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Guidelines for the Storage and Display of Archaeological Metalwork



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How to get the most out of this guide

Metal artefacts are found on the majority of archaeological sites of late prehistory onwards. They comprise objects from every arena of human life, from everyday tools to coinage to valuable high-status objects. They provide vital information about the development of human technology and are an important resource for archaeologists investigating the past. Metals are among the most vulnerable types of materials, as they will often undergo deterioration after excavation. Appropriate storage and display conditions are key to preserving archaeological metals.

These guidelines are intended for anyone involved in the storage and display of archaeological metals, including conservators, curators, archaeologists and museum assistants. It includes an introduction to the reasons why metal objects require particular storage conditions, with detail on the specific problems faced by each metal, based on the latest research. When planning new storage or displays this guide will help to design and implement appropriate environmental controls. It is advisable to consult a conservator in the early stages of planning to address the specific needs of particular objects. To get the most from these guidelines they should be used in conjunction with the case studies and additional information on the webpages.

The guide will facilitate conversations

between conservators and decision makers as well as providing recommendations and examples of best practice. It will help to set priorities and be proactive in avoiding the worst environments and preventing problems occurring, as well as identifying material at risk and discussing how to reduce risk. The case studies illustrate how the latest conservation science is developing pragmatic, evidence-based conservation strategies. Although some limits are recommended, these guidelines are not solely prescriptive; instead, the emphasis is on the need to balance risk to objects against other relevant factors, such as the type of object, the display context, and the resources and costs involved. This will equip the reader to address cost–benefit outcomes of their decisions. It also provides a base line of knowledge to evaluate new or conflicting research and recommendations.

The focus of the guidelines is on strategies for preventive conservation rather than interventive treatments. It does not include procedures for storing objects immediately after excavation; this is covered in *First Aid for Finds* (Watkinson and Neal 2001). This guide is for objects that have been accessioned to an archaeological archive or store where they will remain for the medium to long term requiring management to survive. It also contains information on designing and maintaining good showcase and storage environments, and therefore will be useful to anyone involved in maintaining or displaying archaeological metal collections.

The most common metals found on terrestrial archaeological sites are covered here: iron, copper, lead, silver, gold and their alloys. There is some mention of modern metals, which are rarely found in the archaeological record at present but which will become a larger part of archaeological collections in the future. It does not cover artefacts from marine contexts or historic material, although some of the research on which this guide is based is relevant to both contexts.

Issues such as handling, packaging, radiography, interventive conservation or buildings management are not covered, and information on these may be found in other publications, which the reader is urged to use in tandem with this guide.

Section 1 outlines some basic definitions and introduces information relevant to all metals. It gives information on the most important considerations to be borne in mind when storing and displaying metal artefacts.

Section 2 provides information and recommendations on preventing and controlling deterioration of metals found on archaeological sites. References are given to the research on which the recommendations are based.

Section 3 describes methods of implementing storage and display conditions. It includes guidance on showcase design and storage planning, methods of implementing environmental control, and the importance of monitoring and maintenance.

Case studies are provided on the webpages to illustrate the principles of the guide in action. A list of suppliers and sources of further information is also provided on the English Heritage web pages ([HYPERLINK TO WEB PAGE](#)). A glossary is provided for the most important technical terms, which are emboldened in the text. The sources of the information in this guide are referenced in standard Harvard format, and key references have been highlighted in each section for the reader who wishes to follow up a topic in more depth. New research on these topics is being produced all the time, and relevant references will be updated on the webpages.

Section I: Introduction

I.1 What is archaeological metalwork?

Archaeological metalwork is the category of objects made of or containing a metallic element. There are many metals, but only a small number were regularly used in the past to make objects. Although some metals such as gold are found in their elemental state in nature, most metals have to be produced from **ores**, commonly metal **oxide** or **sulfide** minerals. By heating in a low oxygen environment, the metal is extracted from the ore. It can then be further refined, modified and shaped, or melted and poured into moulds to produce objects.

An **alloy** is a mixture of two or more metals, used to manipulate the properties of the material and reduce the cost lowering precious metals content, such as gold, while maintaining their appearance. Non-metallic elements such as carbon were deliberately introduced to change the properties of the material. Small non-metallic particles of **slag** remain as impurities within the metal from the production process, and also have an effect on the working properties.

Following production the metal was shaped or cast into an object. Working the metal changes



Fig 1. A medieval tinned iron buckle from a London site. © Museum of London

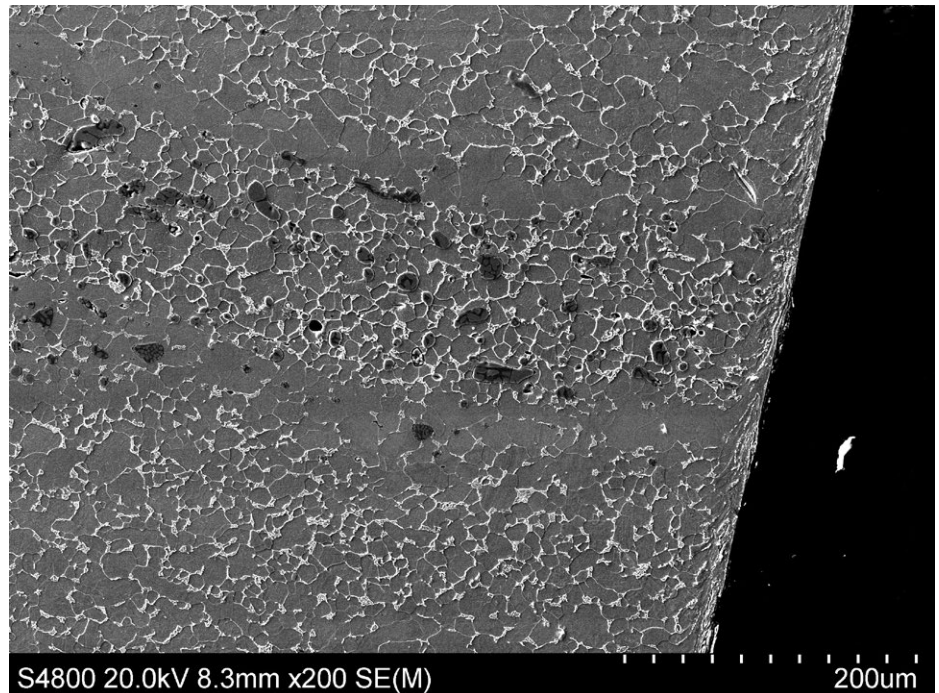


Fig 2. Micrograph of slag inclusions in iron spearhead from Sutton Hoo. © The Trustees of the British Museum

its properties and its traces can be identified to provide technological information. Inlays and coatings of other metals could be added to enhance the appearance or protect the object (eg tinning or gilding). An artefact could be made of different metal pieces joined together (eg an iron pin on a bronze brooch). Finally, other non-metallic materials could be added to make a complete artefact (eg wooden handles on iron tools) and to decorate it.

What emerges from this overview is the complexity of archaeological metalwork, in that it comprises a small number of metals but in an infinite number of combinations, with many possible impurities, and a large number of resulting variations in properties and behaviour.

I.2 What is corrosion?

Metals are inherently **unstable** during burial and in the atmosphere, and will tend to return to their mineral form over time. The **compounds** formed by the reaction of the metal with its environment are distinctive in form and colour, and invariably unlike the metal, resulting in a change in the object composition, structure, properties and appearance. In most cases, the corrosion process requires the presence of oxygen and water. Corrosive substances that come into contact with the object can increase the corrosion reaction rate. These can be **salts** from the burial environment, **pollutants** in the air or even contaminants from past conservation **treatments**.



Fig 3. Metalworking process

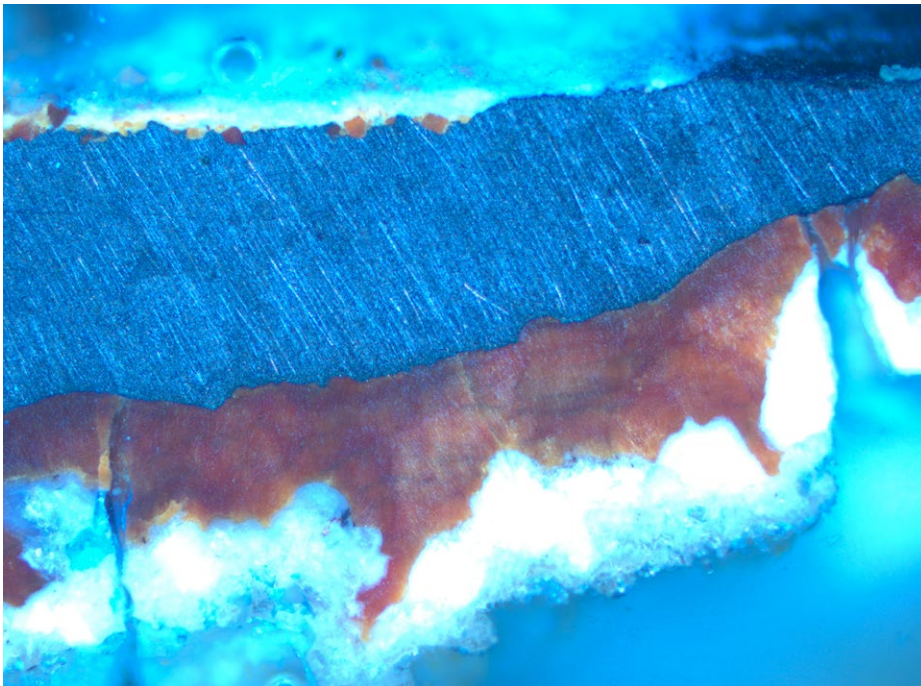


Fig 4. Micrograph of cross section of patinated lead. © The Trustees of the British Museum



Fig 5. Iron objects with corrosion after excavation; both have had partial cleaning to reveal their shape © Museum of London

Corrosion can occur during the use-life of the artefact, during burial and after excavation. The effect of corrosion will vary from a minor surface change to complete loss of the metal. Some corrosion layers protect the object from further corrosion, and provide evidence of use and authenticity. Some corrosion layers enhance the object's appearance and are considered aesthetically desirable; these are termed **patinas**.

In the burial environment, corrosion builds up into thicker layers, which obscure the object, and more metal disappears. The shape of the object and the **original surface products** is often retained in the **corrosion products** and still provides information to the archaeologist. Corrosion layers formed in the burial environment may also contain additional information, such as preserved organic materials. They are therefore an integral part of the object, and cannot simply be removed.

Excavation exposes objects to very different conditions. This can result in a much faster rate of corrosion, allowing artefacts to deteriorate rapidly. New corrosion products form rapidly, and these fast-growing products have a large volume, which causes the object to break up or become disfigured. Such **active corrosion** is very damaging to objects. Conservation treatments can be used to reduce the likelihood and effects of active corrosion. However, the best method of avoiding active corrosion is to control the environment to prevent or reduce the damaging reactions. Once active corrosion has occurred on an object, its effects are difficult to mitigate and the object cannot normally be restored to its previous appearance.

Info box A: relative humidity and its role in corrosion

Many corrosion reactions involve water. In the burial environment, objects are damp from the surrounding soil. In the atmosphere, the moisture content of the object is controlled by the water content of the air.

The amount of water vapour that air can hold is dependent on temperature, and is normally expressed as relative humidity (**RH**). RH is the percentage of the total amount of water vapour air can hold at a given temperature. Warm air holds more water than cold air; therefore, in a closed space, when the temperature decreases, the relative humidity increases. If the amount of water vapour exceeds the maximum amount that the air can hold, water droplets form as condensation.

Water is important in corrosion reactions because reactions require the movement

of **ions**. Water is an **electrolyte**, a conductive medium that allows the ions to move freely, and allows the **reaction rate** to increase. An object in damp air may not have any visible liquid water on it, but there are microscopically thin layers of water **adsorbed** on the surfaces and within the corrosion layers. The higher the RH of the air, the thicker these layers will become and the more freely ions can move, increasing the rate of the corrosion reaction. Conversely, if the RH is low, the water layers will reduce and the reaction rate will slow down or cease.

Particular compounds on objects can increase the amount of water present at a given RH. These **hygroscopic** materials increase the rate of corrosion reactions. They will also reduce the RH **threshold** at which corrosion can begin, because hygroscopic materials attract water even at low humidity. Hygroscopic materials can be corrosion products, salts, which are present in the object from the burial environment, or dust particles.

Because of its central role in corrosion reactions, the control of RH is one of the most important parameters in the storage and display of metal objects.

Key references:

Costa, V 2001 'The deterioration of silver alloys and some aspects of their conservation'. *Reviews in Conservation* **2**, 18–34

Costa, V and Urban, F 2005 'Lead and its alloys: metallurgy, deterioration and conservation'. *Reviews in Conservation* **6**, 48–62

Evans, UR 1981 *An Introduction to Metallic Corrosion*. London: Edward Arnold

Scott, DA 2003 *Copper and Bronze in Art: Corrosion, Colorants, Conservation*. Los Angeles, CA: Getty Conservation

Scott, DA and Eggert, GE 2009 *Iron and Steel in Art*. London: Archaeotype

Info box B: pollutants and their role in corrosion

Pollutants are airborne compounds that cause or enhance corrosion of metals. The source of pollutants may be external (eg car exhaust **emissions** and industrial processes) or internal (eg emissions from the materials immediately surrounding the object in the building, showcase or storage environment). Of these, the most common source of problems for archaeological metals is the effect of **organic pollutant gases** from inside showcase environments.

