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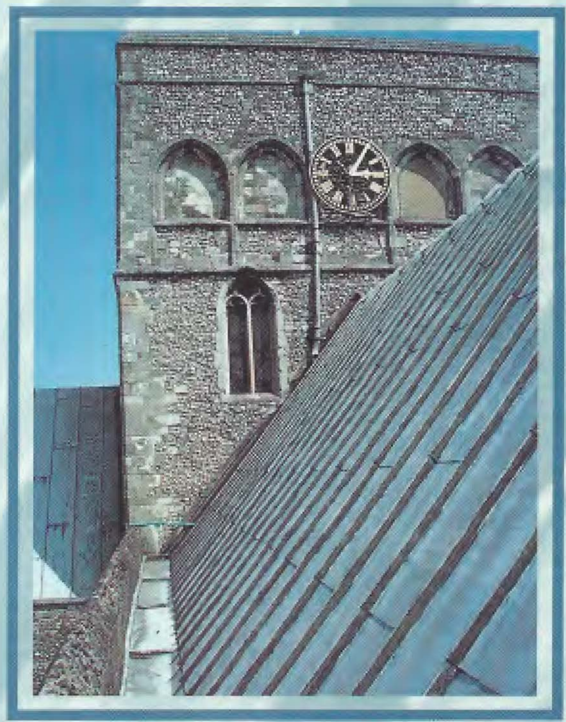
RESEARCH AND CASE STUDIES IN ARCHITECTURAL CONSERVATION



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Front cover
The lead covered roof of the church of St Cross, Winchester
(Bill Bordass/William Bordass Associates, London)

Contents

The underside corrosion of lead roofs and its prevention

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Abstract

This report describes the research project on underside lead corrosion and sets out the findings to date. It covers the earlier work of the 1980s and early 1990s but concentrates mainly on the research programme that was commissioned by English Heritage from 1993–6. This work was needed because of the suspected increase in the occurrence of underside corrosion on historic buildings, with the failure of conventional theories to explain what was happening. The aim of the research was to understand the mechanisms that give rise to corrosion and consider the implications for existing materials and working practices in order to try and prevent its recurrence and minimize the amount of alteration needed to building fabric. Testing was carried out in laboratories, on purpose-made rigs and on a wide range of sites and these are described along with initial conclusions. Much of the information in this report formed the basis of the joint English Heritage/Lead Sheet Association's advice note for specifiers.

Key words

Lead sheet roofing, condensation, corrosion, roof design, treatments

EXECUTIVE SUMMARY

For centuries plumbers have known that lead roofs are susceptible to underside corrosion, but this appears to have been regarded as a normal part of the decay of a nevertheless durable material, with a lifespan to re-casting of typically fifty to one hundred years or more. In the late 1970s, however, awareness and concern about underside lead corrosion increased.

Work in the 1980s, particularly by the Ecclesiastical Architects and Surveyors Association (EASA) and the Lead Development Association (LDA) led to:

- identification of the main problem as the attack of lead by condensed moisture
- promotion of better ventilation underneath the lead
- recommendations against warm roof construction in which moisture could be trapped
- development of ventilated warm roofs for new buildings and major alterations.

By the early 1990s the situation had improved but was not entirely resolved. Some roofs subject to condensation were found to be performing well, while better-ventilated roofs (both ventilated warm roofs and traditional cold roofs with ventilated air spaces) were not always entirely free from underside corrosion. Continuous monitoring also indicated that most corrosion occurred not when the lead was wet but while it was drying out, and site tests indicated that conditions encountered by the lead early in its life might significantly affect its long-term behaviour.

The conclusions for historic buildings were unclear. Given the architectural and historic importance of lead and the principle of minimum intervention, reconstruction as a ventilated warm roof would always be a specification of last resort, but when was it really necessary, how should it be specified and how could its impact be minimized?

After preliminary studies over some five years, in 1993 English Heritage funded a programme of research and investigations by the corrosion engineers Rowan Technologies Ltd (RTL), involving theoretical work, laboratory and full-scale tests and site studies. This ongoing project is also supported by the Historic Royal Palaces Agency (HRPA) and the Lead Sheet Association (LSA). At the same time, English Heritage appointed William Bordass Associates to assist with the technical management of RTL's contract, to liaise with relevant English Heritage advisory cases and other research and to help bring together and present the results.

Summary of findings

At the start of the study, it was thought that the main cause of the perceived increase in underside lead corrosion was an increase in condensation dampness under the lead. This was attributed to changed environmental conditions in buildings and roof spaces through alterations to heating, ventilation, insulation, occupancy and control. However, the research has revealed a more complex set of mechanisms.

Moisture, particularly condensation, is a crucial agent in the corrosion of lead. Their relationship is not straightforward and some roofs known to be subject to condensation show little or no underside corrosion. The extent and temperature of wet/dry cycling are also important, as moisture evaporates and re-condenses, for example in intermittent sunshine. Organic acids are often also present and exacerbate the attack.

Conventional condensation analyses are of limited use in determining susceptibility to underside lead corrosion. Most traditional lead roofs fail these condensation checks and today's good practice design principles, but many have performed well in practice. The normal models also focus on diffusion of water vapour from inside the building in winter, while in practice the passage of moist air is usually more important. Dynamic transient conditions at the lead/substrate interface may also affect corrosion more than the seasonal build-up normally calculated: these include condensation from outside air on still, clear, dewy or frosty nights when the roof surface temperature falls below outside air temperature, and refluxing trapped or ingressed moisture with changes in temperature and solar radiation.

Ventilation of the roof space and the underside of the lead can help to avoid underside lead corrosion. Principles can be difficult to apply and are frequently misunderstood. There are two main mechanisms: 1, ventilation by outside air; 2, ventilation to the underside of the lead.

The dynamic performance of roof spaces with limited ventilation and containing large quantities of hygroscopic buffer material such as timber can provide some protection from corrosion.

Acids from the underlying timbers can greatly increase damage in damp condensing and refluxing environments. These acids are not consumed during the corrosion process, but act as catalysts which are continuously regenerated, and may indeed build up in concentration over time. Manufactured boards such as plywood, hardboard, chipboard and oriented strand board contain acids from constituent timber species, from glues, and may also have been hydrolysed during processing. When these materials get damp, underside lead corrosion can be particularly bad, so they are not recommended for most purposes. Timber preservatives can also cause corrosion, particularly if hygroscopic or if the wood has not been properly dried out before being used. While fresh concrete, mortar and lime are corrosive to lead, once aged and carbonated they can have a protective effect.

Dynamic modelling suggests that the hygrothermal properties of substrate timbers can significantly influence the amount of condensation. Taken together with their chemical properties, this makes a case for selecting timber deckings very carefully.

Under RTL's accelerated laboratory test conditions, no significant differences have yet been found in the susceptibility to underside lead corrosion of clean samples of sand-cast or milled lead, of modern and historic lead or of different chemical compositions. Continuously-cast (DM) lead is now being studied.

Research has found that initial surface conditions can have a significant influence on long-term behaviour. Fresh clean lead will start to corrode at its first encounter with moisture, and after that it is much more difficult for subsequent protection to form. However, lead can be protected from a succession of condensation/evaporation cycles by passive films built up either:

- on site
- exposed outdoors for two to three months and using the weathered topside as the underside
- in the laboratory, when lead is exposed to moist conditions close to the dewpoint but in which little condensation occurs
- in the laboratory by treating the lead with suitable chemicals.

