Critical Knowledge Gaps in Environmental Risk Assessment and Prioritising Research

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Abstract The scientific underpinning for the effects of environment on highly transformed archaeological materials is weak. Archaeological iron has been intensively studied recently, but the three publications about copper alloys disagree on critical RH thresholds and no work on pollutant effects has been published. This paper will assess the present state of knowledge and identify critical knowledge gaps.

The effect of VOCs on organic materials has received very little attention. A recently started project, MEMORI will address this issue. The effects of acetic acid and other VOCs will be assessed. A more economic measurement system will be developed to address the cost barrier presently impeding VOC analyses in heritage atmospheres.

The balance of these risks may change in the future under the influence of climate change. Investigations to predict the changes inside buildings are underway. This information is crucial to prioritise future research to fill the gaps identified and formulate suitable, sustainable mitigation strategies.

Incorrect relative humidity and temperature levels, light and pollutants all tend to act progressively as type 2 or 3 risks, although rapid deterioration can occur (cracking of wood at low RHs and rapid corrosion episodes can take place in a matter of a few hours). This paper will assess the present state of knowledge and identify critical knowledge gaps for archaeological materials. This has been limited to archaeological materials to produce a reasonably succinct piece of work, due to the very large number of references. Excavation records hold essential context information about

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archaeological archives and they have been considered as part of the archaeological collection, hence paper based and photographic records are included. Similar analyses have been carried out for fine and decorative art collections, libraries and archives, natural history and ethnographic collections, and these results will be discussed in the second part of the work but not presented here.

A combined risk and damage audit has contributed to the formulation of a research plan to address these gaps. It has identified both the most damaged materials in English Heritage's 500,000 objects spread over 120 sites and the most damaging risk factors. This information has been used to prioritise English Heritage's collections conservation research program.

The balance of these risks may change in the future under the influence of climate change. Investigations to predict the changes inside buildings are underway. The relative future magnitudes of type 2 and 3 environmental risks are predicted. For example the crystallisation cycles of several salt species are predicted to increase in many properties. This information is crucial to prioritise future research to fill the gaps identified and formulate suitable, sustainable mitigation strategies.

Knowledge Gaps for Archaeological Materials

Experience of a collection's stability within existing environmental conditions is extremely valuable and is the best approach to environmental management, as enshrined in EN15757, *Conservation of Cultural Property — Specifications for Temperature and Relative Humidity to Limit Climate Induced Mechanical Damage in Organic Hygroscopic Materials* (BSI 2010). However, some types of deterioration are extremely difficult to detect with visual and simple conservation examination, for example, the slow embrittlement of organic materials caused byacid hydrolysis or oxidation and reaction with pollutant gases; technical underpinning of preventive conservation; experiments assessing the impact of different environmental factors at different levels and studies of the real deterioration of collections of artefacts in heritage environments provides an understanding of the underlying processes and their balance of effect. The complexity of artefacts with often unknown composition and aging histories and complex conservation histories means experimental work needs confirming with observations on real artefacts. This is especially true for highly transformed archaeological artefacts, which may bear little resemblance and react very differently from fresh materials. There can also be unexpected differences in results between experimental methods. For example lead exposure tests to ethanoic acid have shown different RH susceptibilities with static and flowing systems (Tereault 1998 and Nicklassen 2007).

A comprehensive literature search has been undertaken of journals and conference and meeting proceedings, standards and guideline publications, websites and technical reports and papers from conservation research institutions. The in-