Some metals are more sensitive than others to corrosion damage by pollutants. The extent

to which they are at risk depends on the metal composition, surface contamination, concentration of the gases, the relative humidity and temperature. The main sources of internal emissions are wood and paper products, paints and cloths in showcases. Although fresh materials produce the highest concentrations, even old wooden materials can emit enough organic pollutant gases to cause problems (Glastrup *et al* 2006; Niklasson *et al* 2008). Many modern materials can also emit pollutants: textiles, lacquers, vinyls, polyesters, adhesives and graphics used in new display cases may all be problematic (Schieweck and Salthammer 2011). Testing materials for emissions is one of the best ways of avoiding the corrosion

problems they cause (see Info box H).

Materials that emit gases can do so for a long time, and preventing emissions with sealant materials is not effective in the long term. Strategies for dealing with pollutant gases include: removing the source of pollution; excluding external pollutants through the use of air-tight showcases; using **sorbent** materials and barriers; and using pumps and air filters to remove problematic gases. Further information is found in Section 3.

Key reference:

Tétreault, J 2003 'Guidelines for pollutant concentrations in museums'. *CCI Newsletter* **31**, 3–5

Pollutant	Main indoor sources		Affects
Reduced sulfur species, eg hydrogen sulfide H ₂ S, and carbonyl sulfide COS and dimethyl sulfide, (CH ₃) ₂ S, on coast	wool rubber sealants objects	fabrics, eg felt adhesives polysulfide based rubber and pyrite containing	silver, bronze and copper (Thickett and Lee 2004)
Sulfur dioxide, SO ₂	objects	containing proteinaceous fibres. mineral specimens with pyrite	copper alloys (Tétreault, 2003)
Organic acids, eg formic acid, CHOOH, and acetic acid, CH ₃ COOH	timber timber composites paints adhesives varnishes sealants resins/coatings objects moth and rot proofing linoleum visitors	all, especially oak MDF, plywood, blockboard, chipboard often oil based, many emulsion based. Sp. Acrylic and nitrocellulose paints polyvinyl acetate, some polyurethanes some silicones cellulose acetate	lead, copper alloys, zinc, cadmium, magnesium (Thickett and Lee, 2004), archeological iron (Thickett 2012)
Formaldehyde, CH ₂ O	adhesives timber timber composites fabrics, paints	urea and phenol formaldehyde all MDF, plywood, blockboard, chipboard	high levels can attack most metals under suitable conditions (Thickett and Lee 2004).
Chlorides	plastics fire retardants	PVC, PVDC inorganic salts	copper, aluminium, zinc and iron (Thickett and Lee, 2004)
Nitrogen oxides, NO _x	plastics	cellulose nitrate	copper and iron (Thickett and Lee 2004)
Ozone, O ₃	photocopiers/printers air cleaners		possibly silver and copper alloys (Tétreault, 2003)
Amines: ammonia, NH ₃ , and others	sealants concrete adhesives paints cleaning products visitors paints organic materials	alkaline type silicone emulsions emulsions oil-based eg rubber floor tiles	ammonia blemishes ebonite, corrodes metal (Tétreault, 2003)

Table 1. Pollutants and sources

1.3 Consequences of corrosion for objects

Active corrosion causes a variety of detrimental effects on archaeological objects, from minor surface changes through to damage so severe that the object is no longer recognisable or useful. The level of damage will be different for each object, and relates to the nature of the corrosion products formed, the rate and location, and the state of the object. Section 2 contains specific details on the typical corrosion phenomena for each metal.

Active corrosion often begins beneath the existing corrosion layers and is not always visually apparent; in fact, the appearance of new corrosion product on the surface is a sign that active corrosion processes have already progressed to an advanced and damaging level. The colour, shape and composition of new corrosion can provide clues as to the cause of the corrosion, and this can be clarified by analysis. Accurate condition records, including detailed photographs of objects, will help to identify the appearance of new corrosion products over time. New corrosion can obscure surfaces and reduce the readability and research potential of the objects, as well as reducing their aesthetic appeal.

Cracking and flaking of layers and surfaces is often seen with metals that have thick corrosion layers, such as iron and copper alloys. These corrosion layers are often the most important part of the object, as they contain the original surface, and so disruption is very damaging. It is the result of the increase in volume that occurs when metal turns to corrosion product. Once this has occurred, the physical integrity of the object has been compromised, and is beyond the ability of conservation treatment to restore.

An often invisible but inevitable consequence of corrosion is the ongoing corrosion and disruption of the remaining metal within the

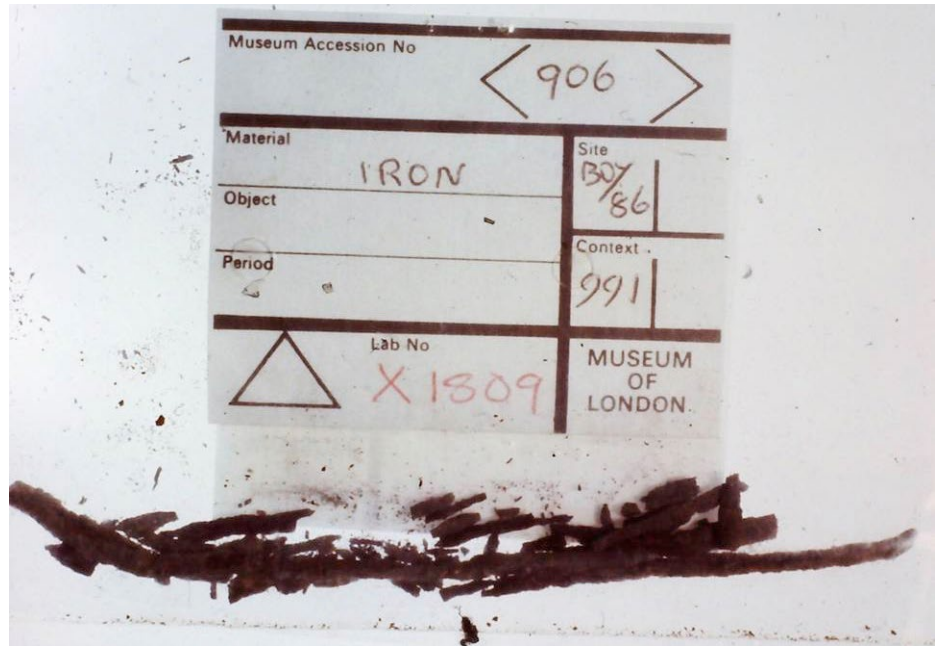


Fig 6. Actively corroding iron pin, in its storage bag from a London site. © Museum of London

object. Although obscured by the overlying corrosion, it contains compositional and **metallographic** information, which is technologically and archaeologically important. If corrosion reactions proceed unhindered, this information will eventually be destroyed.

Even small amounts of active corrosion can lead to significant damage for many metals and alloys, particularly those that undergo rapid and destructive forms of post-excavation corrosion, such as iron, copper alloys and lead. A short period spent in inappropriate conditions initiates corrosion processes that cause damage and the effects of this are cumulative. Objects may be vulnerable to short periods of high RH lasting a few days, and although the effects of this may not be visible immediately, repeated exposure will eventually result in physical damage to the object, reducing their value and damaging the primary record of an excavated site which the objects are part of.

1.4 Preventing and managing active corrosion

The principle of these guidelines is that there is no single 'right' answer to the question, 'How should I store or display my metal artefacts?' Rather, the storage and display conditions chosen for a particular group of objects in a collection will depend on a range of factors. These include the following.

- Type of material: are the objects unique and rare, or are they part of a large collection with many similar items? Are they registered small finds or unregistered 'bulk' items?
- Goal: short-term display or long-term storage? What is the desired 'lifespan' of the objects?
- Current conditions: how are the objects currently stored, what is their current

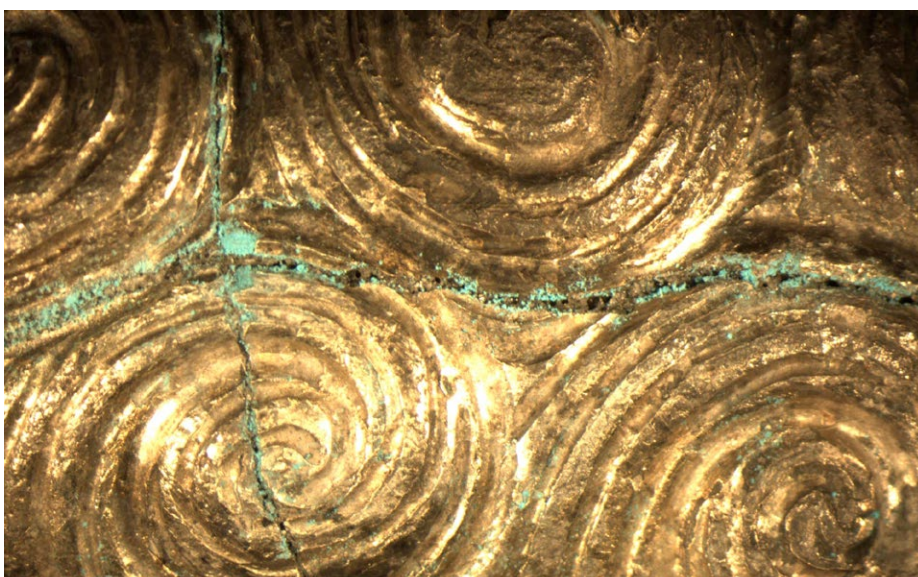


Fig 7. Active corrosion of copper. © The Trustees of the British Museum



Fig 8. Stable corrosion (patina) of copper. © The Trustees of the British Museum

condition and what puts them at risk in their present environment?

- Ideal storage conditions: what are the recommendations? How far are the objects currently away from this?
- Level of risk: what might happen to these objects if nothing is done?
- Resources available: time, money and staffing, and issues of practicality such as location and accessibility. What are the costs of changing things?
- Benefits: how will things be improved if action is taken? What is the likely outcome in the short and long term, and how does that compare to the costs and risks?

Management is an ongoing process dealing with ongoing risks. Care begins with correct handling and packaging to protect fragile objects, and extends through to long-term planning of maintenance schedules and budgets. To make good management decisions about the conditions in which to store a particular collection requires knowledge of what level of risk objects will be exposed to in a range of conditions. Conservation research in the last few decades provides data that helps to assess this and make evidence-based cost–benefit decisions. Choosing environmental conditions is a pragmatic process based on a range of factors, and may differ according to individual circumstance. Being equipped with the knowledge in this guide is an important step towards making informed decisions.

1.4.1 Stopping or controlling corrosion?

The ideal of stopping corrosion reactions completely is difficult to achieve. Removing the oxygen, water, salts or pollutants from an environment sufficiently to make corrosion reactions cease completely is technically difficult, often expensive and requires significant long-term planning and maintenance. In some cases aiming to stop corrosion may be appropriate, based on the rarity and value of the materials. In other cases, it is neither practical nor pragmatic.

The nature of corrosion processes is such that, inevitably, all objects have a finite lifespan.

Info box C: a note about handling and packing

Preventing damage to objects is not only about environmental conditions, although that is the main focus of this guide. Objects are physically and chemically damaged by inappropriate handling and packaging in numerous ways: fingerprints on metals cause corrosion; paper and card storage boxes emit pollutant gases; and damage caused by careless handling can lead to active corrosion as new surfaces are exposed. At all times proper handling procedures should be followed. If an object is damaged during handling the advice of a conservator should

The faster the corrosion rate; the shorter the lifespan, and the sooner the object will be so damaged as to have lost its archaeological value. It follows that actions that retard the reaction rate will increase the overall lifespan of the object, and extend its useful life.

Corrosion control is generally more achievable, by reducing humidity or reducing pollution concentrations to decrease the corrosion rate. The advantage of this approach is that it is more sustainable in the long term, and offers more flexible options for different scenarios. Corrosion control can take into account the needs of different materials, the likely effectiveness of a particular control measure and its duration, the availability of resources and other practical considerations. This approach accepts that some corrosion may occur, and that therefore objects will have a finite lifespan. By reducing the corrosion rates this can be extended to several hundred years, preserving the objects well into the future. Defining an acceptable lifespan is dependent on each object and its importance and context. This approach is not prescriptive, but seeks to use the evidence available to predict the likely outcomes of particular actions.

1.4.2 Taking a proactive approach

The physical damage caused by active corrosion after excavation cannot be reversed and is difficult to repair. Taking a proactive approach to collections storage and display produces better results than reacting to problems as they arise, because it avoids damage in the first place, preserving more of the value of the object. The information in this guide puts the reader in control before corrosion occurs, enabling responsible decisions to be made earlier and avoiding the difficulties associated with responding to problems after they have arisen.

The recommendations in Section 2 are a starting point for determining storage and display conditions, and Section 3 gives guidance on how to put this into action in planning and implementation. The reader may wish to consult a conservator to advise further, and contacts are found on the website.

be sought as soon as possible. Links to packaging guidelines and handling guides can be found on the webpages and should be consulted in conjunction with this guide.

Key points to remember:

Disposable gloves are better than cotton gloves, which can leave fibres on objects or snag on loose fragments. Chloride has been detected penetrating through cotton gloves after just a single use. Their use is not recommended for archaeological metals.