In environments subject to periodic condensation, site and weather conditions at the time of laying can significantly affect initial surface film formation and hence long-term corrosion behaviour. Lead laid in the autumn, or on wet boarding, can corrode immediately.

Laying lead on wet substrates invites initial corrosion. Dry substrates will not only prevent this but suitable timbers (including some pine species), if laid dry or having dried out in the summer, may provide significant protection well into the winter.

Unfortunately spontaneously-formed films cannot be created reliably and the pre-formed ones vary in performance and will be damaged by working and handling on site. Simple ways of passivating or protecting the lead *in situ* have therefore been sought, using products which are widely-available and relatively safe. The most successful of these has been painting the underside with a slurry of chalk powder dispersed in water. This forms a passive film within ten minutes at room temperature. Extended site tests are continuing to determine how much long-term protection this may afford.

Accelerated testing indicates that such passive films can survive 50 or more condensation–evaporation cycles. Preliminary theoretical studies by the Building Research Establishment (BRE) suggest that lead in contact with a timber substrate will not normally encounter this many in the course of a year. However, passive films will break down eventually. Spontaneous repair may occur in moist conditions, particularly when hot, and calcium carbonate can promote this. In addition to the chalk slurry treatment, laboratory and site tests suggest that chalk left in place and/or in an impregnated underlay may provide continued protection. Development tests are continuing.

Underlays can have a significant effect on corrosion behaviour, but in damp situations the observed effects to date are mostly bad. Permeable fleeces improve access of air to the lead (good) but also let through moist air and water vapour (bad), assist drying-out (good), but during evaporation corrosion is faster (bad). Impermeable membranes potentially stop the ingress of moist air and water vapour (good): however, any ingressed water can be trapped (bad) and may then reflux (bad) in a low-carbon dioxide environment (often bad) in which acids may sometimes accumulate (very bad). Double-layer underlays (a lower layer to keep acids and condensation at bay and an upper one to look after the lead) looked promising but have been disappointing in tests. Underlays with controlled permeability and hygroscopicity are now being investigated, as are suitable underlays for the chalk coating process.

Provisional conclusions

For new roofs and major alterations the research endorses the concept of the ventilated warm roof but underlines the importance of attention to detail,[1] in particular:

- full ventilation from eaves to ridge with no dead spots
- a sealed air and vapour barrier below the insulation
- adequately-sized air spaces, ventilation inlets and outlets
- a substrate of low chemical reactivity.

Even where there is no additional water vapour, transient condensation in a ventilated warm roof can cause some underside lead corrosion, particularly over the gaps between the boards, and a second line of defence is desirable. While this has not yet been investigated exhaustively, in marginal cases plain building paper has been sufficient. Chalk treatments may give added long-term protection.

Roof space environments vary tremendously. While Dutch-barn-like environments with high ventilation rates of 100% outside air are one ideal, the research suggests that where air-seals and vapour-control layers separating the building from the roof space either do not exist or are of limited effectiveness, extra ventilation may sometimes be counter-productive. Unless they are dry, well-ventilated and preferably continuously heated, buildings without roof spaces are at high risk of condensation and underside corrosion.

To evaluate existing roofs the following procedures are suggested:

- If there is clearly severe condensation and associated dampness, timber decay etc, the situation needs careful review to define and correct these problems, regardless of the state of the lead
- If, apart from the lead, the roof appears to be in good condition then reconstruction with suitable substrates and chalk treatment might be sufficient
- Even if the underside of the existing lead is also in good condition, like-for-like replacement will not necessarily be immune from lead corrosion because the starting conditions may be different. Precautionary measures are desirable.

For most purposes when selecting substrates:

- avoid acid woods known to be chemically aggressive
- avoid fresh, damp and kiln-dried wood, or any with a pH less than 5.5
- avoid manufactured wood-based boards, particularly plywood, blockboard, chipboard, hardboard and oriented strand board
- keep the wood in a dry atmosphere for as long as possible before use
- do not use wood with a moisture content above 18%, unless the lead has been pretreated
- stop the wood getting wet during the laying process itself.

While penny (or wider) gaps have been traditional they do increase the amount of condensation when it occurs. In a carbonate-rich environment from chalk treatment close-boarding might possibly have advantages in some situations.

No underlay investigated yet has ideal characteristics. Geotextiles are good at providing air access and as a reservoir for chalk, but their high permeability to air also increases the amount of condensation under adverse conditions, and where laid over gapped boarding the chalk may fall out of the bottom.

To help to avoid initial corrosion, it is best to lay the lead in warm, dry weather: May to July is probably best. Conversely, in winter condensation is more likely. Humid, dewy autumn weather is virtually guaranteed to initiate some corrosion under fresh, clean lead, over gaps if nowhere else.

Over many years the experience of the LSA has been that most lead roof failures result from poor detailing, the most common of which are over-sizing and over-fixing (Coote 1994), leading to thermally-induced fatigue cracking. Where underside lead corrosion has seriously contributed to a roof failure, there has often been water ingress (leading to corrosion by the trapped moisture), thermally-induced cracking (which often starts where the lead has been weakened by the corrosion), or high concentrations of organic acids.

While some of the chemical processes discussed are exclusive to lead, underside corrosion failures should not be seen as specific to this material but as symptoms of underlying problems which will affect continuously-supported roofs of other metals to a greater or lesser extent. Moisture movement is virtually independent of the metal used for the roof covering and some other metals are susceptible to underside corrosion in unsuitable combinations of heat, moisture and chemicals. Similarly, any moisture problems identified potentially affect all types of roof, whatever the covering.

Future research

While many of the issues and problems have now been identified, in some ways this understanding has made solutions even more elusive than was first thought. In particular, some physical and chemical mechanisms which have assisted the survival of lead roofs in historic buildings in situations in which they are theoretically at risk are not yet well-characterized. These include:

- local buffering effects by moisture absorption in substrate timbers
- large-scale buffering effects of timbers and other hygroscopic materials in buildings and roof spaces
- self-passivation of lead in some roof spaces with limited ventilation
- dynamic heat, air and moisture movement around the lead/substrate interface.

We see the most important priorities as to:

- continue interpretation and analysis of the monitoring
- avoid including additional buildings in future tests unless there is good reason
- undertake further analysis of temperature, humidity and moisture content data
- test possible solutions to underside lead corrosion problems on site and in the laboratory
- investigate materials' properties and appropriate specifications for substrates and underlays

- consider appropriate details, taking into account the three-dimensional geometry of roofs and gutters.

THE UNDERSIDE CORROSION OF LEAD ROOFS IN HISTORIC BUILDINGS

1 Background

For centuries it has been accepted that lead roofs are susceptible to underside corrosion. Often this is cosmetic, though still undesirable as pollution by lead salts should be minimized. Occasionally, however, underside lead corrosion results in failure, sometimes by corroding through in places, but more often by concentrating thermally-induced stresses in areas thinned by corrosion, ultimately causing cracking and water ingress, which may then cause more corrosion: a cyclical effect.

