damage in organic hygroscopic materials are given in BS EN 15757.*

NOTE 4 *Attention is also drawn to Rhyl-Svendsen et al. (2010).*

4.2 Upper limit for temperature

The temperature shall not exceed an upper limit that is expected to cause unacceptable irreversible chemical or physical change in collection items, as specified in **3.5**.

NOTE 1 *Chemical reactions accelerate exponentially as temperature rises. A practical approximation for organic materials is that reaction rates double with each 5 °C rise.*

NOTE 2 *A temperature on the surface of a collection item exceeding 30 °C can cause permanent distortion, change of gloss or melting. Plastics and waxes are particularly sensitive, others, e.g. resins, adhesives, paints and varnishes, less so. Materials such as acrylic emulsion paints with a glass transition temperature (T_g) near or below room temperature can soften at room temperature. If temperatures exceed 30 °C for long periods of time, slow creep and flow can occur, leading to permanent distortion of these materials. The rate of soiling of these materials also increases in the presence of airborne pollutants.*

4.3 Lower limit for temperature

The temperature shall not fall below a lower limit that is expected to cause unacceptable physical damage in collection items, as specified in **3.5**.

NOTE 1 *The minimum safe temperature for a collection is 5 °C, to avoid the temperature in parts of the building falling below 0 °C with consequent freezing of water pipes and risk of flood damage.*

NOTE 2 *Very low temperatures are effective in slowing chemical degradation, and should be maintained for some types of highly sensitive materials. However, below –30 °C, hygroscopic materials equilibrated to a moderate RH at room temperature can be damaged by the formation of ice crystals. Some materials embrittle below their T_g thus increasing the risk of other physical damage caused by movement or shock.*

4.4 Rate of change of temperature

The temperature shall not change at a rate that is expected to cause unacceptable irreversible chemical or physical change in collection items, as specified in **3.5**.

NOTE 1 If the surface temperature of a collection item changes over a period shorter than its thermal response time, an internal temperature gradient occurs, causing internal stress. Brittle materials (such as ceramics and glass) that have sustained sudden temperature changes can show resulting visible damage. This applies especially to collection items such as mirrors or enamelware, where ceramic or glass is combined with metal or organic layers.

NOTE 2 The thermal response time of collection items varies from minutes to hours, depending on thickness and type of constituent materials. If major temperature changes are necessary for operational reasons, such as seasonal energy savings, the period of adjustment should be spread over a period several times longer than the slowest response time of collection items.

4.5 Linkage of temperature to relative humidity control

4.5.1 Given the linked effects of temperature and RH on the chemical stability of many collection items, a statement shall be documented detailing how the permissible upper limit for temperature has been set in conjunction with the permissible limits for RH specified in **3.5**.

NOTE 1 A useful approximation is that the RH will rise 3% for each degree fall in temperature. However, where temperature and RH are independently controlled by mechanical means or by humidity buffering, there will be no relationship between them.

NOTE 2 Since 65% RH is a precautionary limit for mould germination, it can be estimated that there will be a risk of mould in a space usually maintained at x% RH if a drop in temperature reaches (65 - x)/3 °C. For example, there can be a risk of mould in a room usually maintained at 50% RH in any part of the room that is 5 °C colder than the average temperature in the main volume of the space.

NOTE 3 A useful approximation for a space maintained near 50% RH is that condensation develops on any surface more than 10 °C colder than the temperature at which the RH is 50%. Precise calculations can be made using a standard psychrometric chart.

*NOTE 4 Further requirements and guidance on setting limits for RH are given in Clause **5**, Annex D, Michalski (2000), Michalski (2002) and Michalski (2009).*

4.5.2 Given the variation in RH caused by a variation in temperature within a collection space, the variation in temperature between any part of the collection and the average temperature in the main volume of the collection space shall not be such as to result in unacceptable RH, as specified in **3.5**. In particular, the temperature within areas of a collection space shall not be so high as to cause unacceptable physical damage due to low RH, or so low as to result in RH conditions that allow either condensation or mould germination to occur.

NOTE The usual cause of large temperature variations within a collection space is the location of collection items adjacent to an exterior wall or floor without sufficient space for air circulation, or location close to heaters, air conditioning equipment or air vents, or in direct sunlight.

4.6 General storage

4.6.1 The temperature for collection items in general storage shall conform to **4.2** to **4.5**.

4.6.2 Collection items shall be stored at ambient temperatures only if their chemical stability at those temperatures is acceptable in accordance with **3.5**. Any collection items that would deteriorate rapidly at ambient temperatures shall be placed in cooled storage or cold storage.

NOTE 1 Most materials found in collections are chemically stable and will have an expected lifetime of centuries at room temperatures below 30 °C but many plastics, films and acidic papers have an expected lifetime of only decades at 25 °C.

NOTE 2 Some organic materials can have acceptable expected lifetimes at 20 °C, but their expected lifetimes will fall to approximately one-half at 25 °C and one-quarter at 30 °C.

NOTE 3 The annual average outdoor temperature in the UK varies from 8.5 °C to 11 °C. Where average outdoor temperatures are below temperatures normally maintained for human comfort, general storage can take advantage of both higher chemical stability and lower energy demand by operating below human comfort temperatures, as long as RH requirements are also met.

*NOTE 4 While it is preferable to maintain a stable annual average by means of design of the collection space, it is also acceptable to allow slow and gradual seasonal changes in temperature to improve energy economy, as long as the environmental specification of **3.5** is met.*

NOTE 5 *To reduce energy demand as well as the risks associated with malfunction, it is preferable to avoid or reduce the use of mechanical systems in general storage, unless these are required to reduce damaging pollution. This can be achieved within the requirements of* ***4.2*** *to* ***4.5*** *by means of building design or other methods such as use of enclosures.*

NOTE 6 *Attention is drawn to Padfield et al. (2007).*

4.7 Cooled storage and cold storage

The temperature for collection items in cooled storage and cold storage shall conform to **4.2** to **4.5**.

NOTE 1 *Special precautions are necessary during removal and replacement of collection items in cold storage. Thermal shock can occur. Condensation can occur on and within a collection item and its container as it is moved between spaces at different temperatures.*

NOTE 2 *Attention is drawn to Padfield (2002).*

4.8 Display

The temperature for collection items on display or in use shall conform to **4.2** to **4.5**.

NOTE *Where collection items are on open display or where the environment inside display cases is expected to be at room temperature, local requirements for human safety and comfort apply.*

4.9 Transit

The temperature for collection items in transit shall conform to **4.2** to **4.5**.

NOTE 1 *In transit, risks can arise from short periods beyond the permitted upper or lower limits of temperature, rapid fluctuations in temperature, or a significant variation in temperature from one side of the collection item to another. Insulated packaging with some thermal mass within the insulation helps to protect collection items from these risks.*

NOTE 2 *Attention is drawn to Richard, Mecklenburg and Merrill (1991).*

4.10 Monitoring

4.10.1 Temperature measurements shall be recorded at least hourly along with the date, time and location of the measurements and retained for reference with the data collected in **3.3**.

NOTE 1 *The number and distribution of monitoring points depends on the building and any environmental control system in use.*

NOTE 2 *Where possible, especially when reliable outdoor measurements are not available from other agencies, the outside temperature should be measured in perpetual shade and away from the wall.*

NOTE 3 *More detailed guidance on procedures and instruments for measuring temperatures of the air and the surfaces of objects is given in BS EN 15758.*

NOTE 4 *Attention is also drawn to Padfield (2007).*

4.10.2 Temperature sensors shall be calibrated in accordance with the manufacturer's instructions, and a record kept of the calibration.

5 Relative humidity

Relative humidity (RH) influences the rate of many deterioration mechanisms: chemical, biological and physical. Changes in RH can also cause deterioration. Given the different dependencies on RH of these mechanisms, and their differing impact on collection items, a universally safe RH range and permissible fluctuations for collections cannot be specified. Attempts to establish a universal safe zone for all collection items by providing conditions required only by sensitive collection items can result in unsafe conditions for atypical collections, as well as leading to unjustifiably increased use of energy.

RH is monitored and measured as an indicator of changes in moisture content, which can be damaging to collection items.

5.1 Parameters

The environmental specification in **3.5** shall include parameters for RH that will enable the expected collection lifetime to be achieved, taking into account the materials and structures of collection items and their sensitivity to RH and changes in RH. These parameters shall include:

a) the permissible upper limit for RH;

b) the permissible lower limit for RH;

c) the permissible rate of change for RH; and

d) the permissible fluctuations for RH.

NOTE 1 *A visual representation of the relative risk of damage and deterioration due to RH is given in Figure D.1 alongside the relative energy demand associated with maintaining a particular temperature.*

NOTE 2 *More detailed guidance on the material damage and deterioration and risks associated with temperature and RH is given in Annex E for a representative selection of materials found in collections.*

NOTE 3 *Attention is drawn to temperature and RH requirements for limiting climate-induced mechanical damage in organic hygroscopic materials given in BS EN 15757.*

5.2 Upper limit for relative humidity

5.2.1 RH shall not exceed or remain at an upper limit that is expected to cause unacceptable irreversible physical change in collection items composed of hygroscopic organic materials, as specified in **3.5**.

NOTE 1 *Hygroscopic organic materials include wood, paper, most natural textile fibres, animal glue, gelatine, most photographic media and most paint media. They respond to change in RH with changes in dimensions and mechanical properties. The upper limit in these cases is relative to the RH at which the collection item is equilibrated, for example, for a collection item equilibrated to 20% RH, a rise to 50% RH could be damaging, while 55% RH would be acceptable for a collection item equilibrated at 50% RH.*

NOTE 2 *The response time of collection items to RH change depends on the materials, but it varies primarily according to thickness and permeability. Thin (around 1 mm) sheets of organic materials fully exposed to the air will respond in minutes, whereas uncoated wooden objects (around 1 cm) or tight paper stacks will take days, and heavily coated or massive wood weeks or months to respond.*

NOTE 3 *Enclosed storage of collection items slows the response time of a collection item, depending on the air-tightness and buffering capacity of the enclosure.*

NOTE 4 *Humidity promotes many forms of chemical deterioration, particularly hydrolysis but also oxidation and degradation caused by pollutants. RH should be kept low to reduce the rate of chemical degradation but should not fall below 30% unless this has been specified as acceptable. Lower RH can be beneficial for some materials and is permissible where there is no risk of physical damage.*

NOTE 5 *At 75% RH and above, the dimensional change due to each 5% rise in RH increases exponentially. See Note 2 to Annex D.*

5.2.2 RH shall not exceed or remain at an upper limit at which mould germination is expected to occur, as specified in **3.5**.