Health and safety: there are many issues relating both to hazardous object materials (eg lead) and conservation treatment residues, which

Section 2: Guidelines for storage and display of metalwork

2.1 Iron

Iron was one of the last metals to come into common use, being manufactured in Europe from the 1st millennium BC onwards. In Europe, **wrought** iron made by small furnace processes was the principle form of iron until the development of blast furnaces capable of producing **cast** iron in the late Middle Ages, and becoming common in the Industrial Revolution. Most iron objects are not pure iron, but contain other elements, some added deliberately and others remaining from the ore or smelting process. Almost all iron contains some carbon, and the proportion of carbon has a significant effect on properties and use. Wrought iron contains only low levels of carbon, and was made by heating to reduce the iron ore and remove molten slag. It could then be hammered and forged, but not melted and cast. The addition of further carbon up to *circa* 1% created early steel, which is harder and stronger. To be able to cast, 2–5% carbon content is needed to reduce the melting point of iron sufficiently to melt and pour the metal into moulds, forming cast iron. Most pre-Industrial Revolution archaeological iron is wrought iron, which has significant implications for the nature of its corrosion. Iron is a very versatile metal, and the varied compositions and technologies for manipulating it have lent it to many uses: weapons, tools, household objects, building fittings, construction material and machinery. It can be welded to join, and plated with other metals (see Section 2.5). It is one of the most common metals found on archaeological sites from the late prehistoric to the present, and is normally well represented in museum collections. As it is also one of the most problematic metals from a conservation perspective, large iron collections can be among the most vulnerable.

2.1.1 Identifying iron

Iron objects buried in the ground normally have thick corrosion layers incorporating

are too varied to summarise here. Be aware of warning labels, read any information on object packaging and wear gloves if unsure.

Key resources:

Caple, C 2000 *Conservation Skills: Judgement, Method and Decision Making*. London: Routledge

Cronyn, J M 1990 *The Elements of Archaeological Conservation*. London: Routledge

Selwyn, L 2004 *Metals and Corrosion: A Handbook for the Conservation Professional*. Ottawa: Canadian Conservation Institute

Watkinson D and Neal V 2001 *First Aid for Finds*. London: Rescue/UKIC Archaeology Section



Fig 9. X-ray of object showing underlying features. © The Trustees of the British Museum

soil and organic materials. X-radiography is necessary prior to any conservation treatment or storage to identify the object, the presence of features such as plating and to indicate the extent of corrosion (Fell *et al* 2006).

The outer, obscuring corrosion layer may then be removed by a conservator to reveal the shape of the object preserved in a dark and compact corrosion layer. Objects that no longer contain any metal (totally mineralised) are not likely to corrode any further after excavation, but they are fragile and need careful handling. Objects with a metal core may be susceptible to active corrosion after excavation. Some objects may preserve the shapes of organic materials, such as bone and textiles, within the corrosion layers; these are archaeologically significant.



Fig 10. Iron, copper alloy and gold composite object shield boss. © The Trustees of the British Museum



Fig 11. Iron from waterlogged sites in London showing excellent condition and typical corrosion layers; the blade is half-cleaned. © Museum of London

Objects from waterlogged sites may have developed different corrosion products due to the less oxygenated conditions, developing sulfur-based corrosion products, which may be coloured black, blue or purple. Preservation can be exceptional, preserving features such as plating and maker's marks (Fell and Ward 1998; Ganiaris *et al* 2012; Scott and Eggert 2007).

2.1.2 Signs of active corrosion

Active post-excitation corrosion has a number of characteristic visual symptoms, given in Table 2 (Loeper-Attia 2007). Although not all of these symptoms will necessarily appear together; they are related to each other; eg cracking is the first stage, which may then be followed by flaking and/or delamination, if corrosion is allowed to continue.






Surface corrosion	Often orange or brown, fine crystals across surface or larger individual crystals	
Weeping	Droplets of liquid on surface, often coloured yellow to brown. Dry to form fragile spherical shells	
Cracking	May be longitudinal, transverse or in networked formations, and of various lengths. May contain fresh corrosion products	
Blisters and flakes	Rounded pieces of outer corrosion layers lift, forming blisters, which may then flake off completely. The underlying scar may contain bright orange crystals	
Delamination	Outer corrosion layers lift away from the metal core. Very damaging, can break objects apart completely	

Table 2. Signs of active iron corrosion

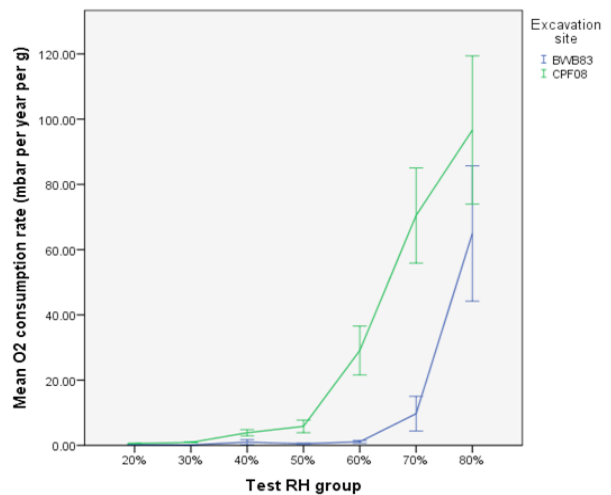
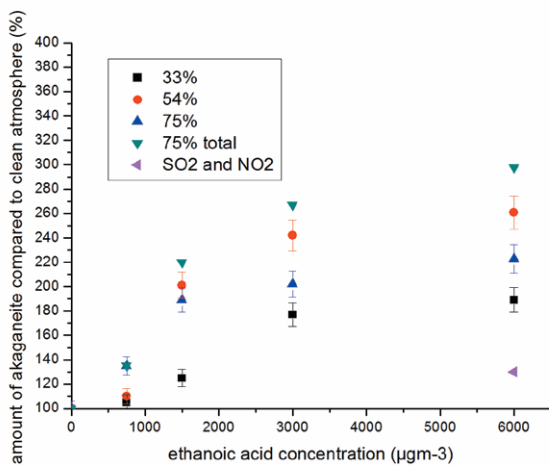
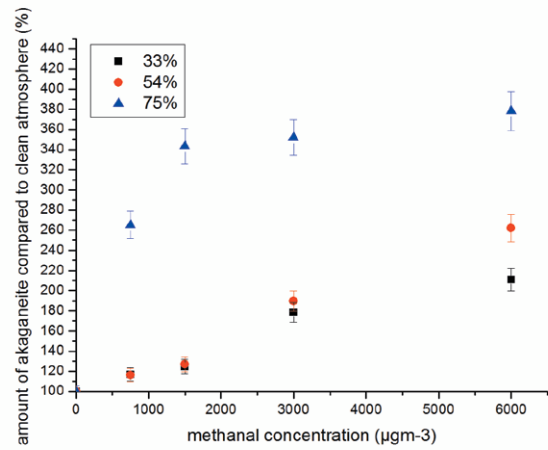
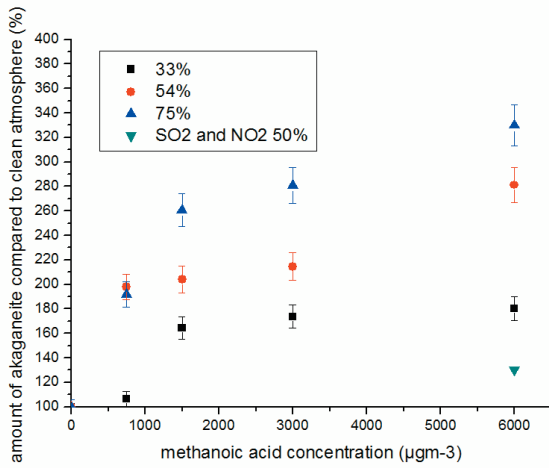


Fig 12. (top left, top right and above) Effect of pollutants on the formation of damaging corrosion products of iron (Thickett 2012)

Fig 13. (above) Graph of changing iron corrosion rate with RH. © University of Cardiff

2.1.3 Causes of active corrosion

Salts from the burial environment are the principle cause for damaging corrosion of iron (see Info box D). The rate of salt-driven corrosion of iron is strongly correlated to the RH.

Research has been carried out to determine the effects of pollutants on the corrosion of iron, and suggests that there is a complex interplay of factors, including pollutant levels alone and in combination with each other, the RH and temperature.

Composite objects that contain iron with copper may be at additional risk. As well as the effects of **galvanic corrosion**, whereby copper corrodes less at the expense of the iron, which corrodes more rapidly, the copper ions present increase the corrosion susceptibility of iron even further (Thickett 2012).

Iron objects from waterlogged sites are normally less susceptible to corrosion from chloride salts and can remain in good condition (Ganiaris *et al* 2012). They may be at risk from sulfur-based corrosion owing to unstable iron

sulfide corrosion products formed during burial.

Many iron objects in museum collections have been previously treated in a range of ways, from stripping of all the outer corrosion layers to chemical treatments to remove salts and mechanical removal of outer corrosion to reveal the original shape of the object. As no treatment is guaranteed to be completely successful, all previously treated objects remain potentially susceptible to the problems of active corrosion.

Info box D: the role of chloride ions in iron corrosion

After excavation, the leading cause of active corrosion in iron is the presence of **chloride ions** (Watkinson and Lewis 2005b). Chloride ions are found in most soils, and enter the object during its burial. As iron corrodes in the soil the metal becomes positively charged and it attracts the negatively charged chloride ions and holds them on the metal surface, under the developing corrosion crust. With liquid water and **ferrous** ions also present,

the metal core is therefore surrounded by an electrolyte solution of ferrous chloride, which is acidic and itself promotes further corrosion of the metal.

On excavation, the object is exposed to drier, more oxygen-rich conditions. The ferrous chloride solution dries out and forms a corrosion product called **akaganeite** ($\beta\text{-FeOOH}$), which contains chloride ions in its structure and on its surface. As it forms, it expands inside the corrosion layers, producing pressure that causes the outer corrosion layers to crack and flake apart (Thickett 2011). At high RH the liquid ferrous chloride

solution may come to the surface and be visible as droplets of orange-brown liquid (see image in Table 2). Over time, the damage to the corrosion layers can become so severe that they break apart, destroying most of the object's value in the process.

The corrosive effect of chloride and akaganeite is related to RH. Both ferrous chloride and akaganeite attract water at low RH, allowing corrosion to occur. Because of this, it is very difficult to prevent active corrosion of chloride-contaminated iron objects except by reducing the humidity to very low levels (Watkinson and Lewis 2005a).

2.1.4 Storage and display conditions

Iron objects may be stable in a range of conditions, depending on whether they contain salts and the nature of their corrosion layers. A significant proportion of objects do not suffer from active corrosion in normal museum conditions (40–55% RH) or even higher RH conditions. It is difficult to predict in advance which objects will be stable and which will suffer from active corrosion and require more controlled environmental conditions. Oxygen depletion testing has been shown to be able to identify unstable and stable archaeological iron (Thickett *et al* 2008). It is only really applicable on material coming from dry storage. Careful observation of objects to detect the early signs of active corrosion is crucial to identifying objects suffering from active corrosion, but all objects must be considered initially at risk. For unstable iron objects on display, control of RH will be needed to extend the object lifespan and reduce the likelihood of active corrosion.

Recent research has identified several RH thresholds for the control of active iron corrosion, summarised in Table 3 and Figure 14 (Thickett 2012; Thickett and Odlyha 2010; Watkinson and Lewis 2005b). To avoid iron corrosion entirely, storage and display environments must be kept below 11% RH. Many iron objects will be stable and will not corrode below 19% RH. A recent survey of 80 objects from a range of contexts,

indicated this was the case for 78 (97.5%) of them. Only the presence of akaganeite formed above 70% RH will lower the threshold to 11% RH (Thickett and Odlyha 2013).

Corrosion rates are relatively slow up to 30% RH. In cases where very dry storage is not possible owing to the presence of other materials or the practicalities involved, keeping RH below 30% should ensure that any corrosion occurring is slow. Above 30% the risk of activating iron corrosion is much greater; and above 50% salt-bearing objects will corrode rapidly.

For display, achieving 11% RH is often impractical; such dry environments are not suitable for many other materials in cases of mixed materials. A target RH below 30% should still be maintained where possible, and this is achievable using appropriate desiccants and air-tight showcases (see Section 3). Materials emitting organic acid pollutants should be avoided (see Info box B). Every effort should be made to maintain RH less than 50% to reduce the risk to some extent. Not all objects will suffer at this high RH but many objects will be at significant risk under these conditions, and detecting objects beginning to display signs of active corrosion in a timely manner in itself requires a rigorous maintenance and monitoring schedule. The time that objects spend at high RH should be limited as much as possible, as damage from active corrosion has a cumulative effect and cannot be reversed.

2.2 Copper alloys

Copper is rarely found as a pure metal on archaeological sites; it is normally alloyed with tin, making bronze, or zinc, making brass. Copper alloys have been in use since the Bronze Age (c 3500–1000 BC) and are used for weapons, household objects, jewellery and coinage. They may be cast or hammered and can be joined by soldering. Bronze objects may be coated with thin layers of other metals such

Info box E: removing oxygen to preserve iron

Oxygen scavengers have also been used to provide oxygen free storage for iron objects. Most testing of these has only been short term, so it is unclear how effective they are as a long-term control mechanism – failure rates of the films and absorbers are not known. Additionally, most of the research has been done using oxygen absorbers that also include desiccants, so it is not possible to separate out the effects. Oxygen scavengers may be suitable as a short-term control mechanism or for composite objects where low RH would be damaging to the non-ferrous parts, but there is no proven long-term effectiveness at present. The costs of maintaining oxygen-free environments for long periods are high. The practicalities associated with sealing objects and reducing accessibility for study must also be considered. More research is needed to determine their effectiveness.