Underside lead corrosion usually takes the form of a powdery, flaky white, pink or yellowish product, sometimes with traces of red and yellow lead oxides, particularly near the underlying lead's surface. While its chemical composition varies, basic lead carbonates usually predominate, though oxides, hydroxides, acetates and formates are often intermediate products which are then converted to the basic carbonate by the action of carbon dioxide in the air. Sometimes the carbonate is found (it is more likely to be formed initially in colder and drier conditions) and sometimes the oxide (more likely in warmer and damper conditions; P Forshaw, pers comm). Occasionally the corrosion product may be converted to sulphate, which is more protective. Deposits are seldom uniform, but in patterns which frequently relate to the geometry of the lead and of the underlying substrate, although in ways which sometimes vary surprisingly but are now beginning to be understood.

In the eighteenth century underside corrosion seems to have been regarded as part of the normal decay and renewal process of a long-lived material which nevertheless needed stripping and re-casting from time to time (Watson 1787). In the late 1970s, however, it re-emerged as a seemingly severe growing problem.

In the early 1980s the Ecclesiastical Architects and Surveyors Association (EASA) set up a sub-committee to investigate it. Its consultation document (EASA 1986a) concluded that:

- the natural durability of lead came from protective surface films which built up on exposure to the weather
- clean lead surfaces were readily attacked by pure water, usually in the form of condensation
- synthetic chemicals (such as wood preservatives) were not significantly involved
- organic acids from some timbers (notably oak, even if well-seasoned) when saturated could cause repeated aggressive action
- softwoods, unless degraded, did not cause significant underside lead corrosion
- the deterioration of lead in contact with new Portland cement was well-known. Although a separating layer of building paper was good common practice, it had a short life in damp conditions.

For lead roof design, the document suggested that:

- the combination of a clean underside lead surface and condensed moisture was sufficient to explain the corrosion observed
- occurrences of condensed moisture in roofs were likely to have been growing owing to changes in heating, ventilation and insulation
- pre-treatment of lead with a sulphate coating did not confer the expected resistance to sustained condensation (Hill 1982)
- the best principle was therefore 'no water, no corrosion'
- moisture under the lead should be avoided 'by ventilation or design'.

While the EASA report did not give firm recommendations, it discussed the three basic forms of roof: 'warm', 'cold' and 'inverted' (see also *Roofs and roof space environments*).

For 'warm' roofs the Building Research Establishment recommended a plywood deck, a vapour barrier of felt bedded in hot bitumen and insulation that was not moisture-sensitive and was capable of withstanding compression by light foot traffic. EASA was uncertain about the durability of the plywood, the rotting of timbers within the insulated zone and the best insulation to resist damage by puncturing and heat from the sun and from leadburning.

To avoid some of these problems EASA suggested that in a 'warm' roof one might consider a ventilated air space above the insulation and supporting the lead on a second plywood deck above that. This foresaw the 'ventilated warm roof' (see below), though not for the reasons it was finally adopted. Today one would not normally choose plywood as a decking, as discussed below in *Chemical properties*.

EASA were strongly in favour of 'cold' roofs but accepted their impossibility in buildings which did not have separate roof spaces. They suggested various methods of improving air flow, but current research indicates that these would not necessarily have been effective.

EASA also saw some merits in the 'inverted roof', where weighted-down insulation is placed over the lead, though in hindsight it is difficult to see why. Not only does this greatly increase the weight and change the appearance of the roof, but it also raises the water table (so the rolls and laps would no longer be watertight): the topside of the lead, no longer being exposed to the weather, might itself suffer from corrosion.

In 1986, just as the EASA report was being completed, news began to come in that 'warm' lead roofs were very efficient at trapping moisture. At first this was attributed to imperfect vapour control layers (VCLs), and this may sometimes have been true. However, contraction of the air enclosed between a good VCL and the lead as the temperature fell could create a partial vacuum under the lead which could draw in rainwater or moist air via rolls and laps by the so-called 'thermal pumping' process. In one notorious case (referred to in Murdoch 1987 and International Energy Agency 1994) a 'warm' roof built to the highest quality standards failed by this mechanism within four years, and after some tests warm roofs were no longer recommended (LDA 1988). These problems were advised to EASA members in an Addendum Sheet (EASA 1986b). To avoid thermal pumping, cold roofs (not permissible for flat roofs in Scotland) or ventilated warm roofs are now recommended (LSA 1993b, pp61–3; Murdoch 1987).

The above findings proved difficult for historic buildings. While one could often upgrade to a warm roof with little change in outward appearance using a minimal layer of insulation, ventilated warm roofs were quite another matter. It was not clear how effective 'cold' roof conditions could be attained in historic buildings, and ventilation could not entirely eliminate condensation, even in completely open roofs such as bell towers and Dutch barns. At the same time many roofs in historic buildings exhibited condensation but no significant underside corrosion.

In 1988 William Bordass Associates was commissioned for an *ad hoc* advisory consultancy to English Heritage on problems in historic buildings related to heating, ventilation and moisture. Recurrent questions included the appropriate environmental conditions for lead roofs and the difficulty of achieving the 'no moisture–no corrosion' principle in practice: nearly all roofs in historic buildings suffer from condensation from time to time. It was agreed to try to monitor when corrosion actually took place, to determine when environmental control measures would be beneficial and to test whether they worked. Following a meeting at the Society for the Protection of Ancient Buildings (SPAB), funds were made available for a research student at CAPCIS Ltd, the commercial wing of UMIST's Corrosion and Protection Centre, to adapt electronic equipment developed for continuous monitoring of steel corrosion for possible use with lead. After this proved successful in the laboratory, English Heritage funded a trial application at Manchester Cathedral (Dicken & Farrell 1990). The electronic monitoring also showed that corrosion was often fastest not when the lead was wet, but while it was drying out (Bordass, Dicken & Farrell 1989).

CAPCIS commented that such behaviour was not unusual in condensing environments (Farrell & Dicken 1990), owing to:

- a partial film of water on the surface promoting differential aeration cells
- evaporation of water causing trace elements in the condensate to concentrate and become more aggressive
- a faster corrosion reaction at the higher temperature.

The CAPCIS work and further *ad hoc* studies for English Heritage, the National Trust and SAS Software Ltd revealed an increasingly complex and often confusing situation. Some damp roofs exhibited very little underside lead corrosion, while some relatively dry ones had considerably more. Sometimes fresh lead samples corroded in roofs which had little or no corrosion, the pattern of corrosion under a freshly-laid sheet of lead could be very different from its predecessor and conditions at the time of laying could have major effects on subsequent corrosion behaviour.

In 1989 English Heritage identified the need for a more detailed research programme and over several years encouraged the BRE, the DTI and the then DoE to undertake work. Unfortunately, none of these initiatives bore fruit and in 1992 English Heritage decided to put together its own programme. The main work was undertaken by the corrosion engineers Rowan Technologies Ltd (RTL), with additional financial and technical support from the Historic Royal Palaces Agency and the Lead Sheet Association (LSA).

At the same time, William Bordass Associates was appointed to assist English Heritage with the technical management of RTL's project, to liaise with other research and with EH's advisory casework, to hold an annual forum Condensation Corrosion Forum of research workers in the field, see Appendix B, and to help to present the results in ways that were accessible to building professionals. The research is intended to:

- obtain a better understanding of underside lead corrosion and its avoidance
- investigate whether changes to the lead and its pretreatment, to underlays and substrates or to the roof space environment can help to reduce underside corrosion
- consider improved specifications for lead roof repair and renewal, particularly in historic buildings where interventions need to be kept to the necessary minimum
- develop tools for corrosion diagnosis and risk assessment, to determine if a lead roof can be repaired or replaced much as it is, or whether it needs minor, or radical changes.