NOTE 1 *Mould germination and rate of growth are dependent on RH, temperature, air movement, time, species of mould and the nutritious quality of the organic substrate. 65% RH (at 20 °C) is a precautionary limit, although at lower temperatures mould will take longer to germinate. To estimate the time taken for visible growth of mould at higher RH, see Ayerst (1969), Michalski (1993) and Sedlbauer and Krus (2003).*

NOTE 2 *Mould is more likely to develop in the presence of carbohydrates, proteins (such as gelatine and animal glue) and some waxes and synthetic polymers such as poly(vinyl acetate). These are found, for example, on soiled or sized paper and textiles, paintings with traditional linings and any collection items heavily soiled by dust.*

5.2.3 Collection items composed of inorganic materials with specific critical RH, such as minerals, archaeological metals, salt-contaminated metals, some types of glass, salt-laden stone and stone which contains clay shall be identified, and RH shall not exceed an upper limit that is expected to cause unacceptable irreversible change in such collection items, as specified in **3.5**.

NOTE 1 *Where such collection items form part of a mixed collection, it might be necessary to isolate them from the rest of the collection. Enclosures might need to be used for such collection items. Further guidance on enclosures is given in Notes 1 to 3 of* ***5.6****.*

NOTE 2 *More detailed guidance on the material damage and deterioration and risks associated with temperature and RH is given in Annex E for a representative selection of materials found in collections.*

5.3 Lower limit for relative humidity

RH shall not fall below or remain at a lower limit that is expected to cause unacceptable irreversible physical change in collection items, as specified in **3.5**.

NOTE 1 *Below 30% RH, the risk of physical damage to most organic materials and some inorganic materials increases rapidly. Each 5% drop in RH below 30% causes almost double the dimensional response as a 5% drop when RH is above 30%.*

NOTE 2 *Most inorganic materials are stable below 25% RH, and for some of these materials low or very low RH is beneficial, e.g. RH below 18% has been recommended for corroded iron, and RH well below 50% for copper alloys where active corrosion has been observed in a collection. Relevant references to support these observations are given in Annex E.*

NOTE 3 *Some hydrophobic materials, such as wax, may become electrostatically charged at low RH, thus increasing the risk of soiling.*

NOTE 4 *Notes 1 to 4 of* ***5.2.1*** *also apply.*

5.4 Rate of change of relative humidity

RH shall not change at a rate that is expected to cause unacceptable irreversible physical change in collection items, as specified in **3.5**.

NOTE 1 *A rapid change in the RH of a hygroscopic collection item compared with the collection item's response time will cause an internal RH gradient, which can lead to physical damage. A gradient can be reduced by lowering both the rate and the extent of the change.*

NOTE 2 *Gradients occur primarily within thick, rigid, uncoated uniform materials. In flexible materials, e.g. books bound with paper, gradients can cause a temporary warp. In extreme cases, this can lead to fracturing. In composite objects containing hygroscopic organic materials, damage can depend more on the extent of the change than on the rate of change (except for very slow change as indicated in Note 2 to* ***5.2.1****). It is important therefore to focus on reducing the extent rather than the rate of change.*

NOTE 3 *Any given change in RH will cause less stress within materials such as wood, paper, animal glue and oil paints if it occurs over several months rather than a few days.*

NOTE 4 *Notes 1 to 5 of* ***5.2.1*** *also apply.*

5.5 Linkage of relative humidity to temperature control

Given the linked effects of temperature and RH on the chemical stability of many collection items, a statement shall be documented detailing how the permissible upper limit for RH has been set in conjunction with the permissible limits for temperature specified in **3.5**.

NOTE *In cooled storage and cold storage, temperature exerts a greater influence on the chemical stability of many materials than RH. RH can therefore be selected according to physical stability and energy demand considerations.*

5.6 General storage

The RH for collection items in general storage shall conform to **5.2** to **5.5**.

__NOTE 1__ The use of well-made display cases can reduce the need to use mechanical systems.

__NOTE 2__ The use of airtight packaging and enclosures can reduce risks from rapid fluctuations in RH. However, packaging and enclosures that concentrate pollutants to unsafe levels should not be used (see __7.1__ and __7.3__).

__NOTE 3__ The use of anoxic or hypoxic packaging and enclosures can reduce the rate of oxidative damage, including photo-activated oxidation. However, packaging and enclosures that concentrate pollutants to unsafe levels should not be used (see __7.1__ and __7.3__), and checks should be made to ensure that the stored materials do not change in the enclosed environment.

5.7 Cooled storage and cold storage

5.7.1 RH for collection items in cooled storage and cold storage shall conform to **5.2** to **5.5**.

__NOTE__ Collection items in cooled storage and cold storage should be stored so that an acceptable level of moisture content is maintained, for example by controlling RH and/or through the use of containers.

5.7.2 During retrieval to higher temperatures and prior to re-entry to cooled storage or cold storage, collection items shall be kept or placed in airtight containers or purpose-built acclimatization chambers until temperature equilibrium is reached.

__NOTE__ Acetate-based film should be placed in permeable containers that permit slow diffusion of any internally generated acetic acid (ethanoic acid). Acetate-based film should only be placed in impermeable containers if kept at temperatures below which the rate of internal generation of acetic acid is slowed to a negligible level. To prevent contamination, adsorbers can be added to impermeable containers to remove acetic acid.

5.8 Display

RH for collection items on display or in use shall conform to **5.2** to **5.5**.

5.9 Transit

RH for collection items in transit shall conform to **5.2** to **5.5**.

__NOTE 1__ In transit, risks can arise from inappropriate RH. Insulated packaging is critical in achieving RH requirements reliably.

__NOTE 2__ Attention is drawn to Richard, Mecklenburg and Merrill (1991).

5.10 Monitoring

5.10.1 RH measurements shall be recorded at least hourly, along with the temperature at the RH sensor, and the date, time and location of the measurements, and retained for reference with the data collected in **3.3**.

__NOTE 1__ More detailed guidance on procedures and instruments for measuring temperatures of the air and the surfaces of objects is given in BS EN 15758.

__NOTE 2__ Attention is also drawn to Padfield (2007).

5.10.2 RH sensors shall be calibrated in accordance with the manufacturer's instructions, and a record kept of the calibration.

6 Light

Lighting is critical to enjoying and enhancing access to collections. However, all sources of light, whether natural or electric, within a collection space can cause extensive and irreversible damage to collection materials. These can undergo chemical changes, for example, inks, dyes and pigments will discolour; or physical changes, for example, mechanical strength can be lost or glossy materials become matt. Organic materials are usually more sensitive than inorganic materials. Some materials, however, are only slightly sensitive to light, and some not at all.

As the wavelength of radiation decreases, the rate of photochemical damage generally increases. Within the spectrum of visible light, damage increases from red to violet, and ultraviolet (UV) radiation is yet more damaging than violet light. Radiant heat from light sources can also cause damage to collections, as it can lead to uneven distribution of heat or moisture within collection items or produce a desiccating environment. Intensive illumination can also lead to accumulation of heat and heat-related stress of collection items.

Light and UV radiation damage is cumulative and proportional to exposure. Damage can be minimized by reducing either the illuminance or the duration of exposure, or both. We generally see things better in brighter light, so the specification of illuminance is always a compromise between preserving the collection item and making it clearly visible.

In this PAS, light is used to mean visible radiation. Many light sources emit UV radiation and infrared (IR) radiation as well as visible radiation and reference will be made to these forms of radiation as distinct from light.

6.1 Parameters

6.1.1 The environmental specification in **3.5** shall include parameters for light that will enable the expected collection lifetime to be achieved, taking into account the materials of collection items and their sensitivity to light, UV radiation and IR radiation. These parameters shall include:

a) the permissible upper limit for light exposure, taking into account both illuminance and the duration of light exposure;

b) the permissible upper limit for illuminance; and

c) the permissible upper limit for the UV to light ratio.

NOTE 1 *Guidance on the sensitivity of materials to light is given in Annex F.*

NOTE 2 *Consideration should be given to providing motion-activated lighting for photo-sensitive collection items and to limiting display of sensitive collection items, for example through rotation of items.*

NOTE 3 *UV radiation is not required for access, so it can be eliminated, or the UV to light ratio reduced if it cannot be eliminated. UV radiation can be minimized in most spaces, even if illuminance cannot be controlled, by using UV-absorbent filters or films.*

NOTE 4 *The need for staff and any visitors to see the collection should be taken into account when setting parameters for light.*

NOTE 5 *Unnecessary exposure to light sources should be minimized.*

6.1.2 Measures taken to optimize the energy efficiency of light systems and identify lower energy light sources by keeping abreast of technological developments shall be documented.

NOTE *In particular, the most efficient balance to be achieved between the use of daylight and electric light should be considered.*

6.1.3 The sensitivity of collection items to light shall be assessed and documented so that an informed decision can be made about light exposure limits for these sensitive collection items, particularly where there is high demand for access.

NOTE 1 Different specifications might be required for collection items of differing sensitivity.

NOTE 2 Attention is drawn to Ashley-Smith, Derbyshire and Pretzel (2002).

6.1.4 In collection spaces where control of lighting is limited, or determined by other factors such as authenticity in historic house display, light and UV radiation measurements shall be used to guide the selection and placement of collection items so that the preservation aims of the organization can be achieved.

6.2 Upper limit for light exposure

The cumulative light exposure of collection items shall not exceed an upper limit that is expected to cause unacceptable irreversible physical and chemical change in collection items within a specified period of time, as specified in **3.5**.

*NOTE When considering a collection with a range of sensitivities, it is usually consistent with **6.1.1** to **6.1.2** to determine light exposure on the basis of the most highly sensitive collection items.*

6.3 Upper limit for illuminance

Illuminance shall not exceed an upper limit that is the minimum acceptable for the visual task and the viewer for which it is intended, taking into account the sensitivity of collection items to light, as specified in **3.5**.

NOTE 1 50 lux is often adopted as the minimum acceptable illuminance that is suitable for the average visitor. This should provide a viewer under the age of 50 with the ability to see moderate detail in a moderately light object during a reasonable period of inspection. 50 lux should not be used as an absolute value, however, if lower illuminance is acceptable for particular displays. Good lighting design should use not only measured lux levels but also a visual assessment, as the balance of lighting and ambience will affect the experience of the visitor.

NOTE 2 A higher illuminance is needed for scholarly study and for conservation work on even light-sensitive collection items. Guidance on illumination for detailed work is given in Michalski (1997) and Michalski (2010).

6.4 Upper limit for the UV to light ratio

The UV to light ratio shall not exceed 75 μW/lumen.

NOTE Filters are available that eliminate all or virtually all UV radiation.

6.5 Storage

Light exposure, illuminance and the UV to light ratio limits for collections in general storage, cooled storage and cold storage, shall conform to **6.2** to **6.4** on the basis that visual access is not required except for an identified set of tasks that need to be conducted safely and effectively.