Key resources:

Thickett, D and Odlyha, M 2010 'Assessment of dry storage microenvironments for archaeological iron', in Williams, E and Peachey, C (eds) *The Conservation of Archaeological Materials – Current Trends and Future Directions*. London: Archaeopress, 187–199

Turgoose, S 1982 'Post-excavation changes in iron antiquities'. *Studies in Conservation* **27**, 97–101

Watkinson, D and Lewis, M RT 2005 'Desiccated storage of chloride-contaminated archaeological iron objects'. *Studies in Conservation* **50**, 241–252

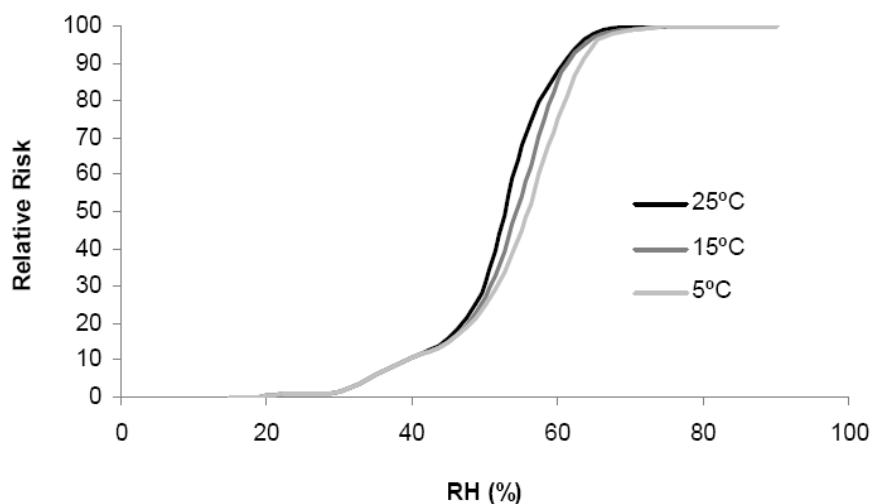


Fig 14. Diagram of risk related to RH level for archaeological iron

Lower RH		Higher RH		
Below 11%	11% to 19%	20% to 30%	30% to c. 50%	Above c. 50%
No corrosion occurs	No corrosion for objects kept below 70% RH since excavation	Corrosion rate increases gradually up to 30%	Corrosion increases more rapidly above 30%	Rapid corrosion occurs
	Very slow corrosion for those exposed above 70%			Exact RH depends on temperature
Reduced corrosion risk		Increased corrosion risk		

Table 3. RH thresholds for the control of active iron corrosion

as tin and gold, or may be inlaid with silver; gold, enamels or other non-metallic decorative elements.

2.2.1 Identifying copper alloys

Copper alloy objects from archaeological sites normally have a greenish-grey smooth patina or uneven corrosion layers. Objects from waterlogged sites may have no corrosion or thin black layers (Duncan and Ganiaris 1987). The shape of the object is clearer than iron, although x-radiography is still advisable to look for decoration and evidence of manufacturing techniques. Many copper patinas are stable and do not cause active corrosion. In certain situations, however, corrosion can occur very rapidly. As with iron, the corrosion products may preserve organic materials within them.

Whether a copper corrosion layer is stable or not is not immediately obvious; observation over a period of time is necessary to detect whether change is occurring. Analysis of the corrosion products (eg by x-ray diffraction, Raman micro-spectroscopy or Fourier transform infra-red spectroscopy) may be necessary to definitely determine the corrosion processes and causes, and it is advisable to arrange this if a particular object is of concern.

2.2.2 Signs of active corrosion

Light green, powdery and voluminous deposits are normally a sign of active corrosion (occasionally referred to as 'bronze disease'), but not all bright green corrosion layers are unstable. Mediterranean and Near Eastern bronzes are most likely to suffer from active corrosion, due to high chloride levels, and monitoring of these objects is highly recommended. Active copper corrosion can commence within hours of excavation as the object is exposed to oxygen. It can also occur on objects that have been apparently stable for long periods of time, if the corrosion layers are disrupted by cleaning or handling (Cronyn 1990). The voluminous corrosion products that form physically disrupt the overlying layers and force them apart. This damages the shape of the object and its associated corrosion patina. Remaining metal in the object will also be attacked by active corrosion, causing an ongoing problem.

Allowing copper alloy corrosion to proceed unchecked will result in serious disruption of the corrosion layers and underlying metal. This results in disfigurement of the visual appearance of the object, loss of object shape and coherence. In extreme instances the object can be rendered to powder.

2.2.3 Causes of active corrosion

Copper alloy objects can develop a corrosion layer of **cuprous** chloride during burial, located at the metal surface under the patina. When this is exposed to damp and oxygenated conditions, it reacts rapidly to form powdery corrosion and disrupt the otherwise stable patina (Scott 2000).



Fig 15. Near Eastern Bronze with bronze disease



Fig 16 Copper alloy corrosion products containing sodium and carbonate as well as copper and acetate

Below 42%	42–68%	Above 68%
Corrosion risk is low	Some risk, but exact level of risk unknown	Very high risk of corrosion

Table 4. Risk profile for corrosion of copper alloy objects

RH is a key factor in whether cuprous chloride reacts to cause active corrosion. There is some dispute about the exact threshold humidity at which active copper corrosion begins to occur: Different studies have produced different thresholds for the commencement of the reaction: 42–46% (Scott 1990); 40–50% (Organ 1963); and 63% (Papapelekanos 2010). Empirical data from the British Museum and English Heritage on the appearance of bronze disease in continuously monitored environmental conditions show that there is certainly a risk above 42%. Above 68%, the point at which cuprous chloride attracts enough water to form liquid, corrosion occurs very rapidly. Between these two points, the exact risk is difficult to evaluate and further research is required.

The cuprous chloride reaction is self-perpetuating, and therefore once exposed to higher RH the

reaction may take a period of time to cease when the RH is reduced (Scott 1990).

High levels of acetic acid are known to cause corrosion of copper above 85% RH (Clarke and Longhurst 1961; Lopez-Delgado *et al* 1998). Unfortunately there is no published research on the effect of organic acids on archaeological copper alloys. Their effect on archaeological iron is different in its detail and risk than that of historical iron and it is possible the effect on historical copper alloys is not the same for archaeological material. Copper corrosion rates are also increased by sulfur dioxide and nitrogen dioxide, particularly when these gases are present together at high RH (Eriksson *et al* 1993).

The composition of the burial environment or prior conservation treatments may also be

responsible for causing active copper corrosion. If corrosion products different from those described are forming on copper alloys, it is best to seek the advice of a conservator in identifying the products and their cause.

2.2.4 Storage and display conditions

The varying results from studies of bronze disease mean that evaluating risk is difficult (Table 4), but all the studies suggest that below a RH of 42% active corrosion is unlikely. Until the risks above this RH can be more fully evaluated, this remains the recommended threshold. Above 68% RH the risk of outbreaks of bronze disease is very high; exposing archaeological copper alloys to RH above this level should certainly be avoided.

An acetic acid free environment is also recommended, although the effect of low amounts of acetic acid at 42% RH cannot be quantified based on current evidence. Once an object is experiencing active copper corrosion, reducing RH to below 42% should help to prevent further problems. Conservation treatment with a corrosion inhibitor such as benzotriazole may be appropriate to halt the copper chloride corrosion. However, there is some empirical evidence that corrosion can continue after benzotriazole treatment, and RH above 42% should still be avoided for treated objects. If an object is displaying signs of active copper corrosion, it should be evaluated by a conservator as soon as possible. Treated



Fig 17. Detail of a copper alloy printing plate with corrosion from a fingerprint. © Museum of London

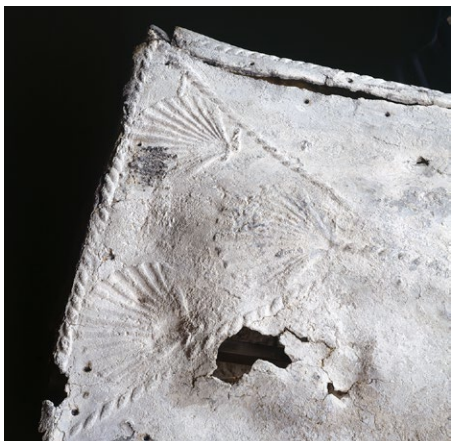


Fig 18. Stable lead corrosion products after Excavation. Lead coffin from St Augustines Abbey

objects should be handled carefully with gloves, due to the hazardous nature of benzotriazole residues and the danger of disrupting protective films.

Key resources:

Organ, R M 1963 'Aspects of bronze patina and its treatment'. *Studies in Conservation* **8**(1), 1–9

Papapelekanos, A 2010 'The critical RH for the appearance of "bronze disease" in chloride contaminated copper and copper alloy artefacts'. *e-conservation magazine* **13**, 43–52

Scott, D A 1990 'Bronze disease: a review of some chemical problems and the role of relative humidity'. *Journal of the American Institute for Conservation* **29**, 193–206

2.3 Lead and its alloys

Lead was one of the earliest metals to be exploited, owing to its relatively low melting point and ease of extraction from the ore (Costa and Urban 2005). Lead has been used for weights, pipes, household goods and as an alloying metal to make pewter; a tin–lead alloy. Lead was also added to copper alloys to improve their casting properties (Cronyn 1990). Tin is discussed in the other metals section.

2.3.1 Identifying lead and its alloys

Lead is in principle a relatively corrosion-resistant metal. On exposure to air it quickly forms a thin layer of lead oxide, which creates a barrier and gives good protection from further corrosion. When buried in soils, corrosion is slow and forms protective layers, which are stable on excavation, although this depends on the composition of the soil. The corrosion products are normally pink to grey, or coloured by the soil, and may be either thin and adhering to the metal or, from certain soils, thicker and cracked (Cronyn 1990; Duncan and Ganiaris 1987). Lead corrosion products formed in soils are insoluble and do not themselves cause corrosion. Pewter objects may have a laminar corrosion appearance with localised black corrosion spots, but it is not always possible to distinguish between pewter and lead objects without compositional analysis.



Figs 19 and 20. Wartiness on pewter. © University of Cardiff

Lead objects can appear to be relatively uncorroded, but may be very fragile and require careful handling. Corrosion is particularly likely where the metal has been stressed, eg by bending. Lead also becomes more brittle with time because of corrosion within the metal structure.

2.3.2 Signs of active corrosion

Despite being normally stable, highly damaging corrosion of lead objects can occur in certain conditions. The appearance of soft white powdery corrosion product that disintegrates on contact is a clear sign of active lead corrosion. If left unchecked, this type of corrosion can cause lead objects to crumble entirely in a very short space of time, just months or even a few weeks. Lead objects should therefore be regularly monitored for even small signs of active corrosion beginning to occur, and early intervention in these cases is crucial.

Pewter, although normally containing no more than 30% lead (Selwyn 2004), may also undergo active corrosion. Pewter objects will have spots of local corrosion appearing as small warts or raised areas. If disturbed, these can lead to further corrosion. Artefacts with this kind of localised corrosion are more vulnerable than those with uniform corrosion layers, and the advice of a conservator should be sought (Tétreault *et al* 1998).

2.3.3 Causes of active corrosion

The main cause of damaging active corrosion of lead and its alloys is gaseous pollution with organic acids, mainly acetic acid, formic acid and other emissions (Info box B). The risk from the pollutants is related to the concentration of the pollutant gas and the prevailing RH. The composition of the metal also plays a role; pure lead is more at risk than lead–tin alloys. Impure lead and alloys are more likely to suffer from localised corrosion owing to the differing behaviour of the various components (Costa and Urban 2005).

Wood products are the most common source of organic acid emissions. In any context where wood or its derivatives are present, lead objects

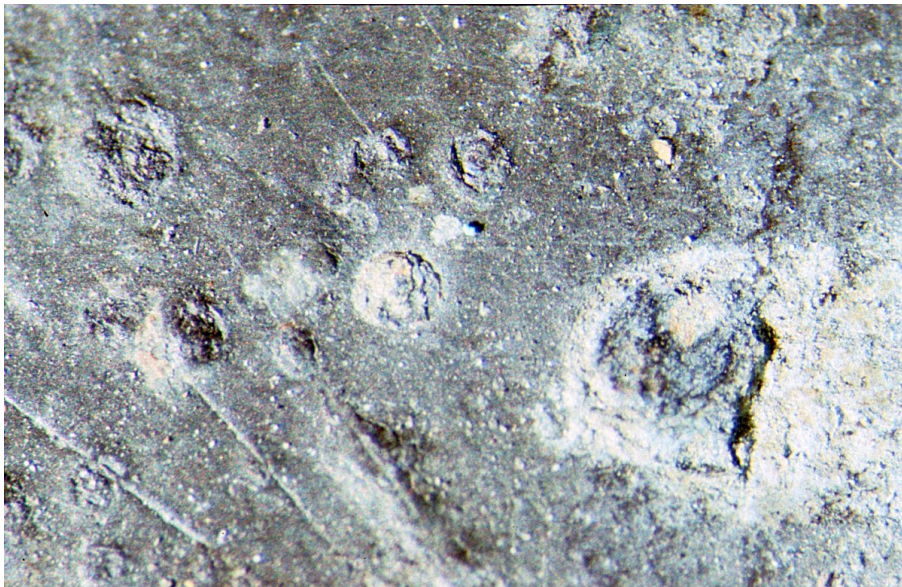


Fig 21. Active corrosion on lead

are at risk from corrosion. The level of risk can be checked with pure lead coupons, or measured using a **diffusion tube** (see Section 3). As the interaction between the various airborne compounds, the RH and the particular objects are complex, those seeking further advice should consult more detailed literature on the subject (see key references below).

2.3.4 Storage and display conditions

Avoiding pollutant gases is the most important factor in avoiding the risk of active lead corrosion. If organic acid pollutants are not present, lead corrosion products are generally stable and require no particular **environmental control**.