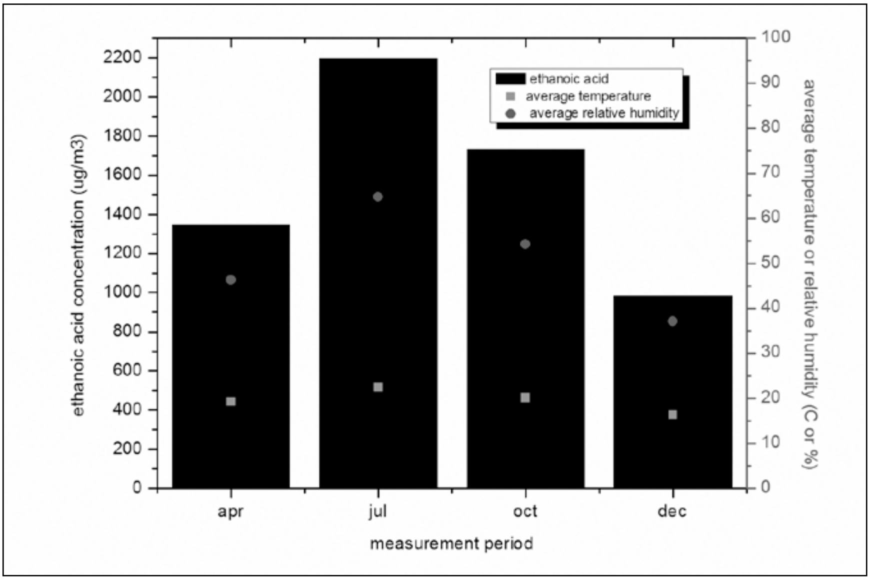

Figure 1. Ethanoic acid and average temperature and relative humidity in showcase throughout the year.

formation available has been assessed against the following criteria. If a reasonably full set of environmental data were available could the risk posed to that type of material be assessed? A reasonable set of environmental data would comprise:

- Continuous temperature and relative humidity data for a year at hourly intervals (three years worth of data is recommended for historic buildings)
- Diffusion tube measurements of external pollutants including sulphur dioxide, nitrogen dioxide and ozone guided by seasonal external concentrations
- Diffusion tube measurements of ethanoic (acetic) and methanoic (formic) acid and methanal (formaldehyde) concentrations or effect/corrosivity sensor measurements with lead coupons or copper coated piezo electric quartz crystals (Knight 1994, Berndt 1990, Thickett 2006, Muller 2000).

In non-air conditioned spaces with enclosures the concentrations and corrosion rates and will be influenced by the temperature and RH conditions, with higher values generating higher concentrations, see Figure 1. These are results for a heated building with a doubling over the seasonal range; other workers have reported much larger variations (an increase by a factor of ten over the seasonal range) in ethanoic (and methanoic) acid concentrations in unheated buildings (Grontoft 2005). This needs consideration when planning monitoring.

- Dust deposition rate measurements with glass slides (Adams, Howell et al 2002) or continuous measurements (Bowden 2004, Hanwell 2011)
- Light measurements; spot measurements for fully artificially lit spaces and continuous measurements or dosimeter measurements (Bullock 1996, Bacci 2003) over a full year

Dust has generally been considered in terms of acceptable soiling and cleaning intervals (Brimblecombe et al 2005) with some object types being considered to be especially susceptible (Tétrault 2003). Many archaeological objects are fragile and cleaning is best minimised. Materials such as PEG impregnated wood are liable to more rapid soiling as the PEG holds dust on the surface. The interaction of dust with objects, particularly direct damage is almost absent from the literature, despite several references in textbooks (Cameron 2006, Harvey 1989). The only examples of direct damage are for non-archaeological objects (Vernon 1923, Thickett and Hockey 2002, Thickett and Pretzel 2010). This lack of information may be attributed to the highly variable composition of deposited dust. A sulfur dioxide molecule is identical and acts in an identical manner where ever in the world it occurs, whereas the composition of dust is determined by the wider environment from which it originates and the composition will determine any interaction with artefacts.

The effects of light are well and sufficiently characterised. Hence, the effects of temperature, RH, external pollutants and internal pollutants were considered. Six subdivisions were considered. Each subdivision was ranked into three categories: no knowledge, some knowledge, enough knowledge to make a full risk assessment from the environmental data.

- Are there agreed RH and temperature stability ranges, well supported by scientific studies?
- If the conditions are outside of these ranges is the relative risk known?
- Are the effects of the external pollutant gases, sulphur dioxide, nitrogen dioxide and ozone known?
- Are their synergistic effects with RH understood?
- Are any effects of internally generated pollutant gases such as ethanoic and methanoic acids and methanal known?
- Are any synergistic effects with RH understood?