NOTE 1 Tasks that might be carried out in storage include retrieval, transportation, replacement, pest inspection, inventory control and security inspections. Acceptable illuminance:

a) for retrieval, transportation, replacement, pest inspection and inventory control should be similar to standard office lighting; and

b) for routine security inspections can be estimated as similar to those required for display, e.g. 50 lux to 150 lux.

NOTE 2 In order to minimize light exposure, daylight and electric lighting in storage areas should be completely excludable, and should be excluded when tasks are complete.

6.6 Display

Light exposure, illuminance and the UV to light ratio limits for collections on display, shall conform to **6.2** to **6.4** on the basis that there is a need for effective visual access by visitors and staff.

6.7 Monitoring

6.7.1 Light exposure and illuminance shall be recorded at a predetermined number of times a day over more than one day, both within the collection space and externally. The date, time and location of the measurements shall be recorded and retained for reference with the data collected in **3.3**.

NOTE 1 Where a light logger is used, light measurements should be taken at least every 5 min.

NOTE 2 UV radiation measurements should be recorded at least once a year for all light sources and to check the performance of UV filtering film, or whenever a light source is changed if this occurs more frequently.

6.7.2 Light and UV radiation sensors shall be calibrated in accordance with the manufacturer's instructions, and a record kept of the calibration.

7 Pollution

This clause covers the identification and mitigation of the effects of pollutants on collection items and its requirements assume that collection items in storage or on display will remain in their environment for more than a year. It advocates an evaluate-monitor-mitigate approach for all collection items affected by or at risk from pollutants, whether in storage, on display or in transit.

7.1 Enclosed storage or display

7.1.1 Collection items in storage enclosures or display cases shall be evaluated to identify materials sensitive to gaseous pollutants generated within or by the enclosures or cases.

NOTE 1 Sources of internally generated pollutants are given in Table G.1.

NOTE 2 Pollutants such as acetic acid (ethanoic acid), formic acid (methanoic acid), formaldehyde (methanal), reduced sulfur gases and volatile organic compounds generally have higher concentrations in enclosures, compared with the external environment. Known pollutant-material interactions in enclosed storage where acetic acid, formic acid or formaldehyde are present are given in Table G.2.

7.1.2 The materials used to construct enclosures and display cases shall be evaluated to determine that they do not emit gaseous pollutants to an extent that would be expected to cause unacceptable irreversible change in the contents of the enclosure, as specified in **3.5**.

NOTE 1 Indicator tests of enclosure materials can be carried out using commercially available coupons or indicator strips. Guidance on testing methods is given in Green and Thickett (1993) and Strlič et al. (2010).

NOTE 2 Examples of known pollutant-material interactions in enclosures that lead to irreversible damage are given in Table G.2. There might be other interactions for which evidence is not yet available. Pollution-related damage is cumulative and it is not possible to specify safe pollutant concentrations for sensitive items, as these depend on exposure time.

NOTE 3 If enclosures are made of or contain materials that emit pollutants, collection items in such enclosures should be observed every six months to identify any pollution-material interactions. If potential interactions are known to be rapid, e.g. in the case of reduced sulfur gases emitted close to silver objects, where damage can occur within days or even hours, the observation period should be adjusted accordingly.

NOTE 4 Many pollutant-material interactions are promoted by high RH. If RH is below 30%, there is evidence to suggest that limestone, ceramic and most metallic collection items, except silver, will not deteriorate even when pollutants are present at high concentration. However, silver is known to tarnish in the presence of reduced sulfur gases at below 30% RH.

NOTE 5 The rate of any chemical reaction increases with increased temperature provided that other factors, especially RH, are unchanged. Thus the rate of pollution-induced damage will increase at higher temperatures.

*NOTE 6 Materials that can emit significant pollutants as they degrade include cellulose nitrate, cellulose acetate and poly(vinyl acetate). In such cases, collection items should be isolated or pollutant concentrations reduced or eliminated. Further guidance on mitigating the effects of pollutants is given in **7.5**.*

NOTE 7 Attention is drawn to Blackshaw and Daniels (1979) and Pretzel (2011).

7.2 Open storage or open display

7.2.1 Collection items in open storage or on open display shall be evaluated to identify materials known to interact with outdoor-generated gaseous pollutants and dust.

NOTE 1 Pollutants of most concern include ozone, nitrogen oxides, sulfur dioxide and dust. Guidance on the effects of these pollutants on particular materials is given in Table G.3.

NOTE 2 Storage and display areas should be designed and fitted with materials that do not emit reactive pollutants.

7.2.2 Published data on local outdoor gaseous pollutant concentrations shall be examined to determine which pollutants, if any, to monitor indoors.

NOTE 1 Local pollution data can be found at http://uk-air.defra.gov.uk.

NOTE 2 Since most externally generated pollutants have fairly constant short-term concentrations, monitoring only needs to be carried out seasonally.

7.2.3 If an outdoor gaseous pollutant concentration is high, and sensitive collection items are held on open display, pollutants shall be monitored indoors to guide action to mitigate any risks identified.

NOTE Pollution-related damage is cumulative and it is not possible to specify safe pollutant concentrations for sensitive collection items, as these depend on exposure time. However, approximate threshold concentrations for a number of pollutant-material interactions are given in Table G.4. These thresholds have been proposed for some sensitive materials based on observation during long-term exposure or accelerated degradation studies.

7.2.4 Collection items in open storage or on open display shall be evaluated to identify materials sensitive to damage by dust.

NOTE 1 Dust is present in every building. It can chemically damage surfaces, for example of metals, and can cause damage by abrasion. It provides a source of nutrients for insects, moulds and bacteria.

NOTE 2 Removal of dust can damage materials, especially historic textiles, if performed incorrectly. Filtered vacuum cleaners should be used by those with training in how to use them.

7.2.5 The rate of dust deposition shall be monitored to guide action to mitigate any risks identified.

NOTE Further guidance on monitoring dust is given in Levashova and Kobyakova (1997), Ligocki et al. (1990) and Lloyd, Grossi and Brimblecombe (2011).

7.3 Transit

7.3.1 Collection items in transit shall be evaluated to identify sensitive items known to interact with gaseous pollutants.

7.3.2 If collection items sensitive to gaseous pollutants are to be held in enclosures when in transit, **7.1** shall apply.

NOTE The total exposure time in transit, together with the pollutant concentration, should be taken into account, as damage is dependent on both pollutant concentration and exposure time.

7.3.3 Materials selected for the transport of collection items shall be evaluated to minimize the risk of pollutant-material interaction.

7.4 Monitoring

7.4.1 Gaseous pollutants specified in **3.5** shall be monitored in the collection space, including in enclosures housing sensitive collection items or collection items in transit, and where pollutant-material damage is observed.

NOTE Low-cost assessment methods (e.g. metal coupons, pH paper, colourimetric indicators or dosimeters) that do not indicate a specific pollutant but indicate the presence of high pollution levels can be used to screen environments. If justified, quantitative pollutant-specific monitoring methods can then be adopted to identify the chemical nature and concentration of the pollutants in the enclosure.

7.4.2 The dust deposition rate and airborne concentration of dust shall be monitored to identify the sources of dust or check the performance of filters.

NOTE 1 An acceptable level of dust will depend on the nature of the collection item and its context. Only a few quantitative standards have been developed for dust levels. The corrosion rates in BS ISO 11844-1 could be interpreted to indicate that a chloride deposition rate below 0.167 mg/m^2/day is acceptable.

NOTE 2 Further guidance on dust is given in Adams (1997), Yoon and Brimblecombe (2000a) and Yoon and Brimblecombe (2000b).

7.4.3 Pollutant sensors shall be calibrated in accordance with the manufacturer's instructions, and a record kept of the calibration.

7.5 Mitigation

7.5.1 If risks of pollutant-material interaction are identified or damage is observed in the collection, collection items shall be removed to a less polluted environment, or the pollution shall be eliminated.

NOTE 1 It should not be assumed that energy-intensive systems are required to deal with pollution-related risks without full investigation of all available options.

NOTE 2 An option to reduce the pollutant content of a display case is to construct the case with active or passive venting.

NOTE 3 *Where internally generated pollution is unavoidable, the air exchange rate (AER) of an enclosure should ideally be high enough to reduce the internal concentration of pollutants to a safe level, but not so high as to prevent effective control of the internal RH or allow the entry of externally generated pollutants or dust. Unfortunately, in many instances both are not possible and one will have to be given priority based on a risk assessment for the collection items, or alternatively, measures such as absorbents or mechanical RH control should be used.*

NOTE 4 *Air filtration is ineffective in reducing the accumulation of coarse dust. Guidance on coarse dust mitigation strategies is given in Lloyd et al. (2002). These include, for example:*

- *keeping visitors away from vulnerable collection items: the coarse dust deposition rate approximately halves for every metre a collection item is away from a tour route;*
- *keeping tour routes straight reduces dust deposition;*
- *frequent cleaning of tour routes reduces dust deposition on items;*
- *screening: a 1.5 m high dust-impermeable screen reduces dust deposition beyond it; and*
- *use of enclosures: the dust deposition rate inside a display case decreases as the AER falls.*

NOTE 5 *Further guidance on pollutants in collection environments is given in Grzywacz (2006), Hatchfield (2002), Nazaroff and Cass (1991) and Tétreault (2003a).*

7.5.2 Pollutant absorbers shall be replaced when measurements taken at predetermined intervals show that they are exhausted.

NOTE *In addition to the use of pollutant adsorbers, indoor pollution emission from materials can also be reduced by the application of barrier materials and/or protective coatings or lacquers.*

7.5.3 Paint, varnishes and coatings that do not emit volatile organic compounds shall be used in the vicinity of collection items whether in storage, on display or in transit.

NOTE 1 *Paints, varnishes and sealants can emit pollutants at high concentrations while maturing after application. Collection items should not be brought near maturing coatings until emissions have fallen below the thresholds given in Table G.4. Emission can continue for years after application, especially in a well-sealed low-air exchange enclosure.*

NOTE 2 *Gum, gelatine, casein and silicate bound paints can be used for brickwork, masonry and concrete.*

Annexes

Annex A (informative) Energy economy

A.1 General

This annex is intended to clarify the relationship between energy economy and environmental specifications for cultural collections, with the aim of promoting an energy-efficient approach to collections management.

Air brought into a collection space might require conditioning, i.e. heating, cooling, humidification or dehumidification, in order to achieve the environmental specification for the collection, as well as to ensure the comfort of staff and visitors. Meeting these sometimes conflicting requirements can be energy-intensive.