The most successful strategy is to plan ahead and avoid putting lead in environments with materials that emit organic pollutants (Info box B). An environment intended for the display or storage of lead can be tested for the presence of organic emissions, either using lead coupons as a qualitative, visible indicator of whether organic emissions are present, or with a quantitative measure using diffusion tubes (Section 3) (Berndt 1990).

If organic emissions cannot be avoided, it is possible to reduce the occurrence of corrosion by lowering the RH in still air (Tétreault 2003). The effect of RH is much less pronounced in moving air (Niklasson *et al* 2008). This is not a long-term solution; control mechanisms can fail, and lead corrosion is very rapid once exposed. If pollutants are known to be present, RH should certainly be controlled to less than 40% to reduce the risk (Tétreault 2003).

Sorbents for organic pollutant gases can also help to reduce the risk, but again this is not a long-term solution.

In planning displays of lead objects, pure lead coupons should be used to determine emissions from all the showcase materials in a materials test (Info box H). Pure lead coupons can also be placed in the showcase

as a visual monitoring system. Showcases made for temporary exhibitions may not be able to avoid using materials such as medium density fibreboard (MDF); if lead is to be displayed, control measures should be put in place with regular monitoring of the lead to avoid problems (see Section 3).

Key resources:

Costa, V and Urban, F 2005 'Lead and its alloys: metallurgy, deterioration and conservation'. *Reviews in Conservation* **6**, 48–62

Niklasson, A, Svensson, J-E, Langer, S, Arrhenius, K, Rosell, C, Bergsten, C.J and Johansson, L-G 2008 'Air pollutant concentrations and atmospheric corrosion of organ pipes in European church environments'. *Studies in Conservation* **53**(1), 24–40

Raychaudhuri, M R and Brimblecombe, P 2000 'Formaldehyde oxidation and lead corrosion'. *Studies in Conservation* **45**(4), 226–32

Tétreault, J 2003 Guidelines for Pollutant Concentrations in Museums. *CCI Newsletter* **31**, 3–5

Tétreault, J *et al* 1998 'Studies of lead corrosion in acetic acid environments'. *Studies in Conservation* **43**(1), 17–32

Thickett, D and Short-Traxler, K 2010 'Practical application of sorbents' in Mardikian, P *et al* (eds) *Metal 2010: Proceedings of the Interim Meeting of the ICOM-CC Metal Working Group, 11–15 October 2010, Charleston, SC, USA*. Charleston, SC: Clemson University, 414–20

2.4 Silver, gold and their alloys

Silver and gold have been in use since the prehistoric period to make jewellery, coins, religious artefacts, decorative elements and other objects. They are rarely found as pure metal, but are normally alloyed with copper, lead or other metals. Objects of silver and gold are usually small and can be highly decorated, including the use of enamels and precious

or semi-precious stones. Both gold and silver may also be found on other artefacts as thin coatings (gilding or silvering).

Gold is one of the most stable metals, and one of the few to be regularly found as a metal rather than an ore in nature. Pure gold normally does not undergo any active corrosion. Most gold objects are composed of alloys with silver or copper and these may experience corrosion associated with those metals, particularly if the gold content is less than 75%. In these cases, the environmental conditions for the alloying metal causing the problem should be consulted (Scott 1983). The rest of this section will deal primarily with the corrosion of silver objects.

2.4.1 Identifying silver

Silver corrodes in the burial environment and in air, forming layers of silver oxides, chlorides and sulfides depending on the conditions. This results in the surface becoming black or grey. If alloyed with copper, green corrosion products may also occur, and can in fact make the object appear, at first sight, to be copper alloy rather than silver.

Silver excavated recently from archaeological sites will not normally have its corrosion layers removed, unless there is good reason to do so. The patinas that develop are normally stable and do not cause active corrosion problems after excavation, as they are protective of the underlying silver. From waterlogged sites, silver can develop a thick dark grey corrosion layer that obscures surface detail; in such instances x-radiography is essential to see detail and treatment may be required (Ganiaris 1998).

Past conservation practice may have stripped silver objects back to their metallic surfaces. Stripping objects of their corrosion products is no longer common practice, as it can cause loss of physical evidence and compromises the shape and surface finish of objects; however, objects treated in this way still remain in museum collections. It is these objects, which have clean silver exposed to the atmosphere, that are most at risk of further corrosion.

Good handling practice for both stripped and non-stripped silver is essential. Buried silver becomes brittle and fragile, and clean silver surfaces will be damaged by fingerprints and dust. Suitable plastic gloves should always be used to handle silver.

2.4.2 Signs of silver corrosion

Clean silver will **tarnish** to form first a yellowish sheen, then a grey/black layer of silver sulfide which thickens over time. This can form a protective layer which slows further damage but is normally considered unsightly, interferes with research and reduces the readability of the object (Costa 2001).

Many silver objects are lacquered after cleaning to prevent tarnishing, but lacquer coatings will eventually begin to break down under the



Fig 22. Lead coupon in showcase to check for pollution

effects of light and humidity (Thickett and Hockey 2002; Thickett and Luxford 2007), and require continued maintenance.

If alloyed with other metals, both silver and gold alloys can show more severe corrosion, and this may be unstable after excavation – eg appearance of copper corrosion. Specialist advice should be sought in these cases.

If sodium chloride is deposited on clean silver; eg from fingerprints, silver chloride may form. This compound is light-sensitive and darkens over time, causing a dark stain that is very visible on otherwise clean silver (Selwyn 2004).

2.4.3 Causes of active corrosion

The main cause of silver tarnishing is the presence of pollutant gases, particularly hydrogen sulfide, dimethyl sulfide and carbonyl sulfide arising from industrial pollution and from certain indoor materials (Info box B) (Costa 2001; Franey *et al* 1985; Graedel 1992; Pope *et al* 1968). Even very low levels of these pollutants can induce tarnish formation. There is some debate about the role of sulfur dioxide in silver tarnishing.

The presence of the external pollutant gases ozone and nitrogen dioxide enhances the formation rate of silver sulfide. This will lead to tarnish layers appearing and thickening more rapidly.

Water is needed for tarnishing to occur; and so higher RH is a factor in increasing tarnish rates. The tarnish rate increases by three times when the RH increases from 15% to 75% RH (Kim and Payer 1999; Pope *et al* 1968). This is much less extreme than with other metals.

Residues from previous conservation treatments and cleaning methods may pose a risk. For example, if formic acid has been used previously to clean copper corrosion products from silver; residues can then increase the tarnishing rate.

Other factors which increase the rate of tarnishing are the contamination of surfaces with dust containing corrosive ions, grease and other compounds (Pope *et al* 1968). Fingerprints left on silver can result in corrosion marks that are difficult to remove.

Although tarnish layers can be removed by a conservator; each time this is done minute amounts of the metal are lost, and so over time the object surface becomes more eroded. It is therefore preferable to slow down or prevent the occurrence of tarnish as much as possible.

Silver is often found as a coating on other metals. The presence of platings within the corrosion layers will make the objects liable to damage and information loss if not stored correctly. Silver plating is of course still susceptible to tarnishing during storage and display. It is also easily destroyed with several cleaning treatments, when applied as thin layers.

2.4.4 Storage and display conditions

The most effective way to avoid or decrease the risk of tarnishing is to ensure that the air in contact with silver surfaces is as pollutant free as possible. To avoid external sources of pollutant gases, it is crucial to maintain silver collections in areas with low levels of these external pollutants and to store silver in air-tight containers to reduce the ingress of external gases. Selecting an appropriate storage room, eg away from external windows and doors, can help to reduce the rate of tarnish. A number of object types will tarnish silver; and storage with objects made of leather, horn and some textiles should be avoided if possible. Archaeological materials from waterlogged sites can also cause tarnish in close proximity. This has been seen for some ceramic and iron objects, presumably due to accumulation of reduced sulfur in

these objects during their burial in anaerobic conditions.

There are a number of possible sources of internal pollutants that cause tarnishing (Graedel 1992)—rubber, paint, wool and other textiles, certain types of wood and adhesives. Materials testing (Info box H) is an effective method of determining whether the materials used in showcase or storage environments are likely to emit pollutant gases that damage silver objects.

To reduce the risk of tarnishing, sorbents can be used to remove harmful gases from the air. Anti-tarnish bags, which contain copper particles, are often good for storing cleaned silver objects and provide an additional layer of protection from low levels of pollutants over time (see Section 3).

Display cases for silver should be constructed with materials that do not emit sulfur pollutants (Info box B). If the source of the pollution is external, air-tight cases will reduce tarnish rates, but can be catastrophic if there is a corrosive pollutant source inside the case. Their use with pumps and filters are the most successful way to clean the air (see Section 3). It is sensible to group silver objects together as much as possible, as the larger surface area will reduce the overall rate of tarnishing.

Reducing RH may help to slow down tarnishing rates, but the effect is limited, and the priority should always be to provide environments that are free from pollutants or mechanisms to remove pollutants from the air.

Key resources:

Costa, V 2001 'The deterioration of silver alloys and some aspects of their conservation'. *Reviews in Conservation* **2**, 18–34

Franey, J P *et al* 1985 'The corrosion of silver by atmospheric sulfurous gases'. *Corrosion Science* **25**(2), 133–43

Graedel, T E 1992 'Corrosion mechanisms for silver exposed to the atmosphere'. *Journal of the Electrochemical Society* **139**(7), 1964–70

Kim, H and Payer, J H 1999 'Tarnish process of silver in 100 ppb H₂S containing environments'. *Journal of Corrosion Science and Engineering* **1**, paper 14, available at <http://www.jcse.org/volume11/paper14/v11p14.php>

Pope, D *et al* 1968 'The tarnishing of Ag at naturally-occurring H₂S and SO₂ levels'. *Corrosion Science* **8**, 883–7

2.5 Other metals

In the 19th and 20th centuries, a much wider range of metals came into use and are now beginning to enter the archaeological record. There is limited information about the corrosion of these metals during and after burial, and little systematic research into how they should be conserved. This section summarises what is known about some of the more common early modern and

modern metals that may be encountered in an archaeological collection, and suggests basic recommendations for their storage based on the current state of knowledge. Tin is included in this section as although it has been used since antiquity there is limited research on its post-excitation corrosion. Any of these metals are used as coatings. The presence of platings within the corrosion layers will make the objects liable to damage and information loss if not stored correctly.

2.5.1 Aluminium

Aluminium, despite being one of the most common elements on earth, was not exploited until the late 19th century owing to the technical difficulty in extracting it from its ore. It is a very reactive metal, and immediately forms a very stable thin oxide layer on contact with air, which then prevents further corrosion. When first produced, its novelty value led to its early use in the decorative arts, the statue of Eros (1893) at Picadilly Circus, London, being a good example. The low density of aluminium has made it invaluable in the aviation, marine and automotive industries as a covering and cladding material. As a metal for casting, it has been widely used in engineering, building, manufacturing, for machine components and in many household applications. It is normally alloyed with small amounts of other metals such as copper, manganese and zinc.

Very little is known about the corrosion of aluminium in a conservation context (Green and Thickett 1993). The action of salts can increase the rate of aluminium corrosion, particularly localised corrosion, which can lead to weaknesses in the metal (Dan *et al* 2012; de la Fuente *et al* 2007). Alloying can also increase susceptibility to localised corrosion (Zaid *et al* 2008).

As with all metals, water is an important part of the corrosion reaction, and so high RH will lead to increased corrosion. There is no research on thresholds for aluminium corrosion, and so it is not currently possible to suggest RH limits for storing excavated aluminium. It is likely that the presence of water-attracting salts will cause increased corrosion, as is the case with iron and copper. Regular monitoring of aluminium objects is recommended, and reduction of RH for objects displaying signs of corrosion.

Aluminium is sensitive to corrosion by organic pollutant gases, notably acetic acid (Clarke and Longhurst 1961) and formic acid (Donovan and Stringer 1971), which destabilise the corrosion-protecting patina that is normally found on aluminium. Environments with these organic pollutant gases should be avoided, or appropriate control measures taken (see Section 3).

Aluminium objects that are showing signs of localised corrosion may require conservation treatment.

2.5.2 Zinc

Zinc is a blue-white lustrous metal, which is softer than iron and somewhat brittle. Although zinc ores were mixed with copper to make brass in the ancient world, it was not 'discovered' as a separate metal until 1746. By the early 19th century, its corrosion and wear-resistant properties were exploited for purposes such as roofing, architectural features, sculptures and linings for containers. As a plating applied to iron (galvanising) it provides corrosion protection. Alloyed with aluminium and magnesium, zinc has also been used for cast coinage and architectural decorations. Zinc and its alloys will normally acquire a dull pale grey appearance after exposure to the air, especially out of doors, owing to the formation of oxides and related products.

As with aluminium, most studies focus on initial corrosion mechanisms of clean zinc surfaces, though there has been some conservation research into the corrosion of outdoor zinc sculptures (Grissom 1994; Grissom and Harvey 2003). There is little information on the behaviour of zinc corroded in soil environments, though as with many metals, the presence of salts can cause deep pitting and surface disruption. Zinc exposed to air forms stable oxide or carbonate patinas, but these can be easily disturbed. Zinc that is permanently damp will undergo rapid corrosion. Zinc chloride is hygroscopic and will cause damage to the patina, and, as with silver, fingerprints can cause localised corrosion patches.

Compounds known to cause corrosion of zinc include organic acids (Clarke and Longhurst 1961; Donovan and Stringer 1971; Green and Thickett 1993), hydrochloric acid, sulfate aerosols and sulfur dioxide (Askey *et al* 1993; Graedel 1989; Oesch and Faller 1997). Overall zinc is generally less sensitive to these compounds than lead.