There has been a significant amount of research into archaeological iron over the past decade (Watkinson 2004, Thickett 2004, Wang 2010, Kapatou 2008) and examples of enough knowledge to make a full risk assessment can be drawn from this work. A suitable RH range would depend on the species present in/on the iron, akaganeite lowers the RH at which corrosion will occur to 11%, copper ions lower it to 15%, otherwise 16% is a well-defined safe value. The risk of RHs above 16% is shown in Figure 2.

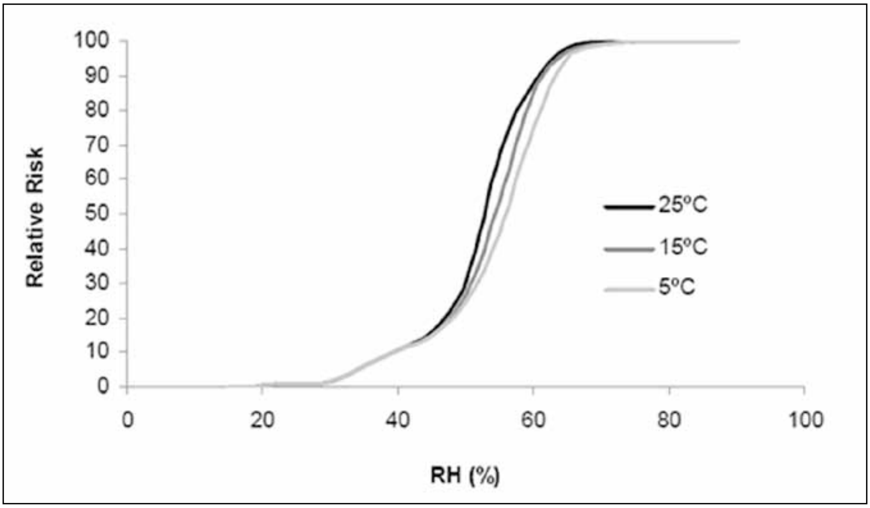

Figure 2. Effect of relative humidity and temperature on the risk to archaeological iron.

This is a combined risk, from the risk of physical disruption from volume expansion on akaganeite formation and the loss of iron from remained metal core (Thickett 2012). The effect of ethanoic and methanoic acid on iron has been quantified (Donovan and Stringer 1971). The effect on the akaganeite formation reactions has been studied using iron and iron (II) chloride powder mixtures and saturated salt and ethanoic, methanoic acid and methanal solutions to generate gas mixtures at set RH values. The effect was determined by quantifying the amount of akaganeite formed with FTIR spectroscopy and comparing this to a clean atmosphere at the same RH. Results for methanoic acid and methanal are shown in Figures 3 and 4. The results of the survey are presented in Table 1.

The scientific underpinning for the effects of environment on highly transformed archaeological materials is generally weak. Archaeological iron has been intensively studied recently and this work has built on that of Turgoose to provide a sufficient body of information to assess environments analytically and in a quantitative way.

The three publications about copper alloys disagree on critical RH thresholds. Experience with a number of collections appears to best coincide with Organ's conclusions. The expansion of local environmental monitoring in heritage institutions means instances of deterioration, such as bronze disease, can be correlated with environmental data. Work on pollutant effects has been extrapolated from that for effects on copper or copper alloys. No work has been published targeted towards archaeological copper and the effects of pollutants on copper chloride and its reactions.