A.2 Principles

The following principles should be adopted to achieve energy economy.

a) The requirements of the collection should be defined before decisions are made on the use of air conditioning systems.

b) Temperature and RH should be specified to allow gradual change on an annual cycle.

c) If new building or renovation is planned, it should not be assumed that energy-intensive systems are required without full investigation of all available options, for example, the use of microclimates for sensitive collection items.

***NOTE** Attention is drawn to Hong et al. (2011) and Padfield et al. (2007).*

A.3 Implications of setting a narrow temperature and RH range

Meeting a tight specification (within ±3 °C for temperature and below ±5% RH) might require a full air conditioning system. Operating such a system is energy-intensive, particularly if adjoining collection spaces have conflicting requirements.

A.4 Implications of using a constant set point

Achieving a constant set point for temperature and RH will require energy use in both winter and summer when the outdoor conditions are different from the required constant set point. Energy is needed to change the temperature and adjust RH.

A.5 Energy-efficient environmental specification for storage

The most economical environmental specification is to allow the indoor temperature to follow ambient conditions. These conditions can and should be moderated by the thermal inertia of the building, enhanced by features such as the use of hygroscopic buffering materials, controlled air exchange and sealed display cases. The annual average indoor temperature will be near to the outdoor annual average. In practice it is possible to keep the annual variation within ±10 °C, although given that it is difficult to eliminate leaks, some dehumidification might be necessary in summer months. Achieving a low air exchange rate (AER) reduces energy use further by reducing the dehumidification load.

A.6 Energy use in cooled storage and cold storage

In cooled storage and cold storage, the temperature is nearly always below the ambient. The energy consumption is proportional to the difference between the cooled or cold storage and the ambient temperature. Since the AER is slow, the energy demand made by humidity control equipment will be low.

A.7 Energy for lighting

Both incandescent and fluorescent light sources are energy-intensive in comparison to compact source light emitting diodes (LEDs), which are more energy efficient and now widely used in collection spaces for storage and display. Making the most effective use of the generated light to illuminate collection items on display is an important means of saving energy while controlling the environmental conditions. The benefits of daylight, appropriately managed by means of blinds and filters, should also be considered.

Annex B (informative)
Interactions between agents of deterioration

Examples of known interactions between the agents of deterioration covered in this PAS are shown in Table B.1.

Table B.1 – Examples of interactions between agents of deterioration

Interaction	Description
Temperature and RH	• Some materials react differently to the same temperature at different levels of RH, and vice versa, e.g. most hygroscopic materials.
Temperature and light	• Light energy will cause the surface temperature of collection items to rise. Some light-induced changes occur more rapidly at high temperatures. • Even in a moderately illuminated showcase, the surface temperature can rise 2 °C above the ambient. This in turn lowers the RH about 6% in the boundary layer next to the collection item's surface, leading to movement of moisture. • Direct sunlight, even through a glass window, can raise the surface temperature of a dark collection item over 60 °C, causing a very low surface RH. • Short periods of high temperature are often caused by direct sunlight or intense incandescent lighting, for example during filming. Some light-induced changes occur more rapidly at high temperatures.
Temperature and pollution	• Internally generated pollution increases with rising temperature because of an increased rate of decay of materials and diffusion of gases to the surface of materials.
RH and light	• High RH increases the speed of photo-activated degradation reactions in paper and many other materials.
RH and pollution	• RH increases the absorption of pollutants. High RH causes the water content of hydrophilic materials to increase and this facilitates absorption of most pollutants by such materials. • High RH causes deliquescence of water-soluble salts, which are common contaminants of collection materials. The aqueous medium allows ionization of absorbed gases, enabling them to react. • Low RH facilitates transfer of dust by electrostatic force, such as that caused by cleaning glass and plastic.

Annex C (informative)
Relative risk of damage and deterioration due to temperature

A visual representation of the relative risk of damage and deterioration due to temperature is given in Figure C.1 alongside the relative energy demand associated with maintaining a particular temperature.

Figure C.1 – Relative risk of damage and deterioration due to temperature

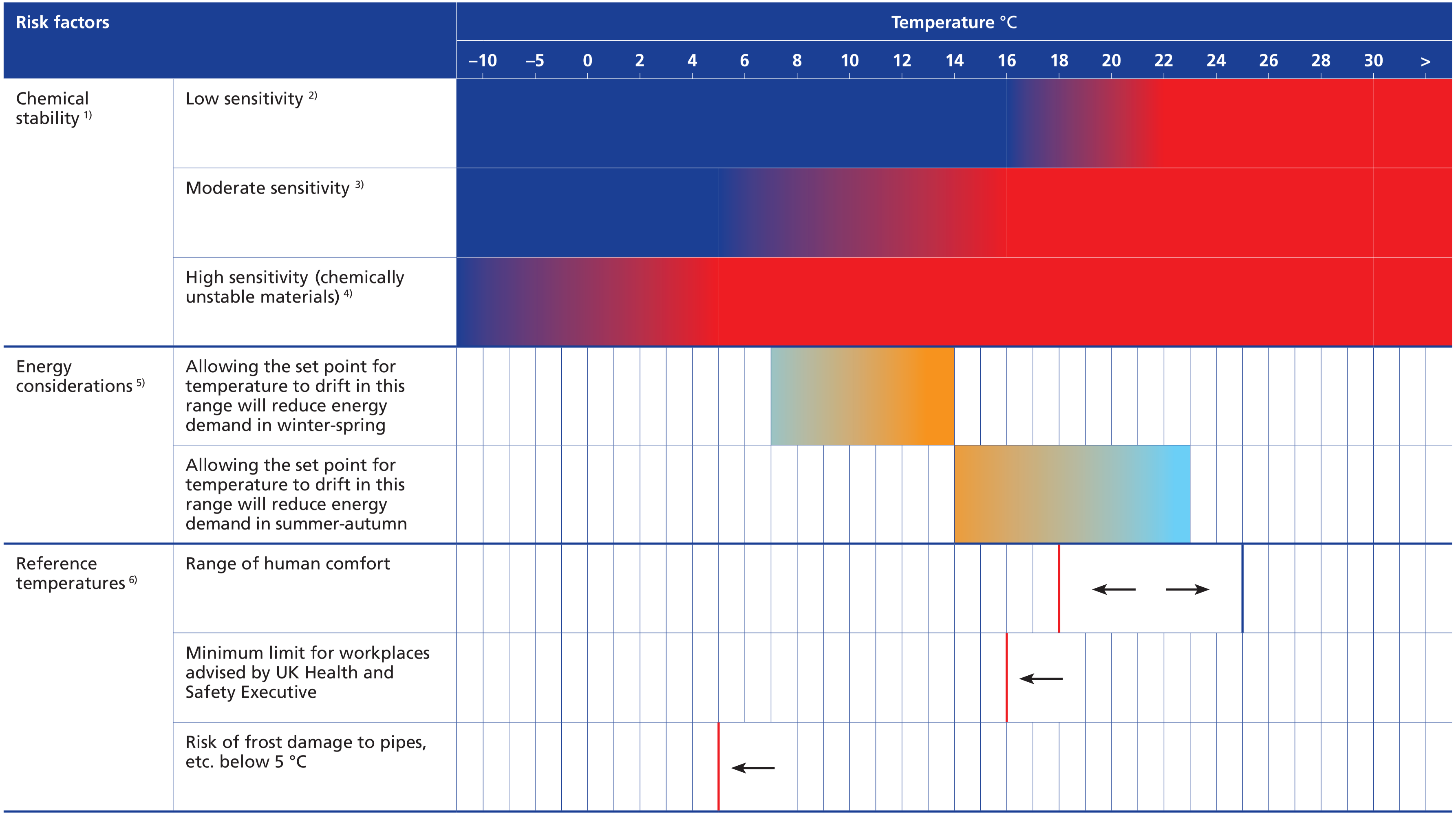


Figure C.1 – Relative risk of damage and deterioration due to temperature *(continued)*

Key

[1] Chemical stability: these ranges show higher temperatures leading to accelerated degradation rates, indicated by the gradation from blue to red.

[2] Low sensitivity: materials with reaction rates less affected by temperature, e.g. ceramic, glass.

[3] Moderate sensitivity: materials with reaction rates moderately affected by temperature, e.g. paper.

[4] High sensitivity: materials with reaction rates highly affected by temperature, e.g. plastics, film.

[5] Energy considerations: these ranges show the energy demand, with the light blue indicating lower demand and the orange higher demand.

[6] Reference temperatures: reference temperatures are included for the purposes of comparison. The human comfort range is between 18 °C and 25 °C, while the lower limit for human occupation in the workplace in the UK is 16 °C (13 °C if much of the work is physical). There is no lower limit for exhibitions that take place in conditions outside the human comfort range. Below 0 °C, there is an increasing risk of frost damage to the building structure, frozen pipes, etc., so a 5 °C limit is a precautionary lower limit based on expectations of spatial and temporal variation.

***NOTE 1** Chemical reactions accelerate exponentially as temperature rises. A practical approximation for moderately stable organic materials is that reaction rates double with each 5 °C rise.*

***NOTE 2** If the period of exposure is sufficient for thermal response (minutes to hours for most collections), there is no difference in the potential for physical damage between short and long periods of low temperature, except in a few special cases such as migration of plasticizers from plastics or of lubricants from magnetic tape.*

***NOTE 3** Many ethnographic and decorative arts collection items have been observed during exposure to –30 °C in collections in cold countries or following the use of low temperature pest control. The consensus is that no visible damage beyond a few small fractures has occurred to the great majority of items.*

***NOTE 4** Low temperatures can cause embrittlement due to a T_g change.*

Annex D (informative)
Relative risk of damage and deterioration due to relative humidity

A visual representative of the relative risk of damage and deterioration due to relative humidity is given in Figure D.1 alongside the relative energy demand associated with maintaining a particular temperature.