As with all metals, reducing the RH slows down the rate of corrosion, but there is currently no research into threshold limits for protecting zinc (Graedel 1989).

2.5.3 Tin

Tin is a silvery-white and rather soft metal, easily shaped by hammering and with a low melting point. It is occasionally encountered as a pure metal in ancient contexts, eg in London in the 2nd century AD where it was used for tableware and canisters (Jones 1983) and has also been used for coinage in several parts of the world. Tin is usually encountered either as an alloy or as a plating on iron to confer corrosion resistance. Tin plating in ancient contexts was achieved by dipping the base metal object into molten tin to provide a rust free surface on items such as spurs, keys and buttons. Since the mid-18th century 'tin plate' has been made in large quantities including hollow-ware for cooking, eating, and storage and, from

the mid-19th century, tin cans for food. Sophisticated rolling techniques were developed from the mid-18th century onwards to produce large sheets of very thin iron, which could then be coated with tin by hot-dipping. Only since the mid-20th century has tinning been achieved using electroplating techniques.

Early reports of 'tin pest', the transformation of tin from its metallic state to a second, powdery form at low temperatures, have now been recognised as generally mistaken. Most museum objects are very unlikely to suffer from this transformation, as they contain impurities of other elements, which render the effect almost impossible. Reports of damage erroneously called 'tin pest' are normally due to localised active corrosion phenomena, induced by humidity and pollutants (Lihl 1962; Plenderleith and Organ 1954).

Tin itself is generally thought to be corrosion resistant in air; but the addition of various alloying elements can cause corrosion. There is very little information on its behaviour in soil environments.

In high humidity (80–90%) tin is sensitive to corrosion by atmospheric gases, but there is no data on the RH threshold for this behaviour or whether it occurs at normal atmospheric levels of the gases (Sasaki *et al* 2003).

The most common form of tin encountered in archaeological contexts is as pewter; an alloy with lead, and sometimes containing small quantities of copper, antimony or zinc (modern pewters contain the latter elements but no lead for toxicity reasons). Because of its lead content, pewter must be protected from organic acid emissions: refer to Section 2.3 (Clarke and Longhurst 1961; Donovan and Stringer 1971).

2.5.4 Nickel and chromium

First discovered in 1751, nickel is a hard, silvery white metal with a slight golden lustre. Because of its corrosion resistant qualities it lends itself for use as an alloy or as a plating. It has, however, been used in its pure form for coinage in a number of countries from the mid-19th century onwards.

Nickel/copper alloys, variously known as cupro-nickel, nickel silver, or German silver, have been used extensively for cutlery and costume jewellery from the early 19th century onwards, and also for modern coinage. After 1840, it became the base metal for silver-plated (electroplated nickel silver [EPNS]) cutlery and decorative tableware. These, and other modern metal alloys, can often be identified from the maker's marks. Nickel plating on iron and brass became common after 1870 on semi-decorative engineering components, such as lamps and scientific instruments, and on many domestic appliances. Nickel plating is still in use today, but usually as a bonding layer between the base metal and chrome plate.

Chromium, a hard, lustrous white metal was discovered in 1797, but not widely exploited until well into the 20th century. Being brittle, objects made entirely of chromium are unknown. However, its tarnish and corrosion resistance made it ideal for plating in the automotive industry, and also for domestic plumbing fittings and appliances. More recently it has even been used for plating onto plastics. It alloys readily with iron, forming stainless steel (see Section 2.5.5).

The archaeological and conservation literature is almost silent on nickel and chromium, nonetheless, objects composed of any mixed metals, whether alloys or plated, will be affected to some extent by burial. Usually one metal will corrode preferentially, covering the object with obscuring corrosion products. Nickel and chromium do not themselves corrode when in contact with base metals, but platings of these metals can be disrupted by the base metal corroding, especially iron. Objects rich in nickel may have a thin covering of blue or green nickel corrosion products.

2.5.5 Stainless steels

Many modern steels are alloys of iron with other metals to provide specific qualities, often of significant corrosion resistance. 'Stainless steel', an alloy of iron, chromium and nickel, was developed in the UK in 1912 and was manufactured in increasing quantities during the 20th century because of its extreme resistance to staining and corrosion. It is still material of choice in industries such as chemicals, drugs and food manufacturing and processing where cleanliness is vital, and to make piping to conduct

corrosive liquids. Since the 1960s, it has also become a commonplace material in the home.

Stainless steels are not severely affected by burial, a thin rust film being the worst to be expected even in the most aggressive environments.

2.5.6 Coatings

Non-metallic surface coatings, such as vitreous enamelling, and various lacquers and varnishes, were commonly applied to utilitarian metal objects from the late 18th century onwards to provide a wear and corrosion resistant, washable and often decorative finish. Once buried in the ground these surface coatings will normally have become chipped and worn, exposing the base metal beneath to corrosion. Such surface finishes can become seriously disrupted and dislodged due to the expansion of the corrosion products as they are formed.

Post-excavation and post-conservation storage of any of these mixed metals should be as per the base metal.

Key reference:

Selwyn, L 2004 *Metals and Corrosion – a Handbook for the Conservation Professional*. Ottawa: CCI

Section 3: Achieving standards for storage and display

Good planning of a new or redesigned display, building of new showcases and the implementation of storage should consider the

needs of the objects from the very beginning. Poor planning leads to objects being placed in unsuitable storage and display environments, and is often a cause of object damage. By considering environmental and pollutant control throughout the planning and implementation stages, many problems can be prevented from occurring in the first place, maintaining the value of the objects and saving time and resources in the long run. This section provides guidance on how to integrate environmental control and monitoring into storage and display environments.

3.1 Planning a display

Many factors are important when planning, designing and implementing a new display, from the basic design of the showcase to the case dressing, graphics and mounting. The MEMORI project has developed a decision support model to guide users through this process. A link is available on the webpages. This shows how considering the objects' materials and environmental risk factors is the first step in creating a new display. By following the steps in the decision support model through, the display is planned in such a way that it conforms to the needs of the objects. Some additional factors that impact on showcase design are summarised in Info box G.

Following through a clear series of planning steps will highlight any areas where it is not possible to create the ideal environment, eg if an existing showcase needs to be reused or for temporary exhibitions where it may not be possible to specify the ideal conditions for budget or time reasons. The guidance in the

Info box F: importance of air exchange rate (AER)

Air exchange rate (**AER**) is a measurement of how air-tight a case or storage box is. It describes how long it takes to replace the air in the case with air from outside, and is measured in air changes per day. AER is a crucial factor in many issues around environmental control, because the effectiveness of control methods is dependent on the rate at which air moves in and out of the enclosure or room. Low AER (good air-tightness) means that, eg desiccant material will last longer because the influx of moist air from the outside is slow, but increases the risk of the build-up of pollutants from sources inside the case. High AER (poor air-tightness) can make RH control mechanisms inside a showcase or storage box very difficult to maintain in the long term, and increases the influx of external pollutants including dust (Thickett and Luxford 2007; Thickett et al 2007a, 2007b). A desirable AER will therefore depend on the objects and the source of the problem to be controlled.

AER can be measured in several ways but one of the simplest is using a tracer gas, such

as carbon dioxide, injected into the case. The carbon dioxide concentration is monitored using a logger inside the case to measure the time it takes to disperse.

Further information on how to carry out AER testing is available in Calver et al (2005), Thickett et al (2007a), Thickett and Luxford (2007) and Thickett (2012).



Fig 23. Measuring air exchange rate in a showcase

Info box G: some principles of showcase design

The design of showcases is critical in achieving good environmental control. Examples of good design are found in the case studies, and guidance on showcase design is provided by some manufacturers (see webpages). The following factors should be considered (Thickett and Luxford 2007).

- Air tightness – the desired air exchange rate (see Info box F) will depend on the intended contents and use of the case, the frequency of maintenance schedules and the external environment. The design type and build quality of the case are primary factors in determining the air exchange rate, and factors such as size, hinge location, lock positioning and seal types should be considered.
- Space for desiccants and buffers – for ease of use, RH buffering materials should be placed in a compartment separate from

the main space. This allows the **silica gel** to be changed without the showcase itself having to be opened. The compartment must be big enough to hold sufficient quantities of conditioning material for the space, and this can be calculated (see web pages).

- Air circulation—movement of conditioned air from the lower compartment to the whole display area is vital. Baseboards separating the silica gel compartment from the display area should be perforated with holes covering 50% of the area. The size of holes is also important: 5mm holes have been shown to be too small, while 8mm holes allow sufficient air exchange (Thickett and Luxford 2007b), and the National Park Service recommends 15mm holes or gaps. Holes in the baseboard may be covered by fabric, but may still be visible. Any aesthetic objection to this is secondary to the need

for good air circulation around the whole case.

- Pollutant materials – cases should be designed in order to avoid materials that are known to emit pollutants. Wood products and other materials that emit organic acids (see Info box B) are most likely to cause problems. Avoiding wood products has the added benefit of making RH control easier: wood is able to buffer RH which makes the creation of low RH environments more difficult, needing much more frequent silica gel changes. Metal, glass and acrylic are suitable materials, including for baseboards.
- Case dressing – paints, fabrics, adhesives and graphics for use in showcases must be tested (see Info box H) and, when applied, enough time left for solvents to dry and off-gas before objects are installed. This process of testing and choosing suitable materials requires time, and must be factored in to the planning process.

Section 2 and the advice of a conservator will help to determine whether it is possible to mitigate the risk by refitting cases. This can be achieved by using additional control mechanisms, the placement of the case in a particular location or rethinking the objects to be displayed. It is possible to balance the potential risks to objects, based on the evidence and advice in these guidelines, against the costs and practicalities in each particular case, and make well-informed decisions.

The requirements for protecting objects can cause problems for the case designer, and need to be discussed well in advance. Design issues can be caused by perforated baseboards, rejection of materials on pollutant grounds, etc, so it is important to be sure that these measures are necessary for the objects in the case before they are specified. Following the appropriate sections in this guide will help to determine which measures are necessary to provide adequate protection to the objects, without over-specifying and causing additional difficulty and expense. More in depth guidance is given at <http://www.memori-project.eu>.

3.2 Achieving good storage

Environmental and pollutant control in storage environments is, if anything, more important than in showcases because the objects are not viewed as often and problems may go undetected for some time. Thus planning good storage is crucial.

Carefully considering the storage space is an important first step. Ideally storage rooms should not be damp. They should be low traffic areas, as frequent movement of people and opening of doors will increase the overall humidity, dust levels and pollutant ingress. For the same reasons, using storage rooms as study spaces is also inadvisable. Rooms that have large daily or annual fluctuations in temperature and humidity are also

not particularly suitable; although micro-environments can mitigate these effects, large fluctuations in the external environment will increase the need for maintenance. Improving any of these aspects is a simple way to improve the overall conditions for the objects.

3.2.1 Packaging

Small metal objects are normally stored in polyethylene or polypropylene boxes with snap-fit lids and **desiccants**. The majority of the air exchange rate occurs through the lid seal, and therefore well-fitting lids are the most important factor in assessing the suitability of boxes.

Most museums use Stewart Plastics boxes for storage of metal finds. After this box was redesigned in the mid-1990s, tests showed that the air exchange rate of the new boxes (made of polypropylene rather than polyethylene, and with a more rigid

lid) was higher. They are also susceptible to deformation of the lid when stacked, causing the air exchange rate to double when a second full box is placed on top (Thickett and Odlyha 2010). Avoiding stacking of boxes will help to prolong the life of the microclimate inside.

Newer brands of polypropylene boxes with compression seals and locking lids have lower air exchange rates and hold low RH for longer, and these are suitable as replacement for Stewart boxes.

Irregular or large objects that do not fit into standard boxes can be packaged using conservation-grade materials, see webpages.

The RH in the room has a surprisingly large effect on the lifetime of silica gel in Stewart boxes and how often it requires changing. Monitoring room RH conditions is advisable,



Fig 24. Stewart box for storing archaeological iron and copper alloy, with silica gel and RH indicator card



Fig 25. Lock and lock box

and the installation of dehumidifiers or climate control systems may be a cost-effective method of reducing the need for silica gel changes and maintenance, particularly for large collections.

3.2.2 RH control in storage

In storage environments controlling RH can either be achieved through micro-environments within the packaging using a buffering or desiccant material, or through the control of whole storage rooms. Using both methods in tandem can often yield good results: by using air conditioning to reduce external fluctuations in the storage area, micro-environments using passive RH control will last longer and be more stable (see Section 3.3).

3.2.3 Pollutants in storage

In storage environments, avoiding pollutants is normally achieved through good packaging. Materials that emit pollutants must be avoided, and only conservation-grade materials are suitable (see Info box B and Table 5). When selecting storage boxes, bear in mind that some types may emit higher levels of pollutants or be less air-tight (Thickett 2012). As levels of pollutants in the environment may be high, any box is normally better than no box at all to reduce ingress of external pollutant gases. If pollutant levels in a storage area are very high because of the presence of fixtures and fittings in emitting materials (eg wooden shelving), it may be advisable to refit the storage space to reduce overall pollutant levels.

3.3 Methods for controlling humidity

Controlling humidity is important for many metal objects (as well as other materials), and Section 2 gives specific detail on what RH conditions are appropriate for each metal. This section gives an overview of the various methods available to control RH.

3.3.1 Desiccation and buffering

RH control can involve either desiccation (drying the environment to below a certain threshold level for corrosion), or **buffering** (maintaining RH within a given zone, neither too dry nor too damp). Desiccation is most often the goal for slowing or stopping corrosion reactions, as for iron and copper; while buffering may be needed for objects made of mixed materials that are sensitive to both dry and damp conditions, or for cases containing objects of different materials. Buffering controls the level of humidity fluctuation around an optimum humidity set point, which is important for materials that are sensitive to rapid changes in RH. Buffering will only control to the average room RH. A conservator can advise on the specific needs for a particular situation.