The research has been using a range of techniques to investigate underside corrosion and its avoidance, including:

- visits to sites with corrosion and those where the lead is performing well
- visits to sites where work has been done to attempt to avoid or reduce corrosion
- at some sites, monitoring existing conditions, in particular temperatures, relative humidities and timber moisture levels, and testing the corrosion behaviour of cleaned areas, various lead samples and remedial treatments
- constructing and operating two indoor laboratory test rigs which can each take eight samples of lead, with substrates and underlays where required, through a series of programmed test cycles of condensation and evaporation
- constructing, operating and monitoring outdoor test rigs with four different roof space environments: fully-ventilated (Dutch barn), ventilated air gap (ventilated warm roof), separate, partially-sealed roof space (as over a vault), and no roof space (roof as ceiling to internal space which was slightly humidified owing to a damp floor)

- experimenting with methods intended to reduce underside corrosion, and in particular different underlays, coatings and chemical treatments.

English Heritage has also been encouraging communication and joint identification of research needs between industry, research organisations, conservation bodies and professionals. Parallel studies of interest are also mentioned in this report, and are summarized in Appendix C.

2 Chemical properties

This brief review of the chemistry of lead and of the materials on which it may be placed picks up points which are particularly relevant to underside corrosion, arranged with the benefit of hindsight from the research to date, and including some results from the laboratory and field studies.

People are often surprised that lead corrodes. Chemically, however, the real surprise is that it does not, and some issues are more easily understood when seen in this light. Lead is attacked by distilled water, and more vigorously so in the presence of air, particularly when the water has a low carbon dioxide content (Hoffman & Maatsch 1970).

The main reason for lead's durability is that most of its salts are insoluble or sparingly soluble, the main exceptions being the moderately soluble oxide[2] and the highly soluble acetate and nitrate. If lead is left exposed to the weather, carbon dioxide and atmospheric pollutants, both from air and rainwater, react with it to form the protective grey patina which gives the material its traditional durability. While sometimes unprotective white salts are formed initially,[3] in due course these are washed off to be replaced by more permanent deposits which gradually take up sulphur[4] and oxygen and become increasingly protective (Tranter 1976). However, organic acid run-off from mosses and lichens can damage these, owing to the soluble lead salts formed.

Underneath, however, the lead is not necessarily passivated in the same manner and if clean lead encounters pure water in the form of condensation, underside corrosion may ensue.[5] Here the corrosion product stays in place and does not get washed off, so once corrosion starts here it is difficult to stop. In addition, any moisture trapped between the lead and the underlay, substrate or porous corrosion product may distil repeatedly, causing further damage, particularly where organic acids are present and also become trapped.[6] Poor access of air is also likely to make the trapped moisture deficient in carbon dioxide and produce corrosive and electrolytic effects.

A Building Research Bulletin in 1929 (Brady 1929) discussed the corrosion of lead by water, lime, cement, timber and soil. Key points reviewed include:

- Mortar can corrode lead owing to the combined action of moisture, oxygen and lime. This was attributed to the removal of any carbon dioxide in solution by interaction with the lime. Aged, carbonated lime did not have this corrosive effect. It was recommended that embedded lead and pipes should be either coated or wrapped, or otherwise packed with old mortar
- Serious corrosion was frequently caused where lead was in contact with timber, particularly oak, though softwoods could cause similar effects to a lesser degree. The presence of moisture was seen to be the controlling factor. Exclusion of moisture, and avoidance of wet and unseasoned timber, was recommended. Where poorly-seasoned oak could not be avoided, covering the boarding with bitumen felt was recommended
- In aggressive soils, it recommended wrapping pipes in bitumen felt, or bedding them in chalk, limestone or well-carbonated lime mortar.

While the above advice is still generally good, the current research has found corrosion on sites where oak has been covered with bitumen felt or bitumen-cored building paper. While these layers may keep most of the moisture and acids away from the lead, any small amounts that do get there cannot readily escape and can then do a disproportionate amount of damage. It also seems that chalk, carbonated mortar and limestone do not merely stop lead from corroding, but actively promote the formation of passive, protective layers.

Lead corrosion and passivation in aqueous environments

In dry environments lead does not normally corrode. In aqueous environments, lead (and all metals for that matter) may react with water, its components (hydrogen or hydroxyl ions), dissolved oxygen, dissolved carbon dioxide and the carbonate ion, or other dissolved materials (eg salts, air pollutants, organic acids and other carbonyl compounds). However, the lead does not necessarily corrode. Strategically, three very different outcomes are possible:

- immunity to corrosion: the metal can't dissolve and nothing present can react with it
- susceptibility to corrosion: the metal can dissolve and things can react with it. The reaction may or may not slow down depending upon the protection afforded to the metal by the corrosion product
- passivation: the metal can react with something present to form an insoluble product which may then protect the metal from further reaction. Strictly speaking, this should be called passivability because the insoluble product will not necessarily provide good protection: it may be porous, poorly-adherent mechanically or removed, by mechanical action or differential stresses under thermal cycling. For lead in air a curious mechanism also applies, see below.

The outcome will depend on many variables, in particular:

- the presence of all possible reagents, in solid, dissolved or gaseous form
- the possible chemical and electrochemical reactions between them

- the solubility of the metal and of all the possible compounds into which it might be converted in the above environment
- the stability (absolute and relative) of all the components that might be involved
- the electrochemical potential of the lead (expressed in volts)
- the acidity or alkalinity of the water (these are interdependent and normally expressed as pH)
- the morphology, porosity and coherence of the corrosion layer.

The susceptibility of a metal to corrosion over the full range of pH and electrochemical potential may be shown graphically on a Pourbaix Diagram. These diagrams are complex to construct as all possible equilibria have to be taken into account (Pourbaix 1966), but they are available in the literature for the lead/water system (Pourbaix et al 1966)

Figure 1 is the Pourbaix Diagram for lead in pure water. The dotted diagonal lines (a) and (b) represent the limits of stability of water itself: below the lower line it will be decomposed to hydrogen and above the upper line to oxygen. For lead on a roof, the main region of interest on the horizontal axis is between pH 3 (acid) to pH 12 (alkaline), and on the vertical axis at around zero electrode potential (E[V]), although locally, owing to the effects of differential aeration, potentials may vary within the bounds of the dotted diagonal lines. In this region of interest, there are no zones of passivation or immunity.

In the presence of dissolved carbon dioxide, however, Figure 2 tells a very different story. Now the insoluble carbonate (Cerussite – $PbCO_3$) provides a potentially safe bridge in the pH range 5 to 12 across the previously continuous corrosive band between the domains of immunity and passivation.

In practice, however, the corrosion behaviour of lead in the presence of air and moisture is more complex (Hoffinan & Maatsch 1970, pp302–4). Partially immersed lead is strongly attacked by distilled water containing air, owing to the diffusion of oxygen and to concentration cells: the more deeply immersed the lead the less the corrosion.