Figure D.1 – Relative risk of damage and deterioration due to relative humidity

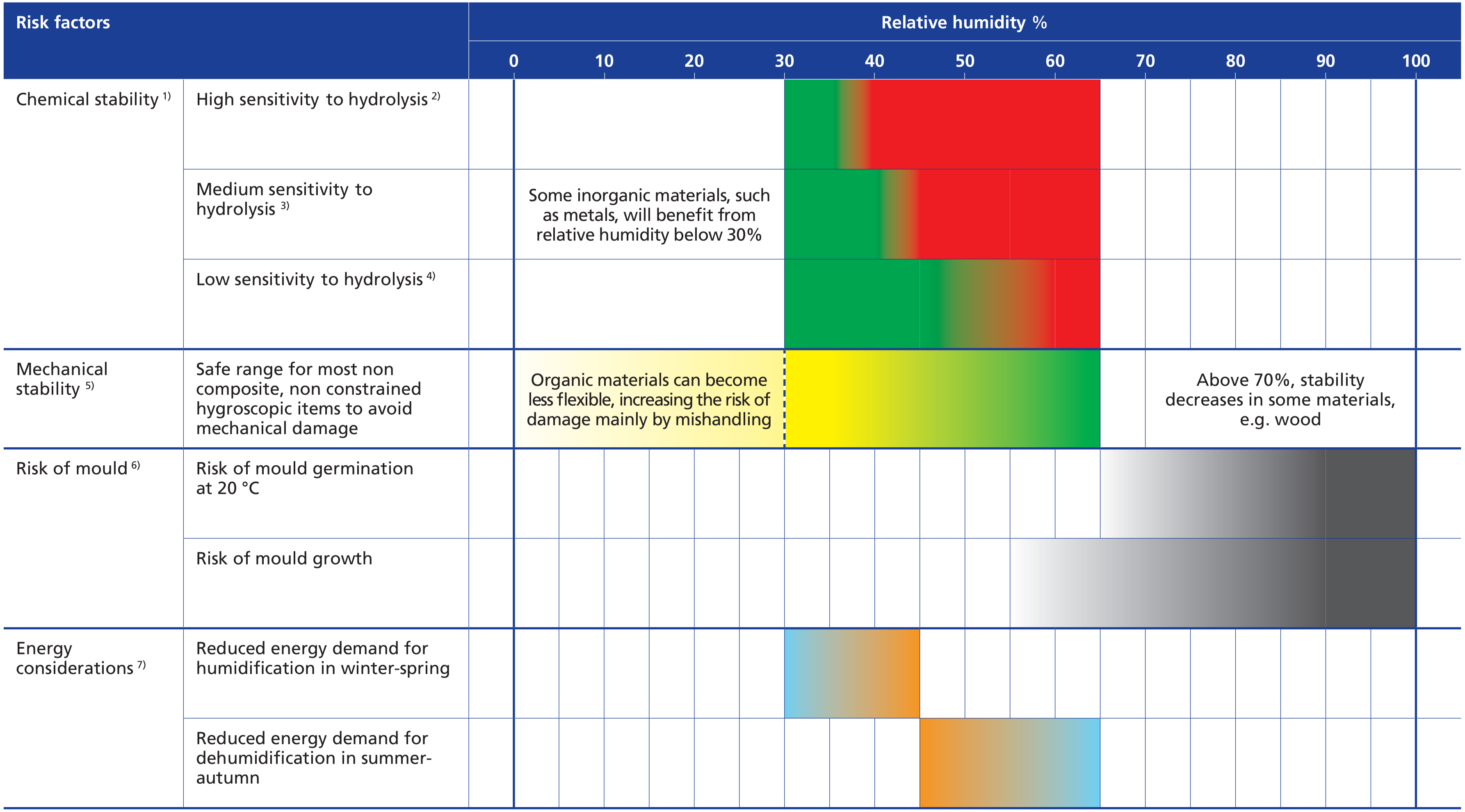


Figure D.1 – Relative risk of damage and deterioration due to relative humidity *(continued)*

Key

1) Chemical stability: these ranges show higher RH leading to accelerated moisture-induced chemical degradation rates, indicated by the gradation from green to red.

2) High sensitivity to hydrolysis: materials with a relatively high presence of hydrolysis-sensitive chemical groups within the polymer chain, e.g. leather and textiles previously acidified by pollution, cellulose acetate film.

3) Moderate sensitivity to hydrolysis: materials with a relatively moderate presence of hydrolysis-sensitive chemical groups within the polymer chain, e.g. some wood pulp papers.

4) Low sensitivity to hydrolysis: materials with a relatively low presence of hydrolysis-sensitive chemical groups within the polymer chain, e.g. rag paper, polyester film.

5) Mechanical stability: the area shown in yellow indicates the range within which the risk of physical damage is higher, while the area shown in green indicates the range within which the risk of physical damage is lower. In the area below 30% RH, the risk of damage to organic materials by mishandling is increased despite the reduced rate of chemical degradation. In the area above 70% RH, for some materials e.g. wood, mechanical stability decreases.

6) Risk of mould: the areas shown in grey indicate a precautionary upper limit of 65% RH to avoid mould germination at 20 °C. The gradation to darker grey indicates increasing risk of mould growth and faster germination times. Note also that mould germination and growth are also temperature dependent.

7) Energy considerations: these ranges show the energy demand, with the light blue indicating lower demand and the orange higher demand.

***NOTE 1** Current research on simple laminar test composites of traditional materials (e.g. wood, oil paint, gesso and gelatine) suggests that at least ±15% RH fluctuation is needed to approach yield or fracture due to either tension or compression in one of the layers. Some collection items are more sensitive in their structure than test composites, and some materials weaken with age, so some aged collection items can fracture with smaller fluctuations.*

***NOTE 2** At 75% RH and above, the dimensional change due to each 5% rise in RH increases exponentially. Restrained layers, especially wood, begin to suffer irreversible compression, causing greater sensitivity to fracture during periods of low RH. Gelatine in, for example, animal glues, paper size and photographic image layers begins to change from a tough strong material to a sticky weak material, causing glued assemblies to become detached and photographs to stick together. Paper and parchment begin to release manufacturing strains, causing permanent cockle. All forms of metal corrosion increase their rates several times.*

***NOTE 3** Attention is drawn to Michalski (2009).*

Annex E (informative)
Material damage and deterioration and risks associated with temperature and relative humidity

Guidance on the damage and deterioration and the risks associated with temperature and relative humidity (RH) is given in Table E.1 for a representative selection of materials found in collections.

The damage and deterioration and risks described are based on evidence from referenced research publications, details of which are given in the bibliography. It is recognized that some entries are more complete than others. Where entries are more complete, this reflects an existing body of published empirical evidence; in some areas, however, it is clear that further evidence is required.

Many collection items are composite objects with a structure that combines a number of different materials. Each element in these diverse structures is vulnerable to change and degradation with time, often as a result of adverse and varying environmental conditions over long periods. These objects are often most affected by fluctuating RH over short periods. Furthermore, composite objects behave in a more complex manner than the sum of their individual components. Historic repairs and previous conservation work can also increase the vulnerability of a collection item.

Table E.1 – Material damage and deterioration and risks associated with temperature and relative humidity

Material	Damage and deterioration	Risk	Evidence
Archaeological copper alloy	• **High RH** (above 50%): can cause powdering and bronze disease.	• Material change can happen quickly, leading to complete loss of collection item.	Organ (1963) Papapelekanos (2010) Scott (1990)
Archaeological iron	• **High RH** (above 50%): delamination (temperature-dependent). • **Medium RH** (below 50%): active corrosion of any remaining metal core. • **Low RH** (below 30%): powdering of surface and small-scale flaking.	• Loss of metallurgical information or complete loss of collection item.	Thickett (2004) Turgoose (1982) Watkinson and Lewis (2004)

Table E.1 – Material damage and deterioration and risks associated with temperature and relative humidity *(continued)*

Material	Damage and deterioration	Risk	Evidence
Ceramics	• **High RH**: can cause corrosion if collection item contains metal or other humidity-sensitive materials. • **Fluctuating RH**: archaeological ceramics can contain salts that will effloresce, causing disfigurement or disruption of surface. • **Low RH** (below 40%): can cause shrinkage away from metal components, cracking and flaking from surface.	• Partial or total loss of collection item.	Buys and Oakley (1996)
Easel paintings: traditional materials *Traditionally made easel paintings are composite objects and include works with oil binder, mixed media or egg tempera, on wood, canvas or other substrates*	• **Low temperature**: oil paint composites (comprising some or all of the following: size, preparation layers, paint and varnish) become brittle below their T_g. Low temperatures can therefore pose a greater threat. While the evidence is incomplete, it indicates that temperatures below 5 °C, held long enough for thermal response, can cause oil films to become less flexible and more likely to crack. • **Fluctuating RH:** Expansion and contraction of paint composite components and wood and canvas substrates, leading to separation between layers (e.g. paint and canvas or within paint layers). Fluctuating RH is considered a greater risk than a stable RH at a relatively high or low level (e.g. 45% to 60%). A consistently higher RH is considered to be less risky to a composite object than a low RH.	• **Low temperature:** response to low temperatures in the form of cracking leads to disruption of the paint surface, flaking or complete loss of paint, with an associated loss of visual integrity and intrinsic value. • **Fluctuating RH:** can lead to severe mechanical damage to paintings on wood supports due to movement of wood where associated materials (e.g. paint or old repairs) cannot accommodate dimensional changes. • **Fluctuating RH:** can lead to severe mechanical damage to paintings on canvas supports due to differential expansion or contraction of the layers in the restrained composite leading to serious distortions (bulges, depressions), associated paint rupture (cracking), delamination of the paint composite (flaking) and loss of paint with associated loss of visual integrity and intrinsic value. • **Sustained high RH:** can result in mould growth, which attacks the paint composite or support, resulting in staining and loss of paint.	Saunders (1993) Thomson (1986) More detailed guidance on conditions for easel paintings made of traditional materials, and the specific environmental parameters required by The National Gallery UK, is available from: www.nationalgallery.org.uk/environmental-conditions

Table E.1 – Material damage and deterioration and risks associated with temperature and relative humidity *(continued)*

Material	Damage and deterioration	Risk	Evidence
Easel paintings: modern materials *Modern (20th and 21st-century) easel paintings are composite objects and include works with oil binder, mixed media, egg tempera and synthetic resins, e.g. acrylic or polyvinyl (acetate), on various substrates, fabric or rigid supports including canvas or wood*	• **Low temperature**: synthetic resins (e.g. acrylic resins, acrylic emulsions) are known to be susceptible to cracking at low temperatures (since they become brittle below their T_g). Temperatures below 5 °C, held long enough for thermal response, will cause synthetic paint layers to become less flexible. Rupture will occur if the materials are stressed in these conditions: the lower the temperature, the more likely they are to crack. • **High temperature**: softening of some paints at high temperatures. • **Fluctuating RH**: expansion and contraction of rigid supports such as wood and hardboards, leading to separation of media layers from the support and associated cracking and flaking. • **Lower RH**: materials can tear or fracture if held under restraint and RH is lowered. • **Higher RH**: acrylic emulsions can swell at higher RH. Paint layers on board can delaminate if paint adhesion is poor.	• Many of the risks listed in the previous entry also apply to modern paintings. This includes the promotion of cracks, distortion, embrittlement, shrinkage or expansion of support, loss of areas of paint, mould growth and distortion of paint surfaces.	Hackney (2004) Jablonski et al. (2004) Mecklenburg (2007) Young and Hagan (2008)
Enamels	• **High RH**: can accelerate chemical deterioration and cause metal to corrode under enamel layer, causing delamination and damage to enamel. • **Fluctuating RH**: can cause crizzling and cracking at the metal/enamel interface. • **High RH**: can accelerate chemical deterioration.	• Partial or total loss of collection items.	Brill (1962) Ryan (1996)