Methods for buffering and desiccation fall into two categories: passive (where a material is included that controls the RH) and active (using a mechanical system).

3.3.2 Passive control methods

Silica gel is the most common desiccant and buffering material. It is made of round silicate particles which are porous and have high surface area. It is capable of **adsorbing** large quantities of water vapour and has a high buffering capacity. The most common type of gel is regular density (RD) gel. Silica gel is the simplest and most cost effective method of controlling RH, although its effectiveness is strongly dependent on proper use and maintenance. The manufacturer's recommendation for conditioning, drying and use should be consulted. The length of time silica gel will maintain the desired RH before it needs to be changed will depend on the air exchange rate of the container; the external humidity and the quantity of gel.

Silica gel can be either bought loose, or in pre-packaged boxes, cassettes or cotton or **Tyvek®** bags. To use it as a desiccant, it must be dried in an oven with air circulation to remove water. Oven-dried silica gel has an RH of around 5%. To buffer silica gel to control humidity around a specific point, it can be conditioned. Some manufacturers recommend adding liquid water to the gel to a specific weight. A second method is exposing the gel to the desired RH for a period of time. Conditioning silica gel takes several weeks, depending on the quantity.

Various types of silica gel are available. Normal silica gel is most effective at low RH, while Artsorb and Proisorb gels are manufactured to give better buffering in particular ranges (Table 5).

Old-style cobalt chloride-impregnated silica gel, which is in crystal form and coloured pink or blue-purple, has fallen generally out of use. It should be replaced with modern silica gel beads and disposed of carefully, as the cobalt chloride it contains can cause asthma and is considered a carcinogen.

Bentonite clay is an aluminiumphyllosilicate clay which can adsorb water. It has a similar adsorption capacity to silica gel below RH 40%, but much less above RH 40%. The chief advantage of clay is that it has a higher packing density, as the particles are much finer than silica gel. It is therefore useful in showcases where there is inadequate space to provide enough silica gel to control the space.

Zeolites are minerals that can be specifically engineered to trap particular molecules. Zeolite 4A traps water vapour, and its adsorption rate is faster than that of silica gel. This is an advantage where rapid desiccation is needed. The main drawback of zeolites to control humidity is that they have limited buffering capacity, and therefore they are not suitable where they cannot be closely monitored and replaced when necessary.

3.3.3 Active control methods

Dehumidification systems can be used to control larger showcases or whole rooms. The use of dehumidifiers requires electrical power and the space to accommodate the unit within the case or room. Their advantage is that humidity can be closely controlled, a particular advantage in cases of mixed materials where a narrow RH band is needed.

Drying wheel dehumidifiers use two air streams to regulate the humidity, one dry air stream, which is fed into the case, and a heated stream to remove water. They function well at

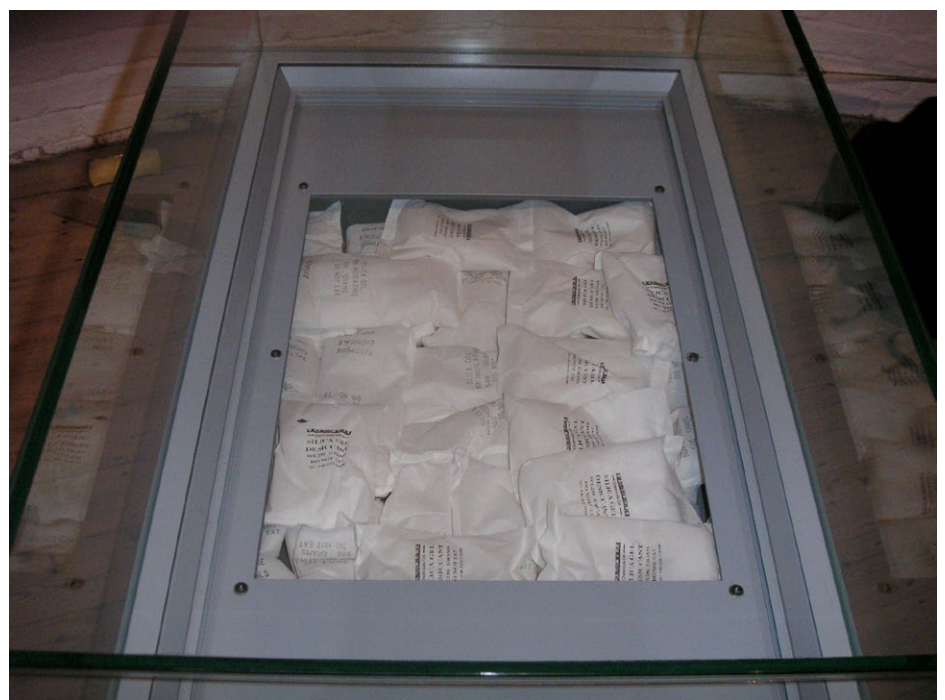


Fig 26. Silica gel (11 kg) used to keep a showcase RH below 30%

Method	Type	Form	Notes
Regular silica gel	Passive	Beads	Inexpensive
		Packaged or loose	Needs regular maintenance
		Cotton or Tyvek® bags	Best performance at 0–40% RH Orange to green indicating gel available (change at c 35%)
Prosorb	Passive	Beads	More expensive than silica gel
		Packaged or loose	Good for buffering Best performance 40–60% RH
Artsorb	Passive	Beads	Contains lithium chloride additive, which may be corrosive to metals, AVOID direct contact with objects
		Packaged or loose	More expensive than silica gel
		Impregnated sheets	Best performance 55–75% RH
RHapid Gel	Passive	Pre-packaged sachets	American brand
		Embedded into sheets	Best performance 32–40% RH Available pre-conditioned if desired
Bentonite clay	Passive	Fine powder	Denser than silica gel – takes up less space
		Packaged in bags	Good below 40% RH
Zeolite 4A	Passive	Loose granules	Very rapid adsorption for drying Little buffering capacity
Condensing dehumidifier	Active		Not in cold temperatures Requires emptying/plumbing Requires power
Drying wheel dehumidifier	Active		Good in cold temperatures Needs an exhaust Requires power
Membrane drier	Active		Requires power Some models produce ozone

Table 5. Methods for relative humidity control

low temperatures, but produce an exhaust of warm damp air which needs to be expelled from the unit.

Condensing dehumidifiers rely on condensation to remove water from the atmosphere. Most can control RH to within 5%, although they will not function correctly below 10°C (Thickett 2012). They also require regular emptying of the condensed water (unless drainage can be supplied), making their use more maintenance heavy than drying wheel dehumidifiers.

Membrane driers use a polymer membrane to remove water from the case. They are relatively simple to use, but some have the disadvantage of producing ozone, which accelerates some corrosion reactions.

3.4 Methods for controlling pollutants

The first step in controlling pollutants is to test the materials used to construct the storage/display case for emissions. This can be done using an accelerated corrosion test or Oddy test (Green and Thickett 1995; Robinet and Thickett 2003) (Info box H). All metals are affected to some extent by the presence of pollutants, but particular care should be taken for cases intended to contain lead and silver. The safest solution for avoiding problems caused by pollutants is to avoid the use of emitting materials in the first place.

There may be some situations where this is not possible: where old wooden showcases are retained for historic reasons, where the cost of replacing all storage is prohibitive or

in environments where pollutants are present and cannot be removed. Some objects are a source of pollution that will affect metal objects. In these cases, control of the gases can be achieved in a number of ways.

3.4.1 External pollutants

In areas where the external air is heavily polluted (eg in cities or marine areas), avoiding ingress of the pollutant gases to the objects is best achieved using cases with low AER. Moving cases to rooms that are further away from doors and windows, and improving the air tightness of window and door seals to reduce the ingress rate of external pollutants may be advisable.

The effectiveness of cases in protecting objects from external pollutants can be enhanced by placing a **sorbent** material in the case seals (see Section 3.4.3 and case study).

In storage environments, polyethylene or polypropylene boxes with well-fitting lids provide excellent protection against external pollutants and do not generate significant amounts of internal pollutants (Thickett and Odyha 2010).

3.4.2 Internal pollutants

Although low AER is desirable from the viewpoint of controlling humidity, the more air-tight a case is, the more any pollutants from the construction and fittings will concentrate.

If pollutants are causing corrosion problems, the first step should be to remove the emitting material, if possible. Old case dressings, fabrics and graphics can be removed and replaced with safer materials. In the long term, removing the emitting materials or replacing the whole case is the best solution, because all other methods require maintenance and have only a limited lifespan.

3.4.3 Using sorbents and barriers

If the problematic material is part of the case itself, sorbents can be used to remove the pollutants from the air or reduce the emissions rate. Sorbents are materials that adsorb the pollutants from the air. They can be very effective, but have a limited life and need to be replaced as they become exhausted.

Carbon, as activated charcoal powder or fabric, acts as an air filter, and its longevity and effectiveness can be calculated based on pollutant levels (Thickett and Short-Traxler 2010). Activated charcoal fabric works best if covering the emissive surface.

Other sorbents include zinc oxide (Bradley 2005) and copper-impregnated foams or bags (Corrosion Intercept®). These may be used in conjunction with an air pump to clean the air and can be used in showcase seals to reduce the ingress of external pollutants (Thickett and Short-Traxler 2010), and to wrap objects in storage.

Barrier foils can be used to seal wooden materials such as MDF to reduce pollutant emissions. Aluminium-based barrier foils are most effective at reducing emission rates, although not always sufficiently to prevent problems entirely (Grzywacz and Tennent 1994). Other sealants such as polyurethane coatings and paints have only limited effects (Grzywacz and Tennent 1994; Miles 1986), and may themselves produce emissions. Dacrylate has been used to seal MDF, but is ineffective in preventing acetic and formic acid emissions (Thickett *et al* 1998).

In storage or displays where wooden cases and drawers cannot be removed, covering as much of the exposed wood with activated charcoal cloth can reduce the pollutant levels, though monitoring is needed to determine whether the levels have been reduced sufficiently (Thickett and Short-Traxler 2010). It is important to note that many activated charcoal cloths contain chloride, which can corrode silver and copper alloys when in direct contact with them, and this should be strictly avoided. Large individual objects can be wrapped in sorbent materials; anti-tarnish bags (for silver storage) may be suitable.

3.4.4 Reducing pollutant concentration

and dry, metal coupons (silver, copper and lead of analytical grade) scrupulously cleaned, very careful handling of all components, and an oven that can maintain a steady 60°C. In addition, the materials being tested are prepared following strict guidelines. Eg for solids such as fabrics, a specified weight is required and any liquids such as paints or adhesives must be applied to films in advance to allow drying time. Sufficient time needs to be allowed for preparing the samples and for retesting if products do not pass. It is wise to allow six weeks for each batch of tests and to test as many alternatives as possible.

Because the results are assessed by eye, there is a degree of subjectivity in interpretation but with experience, the test is regarded as a reliable indicator. There will be times when no material is found for a particular purpose that passes the Oddy test. A conservator should be able to judge on suitability of available products or advise on alternatives based on what is being displayed or stored.

A number of conservation laboratories in the UK carry out the test. An online resource for results would be ideal; currently there is an informal sharing of results by conservators.

Environments with high levels of internal or external pollutants may benefit from the use of pumps with absorbent filters. These can be fitted to cases to remove pollutants and circulate fresh air, and are useful for keeping cases containing silver free from external pollutants. (Thickett 2011; Thickett and Short-Traxler 2010). This approach can also be effective when an object emits pollution that affects other objects in the same enclosure.

Where build ups of internal pollutant gases occur and the offending material cannot be removed, it may be appropriate to increase air circulation to reduce their concentration, provided that external pollutants are not a problem. This approach needs to be carefully considered, as decreasing the air-tightness of a case risks reducing humidity control and allowing dust and pests inside (Grzywacz and Tennent 1994; Thickett 2012). Using sorbents and barriers to reduce the pollutant risk is normally a better solution.

3.5 Environmental monitoring

For any environment that is being controlled, regular monitoring is important to assess how well the control mechanism is working and monitor for any unusual effects. The type and frequency of monitoring will depend on the situation, and can be carried out for both pollutants and RH. The long-term considerations are discussed in Info box J. Monitoring may be vital in securing loans of objects by providing lenders with evidence of the environmental conditions before and during the loan period.

Info box H: testing materials for storage and display

Oddy test: accelerated corrosion test for storage and display materials.

The Oddy test was developed in the 1970s at the British Museum to provide a method of assessing suitable display and storage materials that could be carried out in a conservation laboratory without the need for analytical equipment. It has been adapted over the years but essentially involves exposing metal coupons to the material being tested within sealed glass tubes for 28 days in conditions that accelerate corrosion reactions. The metal coupons are compared to controls and the extent of corrosion (none, moderate or severe) will determine whether a material can be used in the long term or short term, or should not be used. The test is carried out on metals, but the results can be interpreted to determine the effects on other vulnerable materials.

Although a simple test in principle, for reliable results the test must be done to a rigorous standard to eliminate contamination. The test involves: preparation of glassware so it is clean

National museums and some other conservation labs are a good starting point for information about recent test results.