The Pourbaix Diagram in Figure 2 was constructed at a partial pressure of carbon dioxide of one atmosphere. In outside air, with partial pressures of about 1/300th of this, Hydrocerussite ($2\ PbCO_3 . Pb(OH)_2$) is more stable than Cerussite ($PbCO_3$) at all pH levels (Edwards 1994), but because it is even less soluble, the general form of the Pourbaix Diagram is similar. Indeed, when the water is rich in carbon dioxide a protective film forms, and while it is not entirely effective corrosion proceeds only slowly.[7] Hoffman calls this Attack Type I (Hoffman & Maatsch 1970).

However, when condensation is fresh or when there is moisture in confined spaces (for example, between lead and an impervious underlay), the concentration of dissolved carbon dioxide is much lower. Now the air, carbon dioxide and insoluble Hydrocerussite join forces in a different and more aggressive process: Attack Type II. The mechanism goes like this:

> The oxygen first dissolves in the water and begins to attack the lead: the dissolved carbon dioxide concentration at this stage is too low for Attack Type I to occur. The lead dissolves in the carbonate-free water, creating the hydroxide (lead oxide, PbO, may also be formed): $2Pb + 2H_2O + O_2 \rightarrow 2\ Pb(OH)_2$. This diffuses to the surface where it reacts with atmospheric carbon dioxide to form insoluble Hydrocerussite: $3Pb(OH)_2 + 2CO_2 \rightarrow 2\ PbCO_3.Pb(OH)_2 + 2H_2O$.

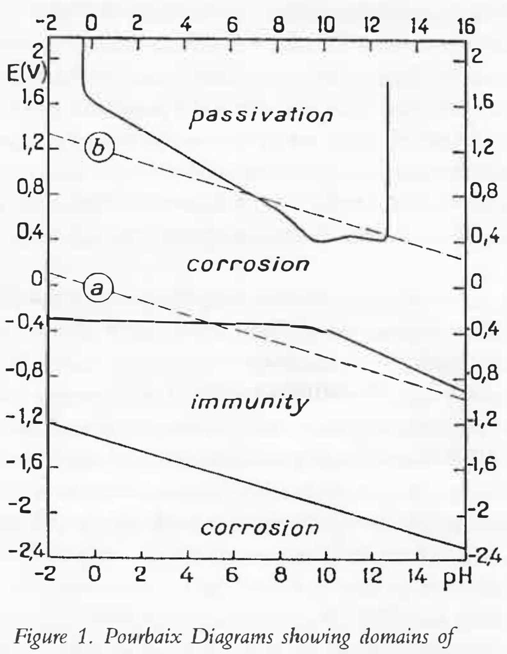

Figure 1. Pourbaix Diagrams showing domains of immunity, passivation and corrosion for lead in pure water (Pourbaix et al 1966, 485–92).

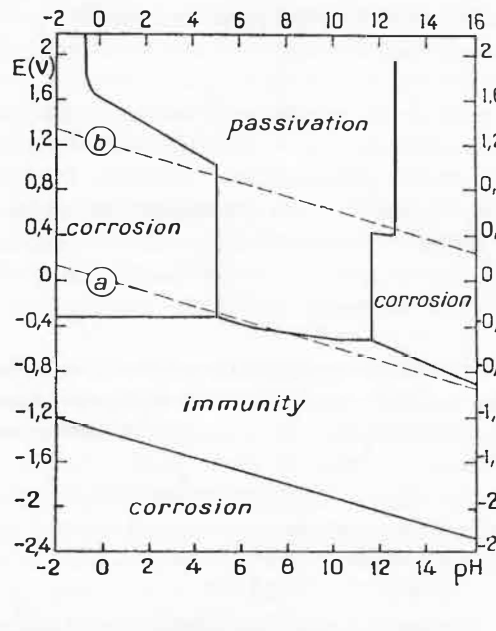

Figure 2. Pourbaix Diagrams showing domains of immunity, passivation and corrosion with added carbon dioxide (Pourbaix et al 1966, 485–92).

The above reaction both fixes the carbon dioxide which might otherwise have dissolved in the water and helped to passivate the lead, and also removes lead ions from solution allowing more lead to dissolve. In the absence of CO_2 the lead dissolves more slowly.

This Type II Attack is non-protective. From time to time the thin crust cracks and is repeatedly replaced. Loose crystals of lead oxide and hydroxide may also be found near the lead surface. Electron micrographs have been produced which show the porous arched non-protective structure of this crust (P Forshaw, pers comm) and on site one sometimes finds underside corrosion which looks superficially dry but which exudes moisture from its pores when scraped.

Passivation processes

If the lead surface cannot be kept entirely free of moisture, something which is normally impossible, it would be best to ensure that it is passivated and resistant to attack by moisture (whether or not air is present) and as far as possible resistant to attack by organic acids as well. This section outlines methods of passivation which have been attempted in the research to date.

Although neither Type I nor Type II corrosion achieve the passivation anticipated by Figure 2, under laboratory and site conditions effective corrosion-resistant passive films can sometimes form spontaneously beneath the lead. In RTL's laboratory condensation test rigs, passivation was observed (RTL 1993–5) under the following conditions:

- for samples exposed to the moist air of the test rig but not artificially cooled
- around the fringe of corroded areas of cooled samples exposed in the test rig.

In both circumstances it appeared that lead exposed to humid but non-condensing (or only lightly condensing) conditions could become passivated rapidly, probably because with only a thin film of water, sufficient carbon dioxide could reach the lead surface.

Since so much can depend on the initial surface condition of the lead, the research has looked into various ways of reliably protecting the underside. Pre-formed layers such as sulphate had already been investigated by EASA (1986a), with disappointing results. Simple, straightforward methods were therefore sought, using readily available safe materials.

- *Self-passivation in air.* Lead sheets usually come to site shiny but if left unrolled for a few days they begin to go dull owing to the formation of an oxide film (Hoffman & Maatsch 1970, p268). Vernon 1927 reported that in his laboratory environment this film was protective but on one occasion the lead instead corroded rapidly, while the pre-tarnished lead was unaffected: he attributed this to turpentine vapours from painting nearby. This film could well help avoid initial corrosion in marginal environments, but in RTL's test rig its resistance to repeated condensation cycles was relatively small in relation to weathered lead (see below)
- *Self-passivation when exposed to the weather.* After two to three months exposed to all the elements, a very corrosion-resistant film forms on the exposed side. However, the time required is unrealistic, the performance varies with location and weather and the problems of damage by working on site remain
- *Application of linseed oil.* Until the 1960s, linseed oil was often used in the rolling process. It persisted in some mills into the 1970s, and a few 'old' mills occasionally used for special purposes (such as sheets over one metre wide) still use it. It may have provided some protection, both directly and by forming lead soaps, which the newer, water-based lubricants do not. It has also been said (R Murdoch, pers comm) that plumbers used to have to scrape new lead clean before lead-burning (which is reportedly not necessary today) and that some of them used to wipe it down with linseed oil afterwards. In the present study, application of linseed oil has been found to confer some corrosion resistance, both in the laboratory and on site. However, there were practical difficulties such as the time it took to cure. If laid before curing, oil might be lost and moisture absorbed, leading to some corrosion. The sticky oil might also anchor the lead to the substrate and make it vulnerable to failure through restrained thermal movement
- *Application of patination oil.* This performed better than linseed oil and was more convenient, having a shorter curing time (typically overnight), though even this may slow down the roofing operation. However, we have found plumbers who pre-form their lead on jigs in a site workshop and apply patination oil to the underside at least a day before fixing, and claim that the time spent is not unreasonable, and that pre-forming brings some productivity gains in standardization and working in bad weather
- *Application of silicone spray (for instance, WD40).* This is sometimes used by conservators of lead sculpture but proved disappointing in initial tests. However, on one site, after one year treated and untreated areas were similarly corroded, but two years later there was less corrosion on the treated area
- *Application of silicone wax (for instance, Waxoyl).* Little benefit was found from this treatment, despite initial hopes
- In situ *chemical passivation.* The Pourbaix diagram and evidence from several sites where lead was found to be passivated over weathered concrete and cement-bonded woodwool slabs led RTL to investigate treatment using carbonate salts. Calcium carbonate (chalk and limestone), sodium carbonate and sodium bicarbonate were tested and finely-powdered chalk proved best (RTL 1995, Report 6). A slurry of finely-powdered chalk (3 microns average particle size) in water was applied by paintbrush to a coverage of some 200 grams of chalk per square metre (or sufficient to cover the lead surface). A durable, protective patina was obtained within ten minutes at room temperature.