Table E.1 – Material damage and deterioration and risks associated with temperature and relative humidity *(continued)*

Material	Damage and deterioration	Risk	Evidence
Film	• **Low RH** (below 30%): will cause loss of moisture affecting the gelatine and emulsion layers, leading to flaking and/or delamination. • **Sustained high RH** (above 50%): gelatine layer becomes soft and sticky, bio-deterioration. • **High RH** (above 50%): and temperature above 7 °C will accelerate the rate of chemical decay of colour image, nitrate and acetate film; and can cause chemical deterioration, e.g. leaching of plasticizers.	• Permanent film deformation (brittleness or curl); loss of information; “blocking” of film reels (gelatine layer adhering to enclosures or adjacent sections of film). • Destruction of emulsion due to fungus growth. • Vinegar syndrome in acetate film. • Loss of information.	BS 1153 BS ISO 18934 Mallinson (1994) Michalski (2000)
Glass	• **High RH**: fluctuating conditions can cause chemical deterioration of unstable glass: crizzling, weeping and alkaline weeping at the surface, leading to eventual cracking. • **Low RH**: can cause localized drying and cracking.	• **High RH**: Partial or total loss of collection items. • **Low RH**: Flaking, particularly archaeological glass.	Brill (1972) Brill (1975) Davison (2003) Koob (2006) Kunicki-Goldfinger (2008) Ryan (1996)
Ink: digital ink	• The extent of change depends on the substrate (usually paper), the composition of the ink, e.g. dye-based or ink-based, and the interaction between them. • **Temperature**: at 20 °C to 30 °C (if RH is below 60%), most digital inks are stable. • **High temperature** (above 45 °C): dye migration. • **High temperature** (above 35 °C): at 50% RH density gain and yellowing of paper support. • **High RH**: above 60% RH, dye migration; a shift at 60% at average temperatures (16 °C to 18 °C for some dyes).	• Gradual change of digital image quality, loss of image, and an associated loss of intrinsic value.	Bugner and Lindstrom (2005) Hill, Suitor and Artz (2000) Kaimoto and Shibahara (2007) McCormick-Goodhart and Wilhelm (2000) Wilhelm (2005)

Table E.1 – Material damage and deterioration and risks associated with temperature and relative humidity *(continued)*

Material	Damage and deterioration	Risk	Evidence
Ink: iron gall ink	• Data suggests iron gall inks are susceptible to both oxidation and hydrolysis. The latter is especially significantly accelerated by high RH and high temperature. Long-term preservation is achievable by cooled storage or cold storage similar to those for rosin-sized acidic papers. The present level of knowledge suggests limits of ±10% RH and ±5 °C in any time interval.	• Ink corrosion ultimately leads to loss of material support, which results in loss of areas with ink application and loss of information. In earlier stages of deterioration, ink lines are prone to cracking during handling.	Kolar and Strlič (2006)
Ivory	• **Fluctuating RH**: ivory is very sensitive to RH, much less so to temperature. It is hygroscopic and anisotropic and suffers from cracks due to stress during expansion and contraction in response to changing RH. Thin sheets of ivory will distort. • **Low temperature**: ivory only suffers from structural change if restrained e.g. in mounts. Efflorescence of magnesium phosphate crystals can rupture paint surfaces on ivory and can be caused by low humidity.	• Cracks, distortion, breakage and loss. • Disruption of painted surfaces and loss of paint and image.	Freund et al. (2002) Lafontaine and Wood (1982) Mecklenburg (2007)
Leather	• **High temperature**: above 20 °C, increase in the rate of chemical-induced degradation; oxidation of protein and tannins leading to loss of stability; and hardening. • **Low RH**: below 35%, desiccation leading to breaks and other physical changes occur. • **High RH**: above 60% mould can develop; and shrinkage occurs, leading to embrittlement.	• Structural deterioration and loss of protein structure; staining and discolouration due to mould growth; loss of intrinsic value.	Bowes and Raistrick (1967) Calnan (1991)

Table E.1 – Material damage and deterioration and risks associated with temperature and relative humidity *(continued)*

Material	Damage and deterioration	Risk	Evidence
Metals (except archaeological metal)	• **High RH**: lead corrodes (when carboxylic acids are present); iron and copper alloys corrode in normal atmospheres above 65% to 70%. Silver will tarnish even in a clean atmosphere (with hydrogen sulfide and carbonyl sulfide at parts per trillion concentrations) and will occur even at low RH.	• Corrosion (lead). • Tarnish (silver).	Graedel (1992) Kim and Payer (1999) Leygraf and Graedel (2000)
Minerals	• Inappropriate RH levels can cause deliquescence, volatilization, hydration, corrosion and efflorescence. • **High RH**: will also promote acidic destruction of pyrite and marcasite in the oxidation process, provoking destruction of associated materials. • Collection items containing oxidized iron disulfide minerals, mineralogical, geological, palaeontological and archaeological collection items containing pyrite and marcasite that has oxidized at RH levels below 60%: exposure to RH above 60% can result in hydration of embedded nono-hydrate oxidation product, szomolnokite, leading to rapid expansion and physical destruction of collection item. 55% should be observed as a precaution.	• Irreversible chemical change or change of state; loss of morphology; change of colour; cracking and loss; damage to, and loss of, adjacent materials.	Howie (1979) Stanley (2004) Waller (1987) Waller (1992)

Table E.1 – Material damage and deterioration and risks associated with temperature and relative humidity *(continued)*

Material	Damage and deterioration	Risk	Evidence
Palaeontological collection items	• **High RH**: RH above 60% will accelerate clay mineral breakdown and oxidation of pyrite (iron disulfide) and hydration of iron sulfate. Exposure to RH above 60% can result in hydration of embedded nono-hydrate oxidation product, szomolnokite, leading to rapid expansion and physical destruction of collection items. (55% should be observed as a precaution) • **Low RH**: in specimens, RH below 35% will cause breakdown of clay minerals leading to delamination and shrinkage of matrix. Embrittlement of iron oxide-rich matrix. Increased risk of bio-degradation if RH is below 65%. • **Fluctuating RH**: will increase rates of mechanical deterioration.	• Oxidation of pyrite will lead to low level powdering to complete loss of specimens and damage to storage enclosures and associated organic collection items. • **Low RH**: cracking to collection item; complete loss of collection item.	Collins (1988) Collins (1995) Howie (1979) Howie (1992) Waller (1987) Waller (1992)
Paper	• **High RH**: above 65%, increased risk of bio-deterioration. Acid hydrolysis significantly accelerates with RH. • Acidic paper and paper containing iron gall ink generally degrade at 10 times the rate of rag and alkaline/pseudo-alkaline sized papers, and require lower temperature and/or RH for long-term preservation. • Fluctuations of ±10% RH and ±5 °C are considered acceptable.	• Brittleness due to hydrolysis or oxidation. Discolouration due to chemical degradation or photo-induced degradation. Stiffness of bindings if RH is below 25%. • Mechanical damage leading to loss of original material, information and intrinsic value.	Bogaard and Whitmore (2002) Menart, De Bruin and Strlič (2011) Sebera (1994) Strlič and Kolar (2005) Wilson and Parks (1983)

Table E.1 – Material damage and deterioration and risks associated with temperature and relative humidity *(continued)*

Material	Damage and deterioration	Risk	Evidence
Parchment	• Setting environmental conditions depends upon the proportion of collagen and gelatine in the parchment. • **High temperature**: causes structural changes in collagen and predisposes parchment to gelatinization. • **Low temperature**: temperatures below 0 °C will induce structural changes in collagen. Effects on historic parchment have yet to be investigated. • **Fluctuating RH**: increased cockling and distortion leading to separation of paint and ink layers from support. • **High RH**: above 65% there is an increased risk of biodegradation. • 38% to 45% RH produces a water content of approximately 14%, which reduces internal stress. • **Low RH**: RH below 30% increases stiffness of bindings.	• Inappropriate conditions will cause permanent distortion leading to loss of information and decrease in intrinsic value of the collection item.	Bowden and Brimblecombe (2002) Dernovšková, Jirsová and Zelinger (1995) Hansen, Lee and Sobel (1991) Larsen (2002) Schilling and Ginell (1993)

Table E.1 – Material damage and deterioration and risks associated with temperature and relative humidity *(continued)*

Material	Damage and deterioration	Risk	Evidence
Photographs	• **High temperature**: dye fading, accelerating degradation, e.g. vinegar syndrome. • **Low RH**: below 20% will cause desiccation of the component parts. • **High RH**: above 50% leads to rapidly increased rates of hydrolysis of cellulose acetate and nitrate-based film. Silver images, particularly with residual chemical agents, will suffer redox reactions, silver mirroring, sulfiding, loss of transparency in glass negatives. • **High RH**: above 70% can suffer micro-organism growth, softening and adhesion of the gelatine layer. • **Fluctuating temperature and RH**: paper prints, film, gelatine, albumen can suffer condensation, differential expansion/ contraction, deformation, desiccation, crazing.	• Loss of physical properties and loss. • Brittleness, breaking, deformation; delamination of cellulose acetate bases, paper prints, gelatine, albumen, glass negatives of collection items. • Disfiguring stains, photographs sticking together; loss of information and intrinsic value. • Breaking, leading to loss of information and intrinsic value.	BS ISO 18934 Lavédrine et al. (2009) McCormick-Goodhart (1996)

Table E.1 – Material damage and deterioration and risks associated with temperature and relative humidity *(continued)*

Material	Damage and deterioration	Risk	Evidence
Plastics	• Oxidation, hydrolysis, often catalytical. • **High temperature**: can induce creep or deformation of plastics with low T_g (PE, PP, synthetic rubber, plasticized PVC). • **Low temperature**: will induce deformation of collection items with low T_g; plasticizer migration. • **High RH**: For hygrophilic plastics (e.g. casein formaldehyde), above 40% leads to deterioration. • **High RH**: For synthetic plastics, higher RH (e.g. 50% to 60%) is advised to avoid deterioration due to possible build up of electrostatic charge. • **Low RH**: For hydrolytically degrading plastics (e.g. polyurethane, cellulose nitrate, cellulose acetate), below 30% leads to deterioration.	• Fading of dyed plastics, loss of flexibility particularly of foams and flexible plastics, crazing, delamination. Yellowing and browning. Composite objects can distort. Migration of plasticizers can affect collection items in contact.	Shashoua (2008) Quye and Williamson (2009)
Stone	• **Fluctuating temperature and RH:** crystallization, powdering, delamination, loss of surface, destruction.	• Salt cycles, deliquescence and hydration, clay hydration.	Arnold and Zehnder (1990) Bradley and Middleton (1988) Price (2000) Zehnder (1993) Zehnder (1996) Zehnder and Arnold (1989)
Textiles	• Range of components and structures means that textiles exhibit range of deterioration pathways, including oxidation and hydrolysis. • Cellulosic textiles often degrade similarly to other cellulosic materials (e.g. paper).	• Loss of textile strength with decreasing molecular weight of polymer; higher temperature and RH also accelerate fading for a range of dyes and textiles.	Cunliffe (1956) Egerton (1948) Giles and McKay (1963) Lovett and Eastop (2004) Luxford (2009) Timár-Balázsy and Eastop (1998)