Fig 27. Oddy test being carried out © Museum of London



Fig 28. Wrapping a wood board with Marvelseal 360 and 3M 425 tape to stop emission of harmful gases from the wood into a showcase

3.5.1 Monitoring RH

RH monitoring is the most frequent type of monitoring carried out. A number of methods are available, each with advantages and disadvantages (Table 8). Some methods will also monitor temperature, which is important because of the temperature-dependency of RH and for documenting the possibility of rapid temperature-related expansion and contraction of metal items, especially silver:

To monitor RH in a case with a separate silica gel compartment, it is important to log the RH in the display space as well as the silica gel tray, to check that there is adequate circulation of dry air. Similarly, where dehumidifiers are installed in rooms, RH should be checked within the space at several points.

Card sensors are the simplest method, and are often used in storage boxes for archaeological metals. They consist of a card or paper impregnated with cobalt chloride or another

RH-sensitive indicating compound which changes colour as RH increases (Daniels and Wilthew 1983). A test of a cobalt chloride impregnated card sensor showed that as they age they tend to give readings that are too low, up to 10% lower after 6–7 years (Thickett and Odlyha 2010). This is particularly problematic for iron and copper, which require accurate RH limits. The reading of the colour is also somewhat subjective (Daniels and Wilthew 1983), and they are therefore not reliable if a clear RH boundary needs to be maintained. For storage areas with many microclimates, card sensors may be the only cost-effective option, but users must be aware of their limitations. Occasional checks with calibrated loggers can be useful.

Digital sensors and loggers are more accurate, though manufacturer specifications vary. Typically they are accurate to within 3–5%, but need regular recalibration to maintain this. Calibration should follow the manufacturer's recommendations and be carried out at least every 12 months. Calibrating sensors can be done by the user, or by the manufacturer. Sensors in polluted atmospheres may need more frequent calibration.

Small digital sensors, which display the current RH and temperature, can be placed unobtrusively in most display environments, and are useful for spot checks. A small sealable port in showcases, allows a single probe to be used to measure their internal RH periodically.

RH monitors	Advantages	Disadvantages	Cost range
Silica gel colour	Built-in to gel itself Easy to see	Highly inaccurate Only measures one RH point No history	Few pence
Card sensors	Cheap Simple Little maintenance needed	Inaccurate/subjective Decay over time Need to be checked manually No history	Few pence
Digital sensor	Reasonable accuracy (1–5%) Measure temperature and RH	No log over time Need regular calibration More expensive	£10–50
Standalone loggers	Log over time Reasonable accuracy (1–5%) Small and unobtrusive Measure temperature and RH	Need regular calibration Limited logging capacity Maintenance (battery changes, downloading data) More expensive	£120–600*
Remote loggers	Real time information (RH and temperature) Reasonable accuracy (1–3%) Multiple loggers in a single system Off-site access to data	Expensive Larger units Need regular calibration	£230–400

Note: *Cheaper loggers are available, but they are difficult or impossible to calibrate. All monitoring requires at least annual calibration to be accurate.

Table 6. Methods for monitoring RH



Fig 29. Various RH sensor types, listed in Table 6

Standalone digital loggers record environmental information, which can then be downloaded to a computer when the sensor is checked. This provides a log of past environmental conditions and the effectiveness of the control methods, and is good when objects are being transported. Many models allow alarms to be set, which will flash warning lights or sounds when the set RH limits are exceeded. These are helpful in environments where the loggers are checked on a regular basis. Digital loggers are significantly more expensive than indicator cards and so may not be feasible for large collections with many individual microclimates. The lifetime of batteries in loggers and the data storage capacity needs to be considered.

Remote or radio-based sensing equipment is also available. These have the advantage of providing real-time information, normally to a central computer on- or off-site where the data can be conveniently viewed and alarms noted. This is suitable where large or dispersed collections require close monitoring, but does come with a significant additional cost.

3.5.2 Monitoring pollutants

For pollutant measuring, **diffusion tubes** are a standard method (Gibson *et al* 1997) that has been widely used in museums. The

analysis is normally carried out by an external supplier. Tubes are exposed in a room or enclosure (usually by removing an end cap) for between 3 days and several weeks. After exposure the tube is sent back to the supplier for analysis and they supply a report with the results. They give an average concentration for the time period measured. Active analysis based on pumps has also been used in a few instances. Care needs to be taken that the sampling procedure does not disturb the environment. These measurements are often for no more than 4 hours and several measurements will likely be required over several weeks to get a good representation of the environment the objects are exposed to as concentrations vary.

Interpretation of results from diffusion tube measurements requires some care, as pollutant concentrations can vary significantly throughout each day, from day to day and season to season. This is even more important for the short-term active sampling. Multiple measurements will likely be required to determine the average exposure of metal objects over time.

As an alternative monitoring strategy, lead and silver coupons can be placed in cases to check whether corrosion is occurring (Berndt 1990;

Knight 1994, Thickett *et al* 2013). These are normally exposed for at least 4 weeks, but can be exposed for much longer periods, up to decades, to provide an early warning system for the occurrence of corrosion, and to record average corrosivity over the exposure period.

3.5.3 MEMORI reader and sensors

The MEMORI dosimeter combines the previously available early warning for organics (EWO) and glass slide dosimeter (GSD) into one dosimeter: The EWO part is sensitive to oxidising pollutants; ozone, nitrogen dioxide, and in certain instances sulfur dioxide and is also sensitive to temperature, RH and UV light. The GSD is sensitive to acidic pollutants, specifically acetic acid. It is also sensitive to temperature and RH. The GSD is a sensitive glass, and the EWO a sensitive polymer that respectively respond in a known measurable way to the environmental parameters described.

Results from the dosimeter are from the past environment; dosimeters are exposed for 3 months. The result is available relatively quickly, with the dosimeter read on site, not requiring lab analysis. However, results are not quantifiable pollutant concentrations. The MEMORI project has categorised varying levels of air quality to provide a risk assessment for the measured environment, giving an estimate

Corrosivity/ pollution monitor	Advantages	Disadvantages	Cost range
Diffusion tube	Small, relatively cheap	Have to return for analysis	£8–130 per measurement
Active monitor	Fast, low limit of detection	May alter a small enclosures atmosphere	£30–250 per measurement
MEMORI	Small, probably will be relatively cheap	Not yet commercially available	
Air Corr	Very sensitive, different metal sensors available, can read logger through glass	Expensive	£1,000 per logger plus £80–330 per sensor
Onguard	Very sensitive	Expensive	£2,200 for a logger with one each silver and copper sensors, £230 per new sensor

Table 7. Common methods for monitoring pollution or reactivity of an environment

of low, medium or high risk for a range of materials including archaeological iron and other metals.

The AirCorr logger has recently been developed; it is an electronic logger for continuous measurements of air corrosivity. It incorporates a sensor that measures electrical resistance along a metallic track. As the sensor corrodes the resistance changes, which is linked to the thickness of the sensor; giving a direct measurement of corrosion thickness. The sensor is available in a number of materials and thicknesses, to allow for measurements in low to high corrosive environments. Sensor sensitivity varies depending on thickness, from as low as 0.1 nm for the most sensitive models. Sensitivity can be traded for longer sensor lifetime by using a model with a thicker metallic track.

The sensors respond to changing conditions within minutes, giving essentially real-time information about current pollutants. As with the metal coupons the measurement is qualitative with respect to pollutant concentration; however corrosion thickness is quantitatively measured.

Sensors of this type have the advantage of providing direct measurements of the aggressiveness of an environment on a specific

metal, accounting for the interplay of all the various factors that influence corrosion rates. However, they may react differently to archaeological metals, especially iron and copper, as the Aircorr sensor is based on the reactions of a clean metal surface and includes no prior contamination, which may be present on objects.

A further development of this type of monitoring is currently being developed, using a chloride-doped iron electrical resistance monitor (Kapatou and Lyon 2008; Kouril *et al* 2007). These will be capable of monitoring corrosion risk at low to medium humidity levels, and will be particular suitable for the assessment of risk for particularly susceptible materials such as iron and copper.

The OnGuard logger employs quartz crystal microbalances to provide continuous monitoring of corrosion. Silver and copper crystals are currently available commercially. The technique is only qualitative for pollutants, however, corrosion thickness is quantitative, and this is reported directly, requiring no further analysis. The technique is very sensitive, as only a small change in frequency is required to indicate that corrosion has occurred.

Info box J: long-term maintenance – considerations for success

When devising a maintenance and monitoring schedule, the following issues need to be considered: how often the collection can be monitored; the sensitivity and accuracy required; ease of data retrieval; availability of software and expertise to analyse data and write appropriate reports; and cost. For maintenance, additional factors include the time taken to regenerate or replace control methods, staff time and resources and access to stores or displays.

Predictions as to how long a specific control mechanism will last can be made based on calculations. For RH, the longevity of silica gel in boxes and cases can be calculated based on AER and the external RH. The accuracy of

these calculations has been found to be good (Thickett and Odlyha 2010). By calculating how long silica gel or other buffers are expected to last, an appropriate maintenance schedule can be designed. Conversely, if a new storage or showcase is being specified, the design can be modified to accommodate the desired maintenance frequency by calculating the required air exchange rate and silica gel capacity.

For pollutants, calculations can also be made as to how pollutant gases will build up within an environment based on emission rates, and/or the ingress of external pollutants based on air exchange (Thickett 2012). Similarly, the longevity of sorbents, such as activated charcoal, can be calculated provided the pollutant levels have been measured (Thickett and Short-Traxler 2010).

The website provides further details on how to carry out these calculations.

Glossary

Active corrosion	Term used in this guide to describe unwanted post-excavation corrosion that is damaging to the objects.
Adsorption	Process by which a gas (e.g oxygen or water vapour) accumulates on a surface in thin layers, often only a few molecules thick.
AER	Air exchange rate: the rate at which air moves in and out of an enclosure.
Akaganeite	Also β -FeOOH, an iron corrosion product that forms after excavation. It contains chloride ions, and is a sign of active corrosion. Yellow-orange in colour; often the cause of flaking of corrosion products as its formation causes expansion.
Alloy	A mix of two or more metals.
Buffering	Maintaining relative humidity around a set point using a passive or active control method.
Cast	Describes metal that is shaped in its liquid state by pouring into a mould.
Chloride	A negatively charged particle (Cl^-) which is responsible for accelerating corrosion of a number of metals, notably iron.
Compound	A chemical substance composed of two or more elements.
Corrosion control	An approach to preventive conservation of metals where the aim is not to stop corrosion but to reduce reaction rates to an acceptable level, giving the objects a longer lifespan.
Corrosion product	The compound resulting from the corrosion reaction of the metal.
Cuprous	Copper oxidised by the loss of two electrons.
Desiccant	A substance that reduces relative humidity by removing moisture from the air.
Desiccation	Reducing the relative humidity of air as low as possible to prevent or reduce corrosion reactions.
Diffusion tube	A method of measuring the concentration of pollutant gases.
Electrolyte	A conducting medium that allows the flow of ions and electric current. In this context, normally refers to a solution of water and salts.
Emission	In this context, a gas which is emitted from materials used within the museum environment, eg showcases.
Environmental control	The term used to describe methods to control various aspects of the environment in order to improve the preservation of objects. Commonly refers to control of humidity, light and/or gaseous pollutants.
Ferrous	Iron oxidised by the loss of two electrons.
Galvanic corrosion	Occurs when two different metals are in contact. The more reactive metal will corrode more rapidly, while the other is protected.
Hygroscopic	Describes a substance which attracts moisture from the air.
Ions	Molecules or atoms which have gained or lost an electron and become electrically charged. Positively charged ions are cations; negatively charged ions are anions.
Metallography	The microscopic study of structure of metals and alloys.
Object lifespan	The length of time an object is expected to survive in a state that retains some or all of its value.
Ore	A mineral or rock which contains compounds from which metals can be extracted.
Organic pollutant gas	A pollutant gas containing carbon.
Original surface	The layer of corrosion products on objects which represents the original boundary of the object. It normally underlies other corrosion products until revealed by conservation treatment.
Oxide	A compound in which oxygen is combined with a metal.
Oxygen scavenger	A material that removes oxygen.
Patina	Corrosion layers, normally smooth and/or thin, which do not reduce the value of an object. Patinas may be protective to objects, and even enhance their value.
Pollutant	Gases in the air which are harmful, in this context to objects. Includes both external pollutants, from outside the building, and internal pollutants, which are generated within the museum environment.
Reaction rate	The speed at which a chemical reaction occurs.
Relative humidity (RH)	The amount of water in air as a percentage of the maximum amount the air could hold at a given temperature.
Salt	A compound formed of two or more ions.
Silica gel	A common passive material for controlling relative humidity.
Slag	Vitreous, glassy material left over when a metal is extracted from ore.
Sorbent	A material which absorbs pollutant gases from the air, reducing their concentration.
Stable/stability	Used to describe the state in which objects do not deteriorate.
Sulfide	A compound in which sulfur is combined with a metal.
Tarnish	A very thin layer of corrosion products (often sulfides) covering a clean metal surface. This is often used to describe the first stage in a corrosion process.
Threshold	A level of humidity or temperature above which a reaction begins to occur or its rate increases substantially.

Treatment	Any intervention with an object that is designed to reduce its corrosion rate, stabilise its physical structure or enhance its appearance.
Tyvek®	A lightweight material made of polyethylene fibres that is permeable to water vapour but not to liquid water. Often used in conservation applications.
Unstable	Used to describe the state in which objects do deteriorate.
VOC (volatile organic compound)	The group of compounds which vaporize readily and cause corrosion of metals.
Wrought	Describes metal that is shaped in its solid state using hammering.

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Front Cover :Member of Ermine Street Guard beside replica Roman armour; the structure of which was determined from the adjacent archaeological iron from the Corbridge Hoard.

Back Cover, top: Corbridge Lanx; bottom: Roman coffin excavated at Lullingstone Roman Villa.



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