While passivation, either in the test rig, on site or using chalk is visible as a darkening of the lead surface, the protective layer is thin and has not yet been well characterized chemically, in spite of exhaustive studies. It may be primarily an oxide [8] (as was also surmised by Vernon (1927), a basic carbonate or a combination of the two.

When lead becomes exposed to dampness, underside lead corrosion will tend to occur unless passivation has already taken place or the conditions are passivating, or preferably both. Lead roofs that perform well are usually either so dry that moist conditions are largely avoided, or have become passivated in the course of their lives and often, it seems, in the early stages. Once underside lead corrosion has begun to occur, although it will not always be serious, by then it is difficult if not impossible to revert to the highly-protective, thin passive layers which are sometimes found on site and can be generated in the laboratory. Of the various methods tried by RTL to promote the rapid formation of passive films, at present the chalk treatment looks particularly promising: not only is a good patina formed rapidly but if the chalk is left in place (for example spread over an underlay), then the environment may remain passivating, helping any failures to repair themselves. Preliminary results from site tests also indicate that chalk left in place may perform better.

Corrosion of lead by wood and wood-based products

Lead is susceptible to severe attack both by contact with damp wood and by the acid vapours emitted[9] (DoI 1979). Corrosion of lead by oak has been well known since historical times, being a method by which white lead was formed. Brady (1929) cautioned against laying lead over oak and over wet and unseasoned timber. Two more recent publications describe the corrosion of metals by wood in more detail (BRE 1985, DoI 1979). Corrosion of metals (and particularly lead) by acid vapours from wood without contact or condensation, in particular in the confined environment of a box, drawer or display cabinet, is well-known to museum conservators who refer to carbonyl pollution, by formaldehyde, formic acid, acetaldehyde and acetic acid (Grzywacz & Tennent 1994).

Organic acids naturally present in wood, including formic and particularly acetic acids, are the aggressive agents (Hoffinan & Maatsch1970, pp292–3) especially because the corrosion products, particularly the acetate, are highly soluble and so do not protect the surface. For acetic acid:

$2Pb$ [lead] + O_2 [oxygen] + $4CH_3COOH$ [acetic acid] → $2(CH_3COO)_2Pb$ [lead acetate] + $2H_2O$ [water]

To add insult to injury, the effect is catalytic. Once formed, acetates (and formates) then react with carbon dioxide in the air to re-form carbonates or basic carbonates, regenerating the acid ready for a second attack, and so ad infinitum. Again for acetate:

$3(CH_3COO)_2Pb$ [lead acetate] + $4H_2O$ [water] + $2CO_2$ [carbon dioxide] → $2\ PbCO_3.Pb(OH)_2$ [Hydrocerussite] + $6CH_3COOH$ [acetic acid]

A small amount of trapped acid can therefore cause a disproportionate amount of corrosion. Over the years, there can even be cumulative growth in acetate concentration as more acetic acid is progressively absorbed. In sufficient concentrations (which site evidence for acetate suggests is over about 50–100 parts per million immediately below the lead), the acids may also attack protective films, such as the oxide and basic carbonate.

In general all timber species are acid to some extent, but some are more acid than others. Oak is notorious, while many of the common softwoods (such as white and yellow pine) are often both less aggressive and less prone to acid formation by chemical degradation. Table 1 lists various woods in order of their vapour and contact corrosion hazard. The woods in the 'severe' category tend to have pHs between 3 and 4, outside the 'safe' range in Figure 2, even before the acetic acid itself is taken into account! Those in the 'high' category are borderline, with pHs between 3.5 and 5.[10] As a general rule, hardwood tends to be more acid than softwood, and new wood more acid than old. However, acid is always present latently in wood (typically the acetyl group comprises between 2% and 5% of its dry weight) and is released in appropriate circumstances, for example by hydrolysis of acetyl groups in warm, damp conditions, for example in the kiln-drying process, during which acids (both originally present and from the hydrolysis) do not have time to disperse. Kiln-dried timbers can therefore be initially more acid than traditionally air-dried ones, though they contain less combined acid that could be set free in later years. In buildings this release continues for very many decades (DoI 1979) and may be re-activated even in old wood if conditions become damper (Werner 1987)

Manufactured timber products, including plywood, blockboard, chipboard, hardboard and oriented strand board can also be corrosive to lead,[11] as has been demonstrated both on site and in RTL's test rigs. There are four main reasons for this:

- the acidity of the constituent timber species, for example birch
- possible increases in acidity by hydrolysis during processing
- acids in glues and binders which often include or generate formaldehyde, formic acid (formaldehyde oxidises to this), acetic acid (viz polyvinyl acetate glue) and phenols
- a greater propensity to trap moisture.

Site evidence in this study suggests that underside lead corrosion can be very severe over moist wood-based boards, although one can find examples of dry boards

Table 1. Acid vapour corrosion hazards of woods (from DoI 1979)

Severe	Oak, Sweet Chestnut
High	Beech, Birch, Douglas Fir, Gaboon, Teak, Western Red Cedar
Moderate	Parana Pine, Spruce, Elm, African Mahogany, Walnut, Iroko, Ramin, Obeche

where all is well. On site, acetic acid also seems to concentrate in hardboard. At Donnington Castle hardboard was laid over oak (Lowe et al 1994, p6). Liverpool John Moores University found acetate concentrations of about 80 parts per million (ppm) in the oak and 600 ppm in the hardboard. Lead corrosion has also been observed in museum cases with hardboard, plywood, chipboard and blockboard (Oddy 1975), and the role of the adhesives was noted. In the museum world it has been concluded that in terms of corrosion risk wood-based boards have considerable disadvantages over carefully-selected natural timbers (Clarke & Longhurst 1961).[12] For lead roofs, the same advice appears to be equally appropriate.

Damp wood itself, whether acid or not, can also cause underside lead corrosion, by the processes already described. As a rule of thumb, if the moisture content at the top surface of the timber is:

- below about 15% it will tend to protect lead in contact with it from corrosion
- significantly over 20% it will tend to promote underside lead corrosion unless the acid content is low, the lead is well-passivated and evaporation-condensation cycles are infrequent
- between 15% and 20% or so it may sometimes promote passivation, if the acid content is not too high.