Work on the tarnishing of silver has been hampered by the difficulty in producing realistic atmospheres for experiments due to the relatively low levels of hydrogen and carbonyl sulphide present. Whilst many experiments at much higher

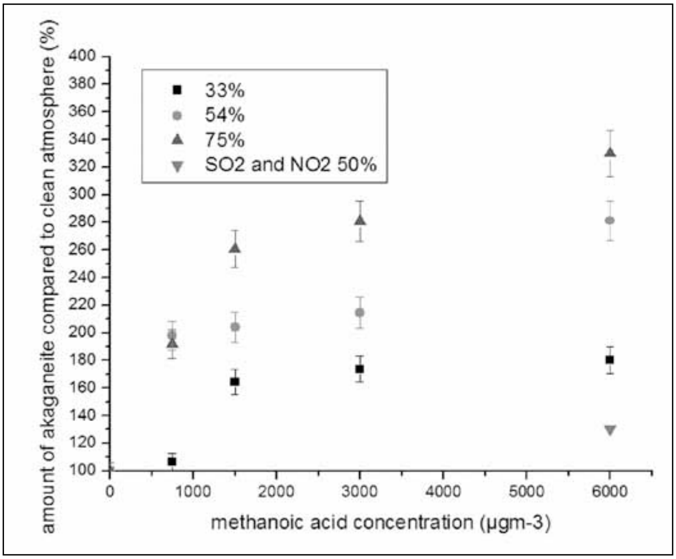

Figure 3. Effect of methanoic acid on the formation of akaganeite in archaeological iron.

concentrations have been undertaken, work has shown the kinetics differ at low, more realistic concentrations, hence these results cannot be assumed to hold in real situations.

There is little information on archaeological bone and the recommendations for ivory depend on a single study. Recommendations for archaeological wood and leather appear to be based on those for non-archaeological materials with some margin to account for higher sensitivity for RH (English Heritage 2010). The effects of VOCs on organic materials have received very little attention.

Paper and photographic records have a more extensive underpinning, but there still is very little published work on effects of VOCs. Recent work has shown that 10 VOCs emitted from paper and paper storage products can accelerate the deterioration of certain types of paper (Strlic 2011). It is likely that this issue affects many other organic material types with preliminary studies identifying affects at high VOC levels for parchment and canvas (Oriola 2011).

Targeting Research

There a number of ways to prioritise research, common examples include forthcoming organisational needs such as exhibition or new storage areas, national (Williams 2009) or international research funding agendas, or results from conservation or risk assessments. Countries with scientists embedded within collection managing institutions can produce well-targeted research due to long term observation of the collections and their needs. There is often a very strong emphasis on heritage

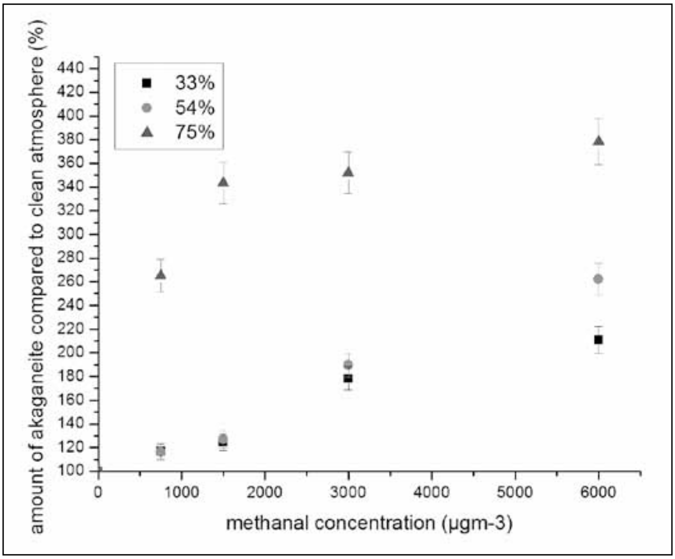

Figure 4. Effect of methanal acid on the formation of akaganeite in archaeological iron.

science, as opposed to conservation science, in such institutions supporting curatorial research, which can limit conservation science. General limitations on research include staff expertise and experience and access to equipment and collection material. Research often only becomes feasible after developments in either instrumentation (in situ, non-invasive and non-destructive techniques can make a unique contribution to degradation studies of real objects) or understanding, allowing realistic model materials to be produced for exposure experiments.