Table E.1 – Material damage and deterioration and risks associated with temperature and relative humidity *(continued)*

Material	Damage and deterioration	Risk	Evidence
Waxes	• **High temperature**: can cause surface stickiness, trapping pollutants. Loss of solvents causes embrittlement over time and vulnerability to physical damage. • **Low temperature**: temperatures below 13 °C can cause surface crystallization of solvents in beeswax, leading to embrittlement.	• **High temperature**: Cracking and loss; loss of surface definition; attachment to other surfaces in contact. • **Low temperature**: Embrittlement, loss of collection item, information and intrinsic value.	Cassar (1982) Murrell (1977) Novotná and Durnovšková (2002) Plenderleith and Werner (1971) Purewal (1997) Reid of Robertland and Ross (1970)
Wood	• Oxidation leading to discolouration. Temperature-related expansion coefficients are small. RH-related expansion coefficients are dependent on species and grain orientation, and can lead to physical damage due to internal stress.	• Cracking, lifting of veneers, loss.	Bratasz, Jakieła and Kozłowski (2005) Jakieła, Bratasz and Kozłowski (2007) Jakieła, Bratasz and Kozłowski (2008) Mecklenburg, Tumosa and Erhardt (1998)

Annex F (informative)
Sensitivity of materials to light

Guidance on the sensitivity of materials to light and supporting research references is given in Table F.1 and Table F.2. In particular:

a) a representative selection of materials found in collections are grouped in Table F.1 in terms of their sensitivity to light; and

b) the time taken for fading to occur at different illuminances is given in Table F.2 for materials with different sensitivities to light.

Exposure to light can result, not only in fading, but also in a reduction in mechanical strength (caused by photo-degradation). Exposure to light can also result in embrittlement through cross-linkage, where the relative proportion of amorphous areas to crystalline areas within a polymer is reduced, resulting in a loss of flexibility. Light exposure can have other effects, e.g. discolouration through darkening: aged cellulosic textiles can look yellow/brown because of the formation of coloured deterioration products. The vulnerability of textiles to photochemical damage is influenced by the types of fibres, dyes and finishes, and the presence of other materials (e.g. decorative elements, such as metallic threads), contaminants (which can serve as catalysts for degradation) and moisture.

Table F.1 – Materials grouped by sensitivity to light [A)]

No sensitivity *Materials that do not change colour due to light but due to ageing or exposure to pollutants.*	**Low sensitivity** *Materials rated ISO Blue Wool #7 and #8.*	**Medium sensitivity** *Materials rated ISO Blue Wool #4, #5 or #6.*	**High sensitivity** *Materials rated ISO Blue Wool #1, #2 or #3.*	**References**
• Most mineral-based pigments, including earth pigments, copper carbonate pigments, and frit (glass-based) pigments. • Many monochrome images on paper, such as carbon inks, but the tint of the paper and added tint to the carbon ink are often high sensitivity. • Rag paper is very stable, but pre-19th century paper varies widely.	• Artists' palettes classified as "permanent" (a mix of truly permanent paints and paints with low sensitivity to light). • Structural colours in insects (if UV radiation is blocked). • Some plant extracts, especially indigo. • Silver/gelatine black-and-white prints, but not those on resin coated paper (if UV radiation is blocked). • Many high-quality modern pigments for external use, e.g. vehicle paints, house paints. • Vermilion (blackens due to light). • Red lead (lightens or darkens). • Polyester.	• Alizarin dyes and lakes. A few historic plant extracts, particularly madder-type reds containing primarily alizarin, as a dye on wool or as a lake pigment in all media. Some are low-sensitivity, depending on the concentration, substrate and mordant. • Iron gall inks. • Colourants found in most furs and feathers. • Colour photographs with "chrome" in the name of the film, e.g. Cibachrome, Kodachrome. • Orpiment, realgar. • Buckthorn, weld, broom. • Wools, cellulosic materials which do not contain lignin, e.g. cotton.	• Most plant extracts, hence most historic bright dyes and lake pigments in all media: yellows, oranges, greens, purples, many reds, blues. • Wood pulp papers, including those containing lignin. • Insect extracts, such as lac dye and cochineal (e.g. carmine) in all media. • Most early synthetic colours such as the anilines, all media. • Most felt tip pens including blacks. • Most red and blue ballpoint inks. • Most dyes used for tinting paper in the 20th century. • Most colour photographs with "colour" or "color" in the name of the film, e.g. Kodacolor, Fujicolor. • Chlorophyll-based colours in herbarium specimens. • Many alcohol-preserved zoological specimens. • Certain mineral specimens, e.g. realgar, silver halides. • Silks, nylon, lignin-containing cellulosic materials, e.g. jute, severely degraded linen with a "bleached" appearance.	Ashley-Smith, Derbyshire and Pretzel (2002) Bullock and Saunders (1999) Chevreul (1837) CIBSE (1994) CIE (2004) IESNA (1996) Michalski (1987) Michalski (1997) Michalski (2010) Padfield and Landi (1966) Pretzel (2008) Russell and Abney (1888) Saunders and Kirby (1994) Timár-Balázsy and Eastop (1998)

[A)] This table is derived from Michalski, S. (2010) *Light, ultraviolet and infrared,* Table 3. It is available from the Canadian Conservation Institute website: http://www.cci-icc.gc.ca/caringfor-prendresoindes/articles/10agents/chap08-eng.aspx.

Table F.2 – Time taken for fading to occur at different illuminances [A)]

Illuminance lux	Extent of fading	Time for fading		
		Low sensitivity	**Medium sensitivity**	**High sensitivity**
50	Just noticeable fade	300 – 7 000 years	20 – 700 years	18 months – 20 years
	Almost total fade	10 000 – 200 000 years	700 – 20 000 years	50 – 600 years
150	Just noticeable fade	100 – 2 000 years	7 – 200 years	6 months – 7 years
	Almost total fade	3 000 – 70 000 years	200 – 7 000 years	15 – 200 years
500 (office)	Just noticeable fade	30 – 700 years	2 – 70 years	7 weeks – 2 years
	Almost total fade	1 000 – 20 000 years	70 – 2 000 years	5 – 60 years
5 000 (window or study lamp)	Just noticeable fade	3 – 70 years	2 months – 7 years	5 days – 2 months
	Almost total fade	100 – 2 000 years	7 – 200 years	6 months – 6 years
30 000 (average daylight)	Just noticeable fade	6 months – 10 years	2 weeks – 1 year	1 day – 2 weeks
	Almost total fade	20 – 300 years	1 – 30 years	1 month – 1 year

NOTE 1 *Each day of exposure is assumed to be 8 hours, each year 3 000 hours. Time for a "just noticeable fade" is given as a range based on the doses for the range of ISO Blue Wools in that sensitivity category as given in Table 4 of Michalski (2010). The "almost total fade" is based on a conservative estimate of 30 times the "just noticeable fade" although fading often slows down, so that an estimate of 100 times the" just noticeable fade" is probable for many colours.*

NOTE 2 *A previously exposed surface of an item is less sensitive to light and UV radiation than an unexposed surface of the same composition (in that collection item or another collection item), i.e. after high sensitivity colourants are faded, the remaining colourants should be medium sensitivity, and so on. Thus an estimate of sensitivity can be based solely on knowledge of prior exposure, e.g. a painting that is known to have been exposed for 100 years at known gallery lighting, or in a fixed historic setting with stable lighting, will not be noticeably faded further until future exposure reaches around 5% of prior exposure, and will not be greatly changed until future exposure matches prior exposure.*

NOTE 3 *The generally accepted range of 150 lux to 200 lux for some types of collection items such as oil paintings cannot be based on a global difference in sensitivity, since many oil paintings contain (or did contain) high sensitivity colourants, and many works on paper are executed in low or no sensitivity colourants. These higher intensities can be, and have been, based on viewer preference studies and on the prevalence of dark and low contrast passages in these collections, as compared to the prevalence of bright and high contrast passages in works on paper.*

NOTE 4 *Current evidence of rates of UV radiation damage is sparse, although attempts have been made to develop damage functions. Common experience shows that UV radiation from full sunlight can yellow newsprint in days, can noticeably chalk oil paint, acrylic paint and bone in a year and can erode wood several millimetres per century. Experience also shows that filtration by window glass alone reduces these effects by at least 10 times to 100 times. Filtration down to 75 µW/lumen will probably reduce this to 100 times to 1 000 times. Reducing illuminance compounds these benefits, since all light and UV radiation damage is proportional to illuminance: compared to sunlight (100 000 lux) the rate of damage of the above examples at 100 lux is slower by 1 000 times.*

NOTE 5 *UV affects organic materials, but rarely inorganic materials. Given Note 4, any material known to be able to survive several years in outdoor sunlight without noticeable effect (beyond those attributable to pollutants, rain or oxygen) can be considered unaffected by UV, e.g. stone, ceramics, metals.*

[A)] This table is derived from Michalski, S. (2010), *Light, ultraviolet and infrared*, Table 3. It is available from the Canadian Conservation Institute website: www.cci-icc.gc.ca/caringfor-prendresoindes/articles/10agents/chap08-eng.aspx.

Annex G (informative)
Sources of pollutants and their effects on materials

Guidance on sources of pollutants and the effect of pollutants on certain materials is given alongside supporting research references in Tables G.1 to G.4. In particular:

a) sources of internally generated pollutants are given in Table G.1;

b) pollutant-material interactions in enclosures are given in Table G.2;

c) pollutant-material interactions in open storage or open display are given in Table G.3; and

d) approximate threshold concentrations for a number of pollutant-material interactions are given in Table G.4.