A Swedish study (Werner 1987) of the corrosion of iron found that:

- an increase in atmospheric relative humidity could cause acids to be released rapidly from wood
- the effect was much increased by raising the temperature by only a few degrees
- birch plywood and chipboard were particularly active, but 50 year-old pine, although much less active, also began to release some acid if atmospheric relative humidity and temperature were increased.

High humidity has a two-fold effect, both increasing the production of acid and the subsequent corrosion by that acid (Clarke & Longhurst 1961).

While EASA concluded that timber preservatives had no significant effect on underside corrosion (EASA 1986a), on site we have observed effects which differ for solvent-based and water-based materials. Further investigation is desirable. For the solvent-based materials:

- organic solvent-based preservatives can sometimes change the appearance of the underside of the lead and of any initial corrosion product. This may be a direct effect or possibly a leaching of resins from the timber. We have as yet no evidence of increased corrosion rates over the timbers, although on one site there was more corrosion over the gaps between preservative-treated than between untreated boards
- where bitumen-cored building papers are laid under the lead, the preservative's solvent has occasionally leached out the bitumen and brought it to the surface, sometimes adhering the paper to the lead, with possible adverse mechanical effects. Underside lead corrosion is often more severe over these leached areas, where moisture is more easily trapped.
- Solvents may also inhibit initial protection passivation (Vernon 1927).

For the water-based materials (both for timber preservation and for fire protection):

- often the timber comes to site very wet, initiating underside lead corrosion as soon as the lead is laid. Initial moisture content should be no more than 18%
- the preservation salts themselves may be hygroscopic, which will tend to increase the moisture content of the timber, at least when the atmospheric relative humidity is above the level at which the salts dissolve. Salts from sea spray or salt water immersion can have similar effects, as can the salt seasoning process, used in some parts of the world for controlling the drying of certain woods (DoI 1979)
- the salts themselves are often corrosive to steel and other metals: both chemically and because their constituent ions increase the conductivity of trapped and condensed moisture, and hence the rate of any electrolytic corrosion. This can often weaken nails and other fixings. However, for lead itself, salt contamination may slow down condensation corrosion attack because insoluble lead salts may be deposited (Hoffman and Maatsch 1970)
- EASA also noted that preservative salts could destroy building paper underlays, particularly those with aluminium foil facings (EASA 1986a)
- metal corrosion by preservative salts is also reported if timber is above 20% moisture content for long periods (International Energy Agency 1994, pp4–10).

From the work to date, it appears that the solvents, hygroscopic and conductivity effects may have more effect on underside lead corrosion than the treatment chemicals themselves. While EASA (1986) preferred solvent-based products, these are now criticized from the environmental point of view and water-based chemicals are becoming more common, as are their related problems. Many treatments (and certainly blanket treatments whether water- or solvent-based) are seen by environmentalists as unnecessary and needlessly polluting, particularly for decking which seldom seems to rot. However, indemnity insurance requirements and health and safety regulations are tending to force many specifiers towards the universal and sometimes unnecesary adoption of pre-treated timbers.

For avoiding corrosion by wood the following list has been developed from the Department of Industry's recommendations for packing cases (DoI 1979). For lead roofs, we have also added the points asterisked:

- avoid the woods in Table 1, particularly the severely and highly corrosive ones

- choose a wood with a pH value greater than 5.0 (any laboratory can determine this quickly and easily). For lead we would prefer a minimum pH of 5.5
- avoid, fresh, damp and kiln-dried wood
- avoid manufactured wood-based boards, and particularly plywood, blockboard, chipboard, hardboard and oriented strand board
- keep the wood in a dry atmosphere for as long as possible before use
- do not use wood with an initial moisture content above 18% (and preferably 15%)
- stop the wood getting wet during the laying process itself.

The Department of Industry also commented that to disperse acid vapours a small amount of ventilation was useless. Lime-washing the wood, which had been expected to absorb acid vapours, had also proved ineffective. However, in the current study laboratory and site tests suggest that the chalk treatment developed may provide some protection from organic acids, at least in the short term if in direct contact with the lead. The chalk used also had a pH of 8.9, a level close to that at which lead oxide and hydroxide is least soluble.

Chemical and metallurgical properties of the lead

Many building professionals feel that lead is not what it used to be, and are hoping for some new alloy which will resist underside corrosion. On the basis of the research to date, this seems unlikely. In accelerated tests in the laboratory, and in materials evaluation tests on site, no significant differences have yet been found between clean samples of sand-cast and milled lead, and between modern lead and cleaned lead taken from roofs up to 200 years old. Tests using continuously-cast (DM) lead are not yet complete. The main difference is in the surface condition: lead which for some reason has developed a passive film is the more corrosion-resistant, though in aggressive conditions even passive films from ancient roofs break down eventually.

The main reason for sand-cast lead's greater reputation for durability is probably its use in greater thicknesses than milled lead, so corrosion must be more advanced for visible failure to occur. The extra mechanical strength will also delay any onset of corrosion-assisted fatigue.

It is just possible that the 'steaming' of the underside during the sand-casting process might initiate a similar passivation process to that observed in moist but non-condensing conditions in the test rig (see above). As yet there is no direct evidence for this although RTL is now carrying out laboratory tests under milder conditions. Even if some effect were found, the information to date suggests that it would be unlikely to be substantial enough to be of more than marginal interest to a specifier.

In a small amount of work at Cambridge (Bordass, Charles & Farrell 1991) there was some indication that machine-cast material of high copper content (> 0.05%) with a coarse grain boundary distribution of the copper phase, corroded more quickly under water than milled lead, where the copper is more uniformly distributed. At lower copper contents there was no difference. One sample recently tested by RTL was also subject to pitting corrosion, but this may have been from a manufacturing fault. Further investigations are being undertaken and the tests repeated.

In wooden museum cabinets it has recently been shown that the amount of corrosion observed depends greatly upon the purity of the lead (Tennent, Tate & Cannon 1993). In one display case, a tin content of 1.5% rendered the lead resistant to corrosion. In another, containing a wide variety of lead badges, only two showed any corrosion: these were the only ones with a purity over 99%. While these alloys may well be inappropriate metallurgically for use on a building, and the conditions on a building will often be more aggressive, there may be something here worth investigating.

3 Roofs and roof space environments

This section discusses the construction of roofs and the underlying roof spaces, and the relationship of heat, air and moisture flows in these to the external climate and to the rest of the building. We start with requirements for modern buildings, as this helps to identify gaps between today's expectations and the actuality of historic buildings, many of which have performed well in practice. The difference partly relates to changed conditions in modern buildings: occupancy, management, habits, heating, ventilation, control, appliances, materials, insulation, materials and workmanship, which also creep up on historic buildings. However, some mechanisms which have helped roofs on historic buildings to survive appear not to have been fully appreciated, including moisture buffering by hygroscopic materials and conditions which may help to passivate the lead.