Within an organisation the balance of risks depends on the composition and location of the collection. English Heritage has a particularly challenging situation with 500,000 artefacts spread over 130 sites, each with very distinct environments. The environments range from: very dry properties open and comfort heated through the winter, producing RHs down to 20% to very damp underground chalk tunnels with the RH exceeding 90% for three months of a year. Several properties have relatively unpolluted rural environments, although ozone concentrations can be high in spring. Two locations are very near a ferry port experiencing very high (for Western Europe) sulfur dioxide and particulate levels, and within 5m of an extremely busy traffic junction generating very high nitrogen dioxide and diesel particulate concentrations. English Heritage has over 400 showcases and numerous other enclosures used in storage. Several of the showcases are historic in their own right and would not be replaced with more modern versions. The materials in these cases can generate up to 10,000 μgm^{-3} of ethanoic acid. Additionally there are over a hundred older cases with plywood and MDF generating considerable concentrations of ethanoic acid, cases with unsuitable paints generating high concentrations (5500 μgm^{-3}) of methanoic acid and particle boards producing high concentrations

Table 1. Scientific underpinning of preventive conservation of archaeological artefacts.

	RH range	RH risk	External pollutants	External pollutants and RH	Internal pollutants	Internal pollutants and RH
Iron	Turgoose 1984	Watkonson 2004; Thickett 2004; Wang 2007; Kapatou 2008	Oesch 1996		Green 1995; Clark 1961; Donovan 1971	Thickett 2012
Copper Alloy	Organ 1963; Scott 1999	Papapelekanos 2010	Graedel 1987;	Eriksson 1993	Clark 1961; Donovan 1971	Lopez-Delgado 1998
Lead				Niklasson 2007	Clark 1961; Donovan 1971	Tetreault 1998; Niklasson 2007
Silver		Graedel 1992; Kim 1999	Pope 1968; Franney 1985	Graedel 1992; Kim 1999	Pope 1968; Franney 1985; Donovan 1971	Graedel 1992; Kim 1999
Stone		Arnold 1990; Bradley 1988; Price 2000	Johannson 1988; Mororni 1996		Gibson 2005	
Ceramic		Arnold 1990; Bradley 1988; Price 2000			Linnow 2007	
Glass	Brill 1972	Brill 1975; Ryan 1996	Melcher 2004		Ryan 1996;	Robinet 2007
Wood	Mecklenburg , 1994, 2007; Jakiela 2008; Harvey 1989	Bratasz 2005; Jakiela 2007				
Bone						Brockerhof 1996
Leather	Cameron 2006		Spedding 1971; Tetrault 2003; Brimblecombe 1997			
Ivory	CCI 1988; CCI 1995; Smithsonian	Mecklenburg 2007; LaFontaine 1982;				Brockerhof 1996
Paper	Bogaard 2002	Menart in press; Wilson 1983; Strlic 2005; Sebera 1994	Baer 1985; Johansson 2000; Reilly 2001; Edwards 1968		Strlic 2011	
Photographs		Lavedrine 2009; McCormick-Goodhart 1996 Fenech 2011	Zinn 1994; Nguyen 1997			Fenech 2011
		enough knowledge to make a full risk assessment		some knowledge		no knowledge

of methanal. New showcases, over 100 have been installed in the previous 8 years, are designed to have no ethanoic or methanoic acid or methanal present.

A combined risk and damage audit has been carried out across all the sites with collections (Xavier Rowe 2011). This has identified which materials have been most damaged within English Heritages collections and the highest risk factors at present. The audit identified stores as having the highest risks across all territories. This caused a refocusing of the English Heritage Collections Research Strategy away from the risks on open display and towards quantifying and controlling the risks for stored materials. Table 2 shows the most damaged and most at risk material types present and the research projects or collaborations that have been formed to understand and mitigate them. The European Science Foundation COST actions have been particularly valuable in networking scientists working in particular fields and presenting the state of the art in that area. A significant proportion of the work presented at these meetings will unfortunately not be published and will remain in the grey literature that can be extremely difficult to access. Although several actions have very extensive web based dissemination. [insert table 2 near here]