Table G.1 – Sources of internally generated pollutants

Source	Pollutant	References
Acrylic and nitrocellulose paints	Acetic acid (ethanoic acid) Solvents	Donovan and Moynehan (1965) Tétreault (1992)
Cellulose acetate collection items, cellulose triacetate film	Acetic acid (ethanoic acid)	Allen et al. (1987) Allen et al. (1990) Aubier (1996) Edge et al. (1992) Edwards et al. (1993) Quye (1998) Ram (1994)
Cellulose nitrate collection items and photographs	Camphor Formaldehyde (methanal) Nitrogen	Edge et al. (1990) Jutier et al. (1987) Miles (1955) Phillips, Orlick and Steinberger (1955) Wolfrom et al. (1955) Yarsley et al. (1964)
Plastics, rubber	Acid vapours	Knotková-Čermáková and Vlčková (1971)
Polyisoprene rubber (carpet backing), vulcanized rubber, wool and certain sulfide minerals	Reduced sulfur gases	Brimblecombe, Shooter and Kaur (1992) Donovan and Stringer (1971) Sease et al. (1997) Waller (1999)
Poly(vinyl acetate)	Acetic acid (ethanoic acid)	Bataille and Van (1975) Down et al. (1996) Grassie (1952) Grassie (1953) Servotte and Desreux (1968) Tétreault (1992)
Poly(vinyl chloride)	Hydrochloric acid	Kelen (1983)
Resins/coatings	Acetic acid (ethanoic acid) Formic acid (methanoic acid) Solvents	Tétreault (1992) Tétreault and Stamatopoulou (1997)

Table G.1 – Sources of internally generated pollutants *(continued)*

Source	Pollutant	References
Wood	Acetic acid (ethanoic acid) Formic acid (methanoic acid)	Arni, Cochrane and Gray (1965) Budd (1965) Clarke and Longhurst (1961) Donovan and Moynehan (1965) Donovan and Stringer (1971) Farmer (1967) Gibson and Watt (2010) Grzywacz and Stulik (1993) Knotková-Čermáková and Vlčková (1971)
Wood-based panels (sealed with urea-formaldehyde or phenol-formaldehyde resins)	Formaldehyde (methanal)	Andersen, Lundqvist and Mølhave (1975) Grzeskowiak, Jones and Pidduck (1988) Lehmann (1987) Matthews et al. (1986) Meyer, Hermanns and Smith (1985) Myers (1984) Myers and Nagaoka (1981)

Table G.2 – Pollutant-material interactions in enclosures

Material	Pollutant	Damage	References
Copper	Acetic acid (ethanoic acid)	Transformation of copper metal to green copper-based salts	López-Delgado et al. (1998) Thickett and Odlyha (2000)
Lead	Acetic acid (ethanoic acid) Formic acid (methanoic acid) Formaldehyde (methanal) Reduced sulfur gases	Transformation of lead metal to white salts; severe pitting and/or complete destruction of small collection items such as coins/tokens	Allen and Black (2000) Clarke and Longhurst (1961) Coles, Gibson and Hinde (1958) Donovan and Moynehan (1965) Donovan and Stringer (1971) Edwards, Bordass and Farrell (1997) Fitzhugh and Gettens (1971) Hatchfield and Carpenter (1986) Knotková-Čermáková and Vlčková (1971) Raychaudhuri and Brimblecombe (2000) Streigel (1992) Tennent and Cannon (1993) Tétreault, Sirois and Stamatopoulou (1998) Thickett (1997)
Lead-based pigments	Hydrogen sulfide	Formation of black spots	Wohlers and Feldstein (1966)
Limestone, ceramics, fossils, pottery	Acetic acid (ethanoic acid)	Salts form on the surface of collection item, leading to severe pitting and disruption of glazes	Fitzhugh and Gettens (1971) Gibson et al. (1997) Gibson et al. (2005) Linnow, Halsberghe and Steiger (2007) Van Tassel (1958) Wheeler and Wypyski (1993)
Paper (cellulose)	Acetic acid (ethanoic acid) Volatile organic compounds (VOCs)	Increased brittleness, friability due to weakened structure	Dupont and Tétreault (2000) Strlič et al. (2011)
Shells, eggshells, carbonate, borate, phosphate and similar soluble minerals of weak acids	Acetic acid (ethanoic acid) Formic acid (methanoic acid)	White salts form on the surface of collection item leading to pitting, loss of lustre on minerals	Agnew (1981) Byne (1899) Nicholls (1934) Tennent and Baird (1985) Tennent and Baird (1992) Waller (1999)

Table G.2 – Pollutant-material interactions in enclosures *(continued)*

Material	Pollutant	Damage	References
Silver	Reduced sulfide gases	Transformation of silver metal to silver sulfide causing pitting, tarnishing and blackening of metal surface	Brimblecombe, Shooter and Kaur (1992) Blackshaw and Daniels (1979) Franey, Kammlott and Graedel (1985) Oddy (1973) Pope, Gibbens and Moss (1968) Sease et al. (1997)
Unstable historic soda silicate glass	Formic acid (methanoic acid) Formaldehyde (methanal)	White salt formation formed on surface weakens structure of glass	Cummings, Lanford and Feldmann (1998) Nockert and Wadsten (1978) Robinet et al. (2004) Robinet et al. (2007)
Zinc	Acetic acid (ethanoic acid) Formic acid (methanoic acid) Hydrogen sulfide Nitrogen dioxide	Transformation of zinc to salts causing pitting	Clarke and Longhurst (1961) Donovan and Moynehan (1965) Donovan and Stringer (1971) Svensson and Johansson (1996)

***NOTE** Lead collection items, which are particularly sensitive, should not be stored in wooden enclosures.*

Table G.3 – Pollutant-material interactions in open storage or display

Material	Pollutant	Damage	References
Colour photographs	Acetic acid Nitrogen dioxide Ozone	Fading, yellowing	Bard et al. (1980) Fenech et al. (2010)
Lacquers	Dust	Change in visual appearance, mechanical damage due to cleaning	Lloyd et al. (2002)
Leather	Sulfur dioxide	Reduced mechanical properties ("red rot")	Spedding, Rowlands and Taylor (1971) Tétreault (2003b)
	Dust	Change in visual appearance, soiling, mechanical damage due to cleaning, increased rate of/providing catalyst for chemical degradation	Lloyd et al. (2002)
Metals, soft polymer surfaces, varnishes, watercolours	Dust	Change in visual appearance, mechanical damage due to cleaning, increased rate of/providing catalyst for chemical degradation	Lloyd et al. (2002)
Natural organic colourants on paper	Ozone Nitrogen dioxide	Fading	Grosjean, Grosjean and Williams (1993) Salmon and Cass (1993) Whitmore and Cass (1988) Whitmore and Cass (1989) Whitmore, Cass and Druzik (1987) Williams, Grosjean and Grosjean (1992)
Paper and papyrus (cellulose)	Acetic acid Nitrogen dioxide Ozone Sulfur dioxide	Reduced mechanical properties, yellowing (especially of paper containing lignin)	Baer and Banks (1985) Johansson and Lennholm (2000)
Pigments	Ozone	Fading	Cass et al. (1991)
Rubber	Ozone	Reduced mechanical properties and cracking	Grosjean et al. (1988)
Stone	Sulfur dioxide	Change in visual appearance, soiling, mechanical damage due to hydrated sulfonated salts	Braun and Wilson (1970) Hoke (1978) Wieczorek-Ciurowa (1988)
Synthetic materials	Nitrogen dioxide	Yellowing	–
Textiles	Formaldehyde (methanal) Nitrogen oxides Sulfur dioxide	Reduced mechanical properties	Baer and Banks (1985) Kamath, Hornby and Weigmann (1985) Nockert and Wadsten (1978)
Textile dyes	Ozone Nitrogen dioxide	Fading	Grosjean et al. (1988) Thompson (1986)

Table G.4 – Approximate threshold concentrations for certain pollutant-material interactions

Material	**Pollutant and associated approximate threshold concentrations** parts per billion by volume						
	Acetic acid (ethanoic acid)	**Formic acid (methanoic acid)**	**Formaldehyde (methanal)**	**Reduced sulfides**	**Sulfur dioxide**	**Nitrous oxide**	**Ozone**
Historic soda silicate glass	–	500	300	–	–	–	–
Limestone, ceramics, fossils, pottery	1 000	–	–	–	–	–	–
Shells, eggs	1 000	500	–	–	–	–	–
Lead	100	–	–	10	–	–	–
Copper	1 000	–	–	–	–	–	–
Silver	–	–	–	10	–	–	–
Zinc	–	–	–	10	–	–	–
Lead-based pigments	100	–	–	10	–	–	–
Paper	100	–	–	–	1	10	10

NOTE 1 *Approximate threshold concentrations are given for those pollutant-material interactions where thresholds have been published. Threshold concentrations have yet to be agreed for other materials such as textiles, plastics, organic colourants and leather, although most organic materials are susceptible to oxidizing pollutants (e.g. ozone and* NO_2*) and acidic pollution (e.g.* SO_2 *and organic acids). In the absence of published threshold values, the values for paper may be used as approximate guidance.*

NOTE 2 *Further guidance on pollutants in collection environments is given in Grzywacz (2006), Hatchfield (2002) and Tétreault (2003a).*

Bibliography

Standards publications

For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

BS 1153, *Recommendations for processing and storage of silver-gelatine-type microfilm*

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BS EN 15757:2010, *Conservation of cultural property – Specifications for temperature and relative humidity to limit climate-induced mechanical damage in organic hygroscopic materials*

BS EN 15758, *Conservation of cultural property – Procedures and instruments for measuring temperatures of the air and the surfaces of objects*

BS EN 15898, *Conservation of cultural property – Main general terms and definitions*

BS EN ISO 11844-1, *Corrosion of metals and alloys – Classification of low corrosivity of indoor atmospheres – Part 1: Determination and estimation of indoor corrosivity*

BS ISO 15489-1, *Information and documentation – Records management – Part 1: General*

BS ISO 18934, *Imaging Materials – Multiple media archives – Storage environment*

BS ISO 31000, *Risk management – Principles and guidelines*

BS ISO 80000, *Quantities and units – Part 7: Light*

PAS 197:2009, *Code of practice for cultural collections management*

PD 0024:2001, *Archival documents – Guide to the interpretation of BS 5454:2000 – Storage and exhibition of archival documents*

PD 5454:2012, *Guide for the storage and exhibition of archival materials*

Research publications

All listed research publications are referenced in this PAS. Some provide direct research evidence for material damage functions relating to temperature, RH, light and pollution, and have appeared as articles in peer-reviewed journals, or in the published proceedings of professional conferences. However, as there are still many areas where evidence for damage functions is sparse or absent, other research publications have been included which either provide a useful context for considering the care of particular collection items or give advice intended to help users of the PAS to follow its requirements.

Note the following abbreviations for publications from the International Council of Museums (ICOM):

- Preprints of the ICOM-CC triennial, Sydney, 1987.

  Grimstad, K. (ed.) Preprints of the ICOM Committee for Conservation: 8th triennial meeting, Sydney, Australia, 6-11 September 1987. Los Angeles: The Getty Conservation Institute.

- Preprints of the ICOM-CC triennial, Washington D.C., 1993.

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