The MEMORI, "Measurement, Effect Assessment and Mitigation of Pollutant Impact on Movable Cultural Assets–Innovative Research for Market Transfer" project is supported through the 7th Framework Programme of the European Commission (http://www.memori-project.eu/memori.html). It aims to provide the conservation market with an early warning technology for easy assessment of environmental impact. The project will optimise active and passive control for enclosures, assessing a large range of sorbents and their most efficient deployment methods. The sustainability of the different methods will be assessed. The results will be integrated with existing preventive conservation strategies. This will facilitate the use of enclosures across the heritage field. The project will address one of the critical knowledge gaps described previously, the effect of internal pollutants on organic artefacts. The materials most relevant to archaeological artefacts studied in the project are; leather and parchment, pigments, textiles and cellulosic materials. The effects on the materials will be assessed with a variety of analytical methods. Degradation markers characteristic of ethanoic acid exposure will be determined. Artefacts with recorded long-term exposure to ethanoic acid (greater than 160 years in some instances) will be analysed and their state of degradation compared to the environment to which they have been exposed and with objects that have been subjected to accelerated tests.

Future Prospects

English Heritages Collections Research Strategy has been re-formulated to address the priorities from the national audit. However with the effects (direct and indirect) of climate change and increasing energy costs, the balances of the risks may

Table 2. Most damaged materials in English Heritage collections as identified by the National Audit and research initiated to understand and mitigate type 2 and 3 environmental risks.

	EC Projects	Heritage Science Projects	Internal Projects	COST networks
1 ferrous metal		Evidence-based Condition-Monitoring Strategy for Preservation of Heritage Iron (IDR)	Post excavation changes and preventive conservation of archaeological iron (D) Anoxic storage of iron (M) High performance showcases for archaeological iron (I)	D42
2 wood		Change or Damage? Effect of Climate on Decorative Furniture Surfaces in Historic Properties (PD)	Response rates of wooden objects to fluctuating RH (I)	IE090
3 paint	MEMORI, Propaint	The Next Generation of Optical Coherence Tomography (OCT) for Art Conservation - in situ non-invasive imaging of subsurface microstructure of objects (IDR)		D42
4 non-ferrous metal				D42
5 paper	MEMORI	"Collections Demography" On Dynamic Evolution of Populations of Objects (IDR) Heritage Smells (IDR)		D42

Notes: IDR Heritage Science Program (www.heritagescience.ac.uk/) interdisciplinary research project; PD Heritage Science Program postdoctoral research project; D doctoral research project with Birkbeck College; M masters research project with Haute Ecole Suisse; I internal English Heritage project

alter and the relative affordability of different environmental control options may also change. Research is a long-term investment and research capacity is very limited both within English Heritage and the field as a whole. Securing the significant external funding required for some projects can take several years. Additionally it takes some time for research findings to influence practise across the conservation profession. Finding practical solutions within challenging environments such as historic buildings requires an amount of trial and error. Hence it is important to be able to predict emerging risks.

The economic risk from increasing energy costs of environmental control systems, and the effect of government policies to tackle climate change are areas requiring significant extra work. For example many institutions have moved to LED lighting for energy and cost saving. Whilst some work to assess the likely impact of the changed spectral energy distribution of such lighting has been undertaken in institutions, this has not been published and is at present not widely available. Accurate energy costs have been determined for the whole range of environmental control options used within English Heritage, to inform decisions made within the institution. Methodologies to predict these costs for new situations have been developed and tested.

A doctoral project at University of East Anglia with English Heritage, The National Trust and Royal Historic Palaces, has investigated the likely internal environments inside historic houses in the future. Ensembles of climate models are used to generate distributed external temperature and RH predictions. Transfer functions for particular rooms in buildings are calculated from past environmental data and the internal temperature and RH is predicted. Combined with pollution predictions and damage functions this information can describe the balance of risks for collections in a particular property for the future. The work has generally produced results from overlapping thirty-year periods (from UKCP) and up to around 2045 the climate predictions almost coincide no matter which emission scenario is used. Beyond 2045, the models have somewhat different predictions depending on the emission scenario used, the high emission scenario has been used for a worst case scenario (Lankester 2012). Combining this work with the National Audit results allows research to be planned to mitigate future risks.

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