Roofing principles in modern buildings (Figure 3)

Roofs are normally designed on one of three principles (BRE 1986 and 1987), at least in theory:

- *WDI, warm deck roof: inverted construction.* Water-resistant insulation is placed on top of the weather-proofing layer. This design is not appropriate for lead roofs and so will not be discussed
- *CDR, cold deck roof.* Beneath the weatherproofing layer (lead in this instance) and its supporting substrate (and intervening underlay where fitted) is a space ventilated by 'cold' outside air. For flat and inclined roofs, this usually consists of a gap of typically between 25 to 250 mm in height, with ventilators at both ends. For ventilated pitched roofs (VPRs), except where there are rooms in the roof, there is often a walk-in or crawl-in ventilated roof space. Any insulation should occur below these ventilated spaces, usually with a vapour control layer (VCL) underneath it to control water vapour ingress, and often more importantly moist air ingress from the building, so we call it an air and vapour control layer (AVCL). Advanced designs may have a gap (sometimes insulation-filled[13]) between the AVCL and the internal lining to permit

services to be distributed without puncturing the AVCL. Condensation risks in CDRs increase with insulation level, imperfections in the vapour control layer and in cold or moist climates
- *WDS, warm deck roof: sandwich construction.* Here there is no outside air ventilation: there is insulation immediately under the substrate and an AVCL below that. This construction has been widely used for felt, asphalt, tiled and profiled metal roofs, with varying degrees of success although increasingly reliable products and specifications are now available.

For lead roofs, however, WDS construction, which was advocated by the BRE, the British Standards Institution and consequently by the LDA from the mid-1970s, created an unexpected and, for lead, a major problem. If the AVCL was poor, moisture from the building could come through and condense, creating a high risk of corrosion. If the AVCL was good, air trapped in the sandwich expanded and contracted with changing temperature, relieving pressure via the joints in the lead covering. In the contraction phase, 'thermal pumping' (International Energy Agency 1994, pp4–43) could draw moist air and occasionally even rainwater into the construction from outside. Occasionally movement under fluctuating wind gust pressures could do the same, if not

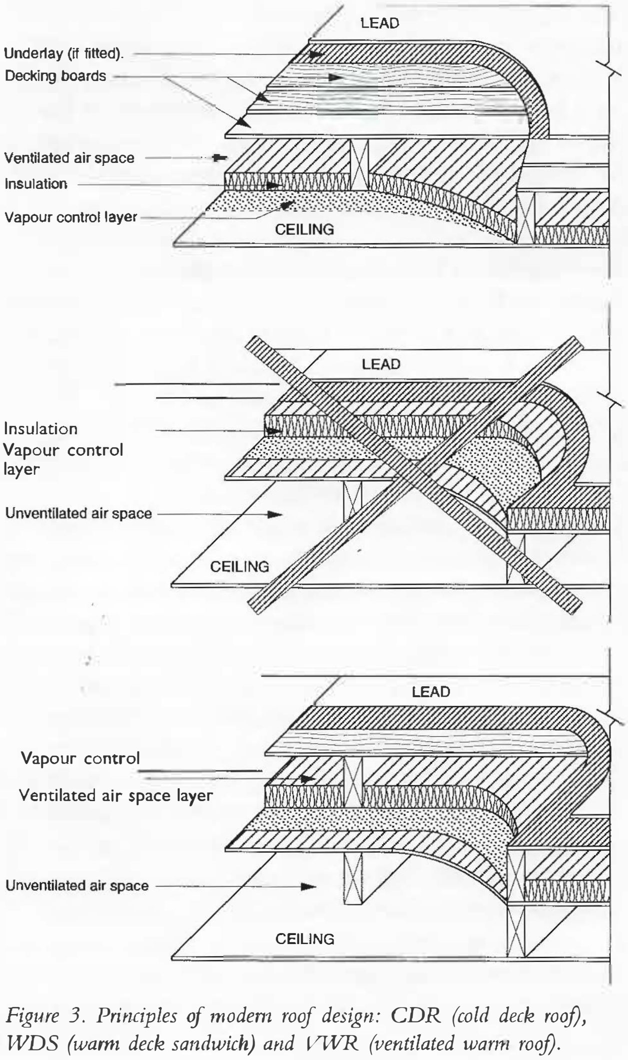

Figure 3. Principles of modern roof design: CDR (cold deck roof), WDS (warm deck sandwich) and VWR (ventilated warm roof).

for lead certainly for the lighter metals. Whatever its origin, the trapped water had severe consequences for the lead, especially if organic acids were present. While such water accumulation problems are not unique to lead (though splashlap details increase the risk) lead's corrosion chemistry makes its effect on the life of the roof particularly severe. In 1986 this construction was outlawed for lead roofs (LCA 1986) and this was subsequently recognised in BS 5250 (British Standards Institution 1989). However, survivors are still found, including a 1980 example which this study is examining.

To overcome problems with WDS, the 'ventilated warm roof' was introduced (LCA 1986). This has a ventilated air space between the upper surface of the insulation and the underside of the substrate. These roofs now tend to be constructed as fully-ventilated designs with ventilation openings at top and bottom, and so follow the same principles as the CDR. [14]

While there are no explicit UK recommendations for the size of the air gap in a metal-clad ventilated warm roof, for an inclined tiled or slated roof BS 5250 (British Standards Institution 1989) recommends the following:

- bottom inlet: equivalent to a 25 mm continuous slot
- top outlet: equivalent to a 5 mm continuous slot
- air path in between: 50 mm gap
- below obstructions such as rooflights: equivalent of a 5 mm continuous slot
- above obstructions such as rooflights: equivalent of a 10 mm continuous slot.

In practice, ventilated warm roofs found in the UK usually seem to have typical air gaps of 20–50 mm and inlets and outlets of 10–20 mm each.

Ventilated warm roofs are widely used in continental Europe for metal-clad roofs such as copper, zinc and stainless steel: lead roofs are not so common there. Recommended air gaps tend to be larger than in the UK. For example, the German specification based on DIN 4108 (Rheinzik GMBH 1988, 17–18) [15] recommends a 50 mm ventilation space for roofs above 20° pitch, rising to 100 mm between 3° and 20° and to 200 mm below 3° (and this includes beneath gutters!).

Recommended inlet and outlet openings are typically 1/400 of roof area (equal to 2.5 mm gap per metre length from inlet to outlet), though for pitched roofs the inlet size reduces to 1/500 (2 mm per metre).[16] Inlets should be as low as possible and outlets as high as possible, and if they are more than 10 m apart their sizes should be increased. For vertical cladding, the ventilation space is reduced to 20 mm and the inlets and outlets to 1 mm per metre.

Dutch practice for zinc-titanium is very similar to the German (Billiton Zink BV 1992). However:

- recommended ventilation inlets and outlets are of equal size
- for roof pitches over 20° the inlets and outlet sizes are reduced to 1 mm per metre
- underlays are not mentioned, instead sawn softwood boarding with 5 mm gaps is recommended, increasing to 10 mm if desired on roofs over 45° pitch.

For lead-clad stainless steel roofs the French (Centre Scientifique et Technique du Bâtiment 1991) require air gaps of 40 mm for distances up to 12 m and 50 mm for greater distances, but with only 0.3 mm per metre for air inlets and outlets, though with a minimum of 10 mm. Mountainous regions (over 900 m above sea level) require double-ventilated roofs, with a secondary weathering/vapour control layer between the two air spaces, of minimum 60 mm each.[17] Presumably:

- the lower ventilated layer allows any moisture penetrating from the building below to be ventilated away by outside air without condensing under the roof
- the upper layer allows the underside of the roof to be ventilated entirely by outside air
- the secondary weathering layer collects any condensation or melted ice that forms.

Complicated details are illustrated which maintain double-ventilation around obstacles. [18]

For the purpose of condensation control, BS 5250 (British Standards Institution 1989) identifies two types of 'cold' roof:

- roofs with limited space which may be difficult to ventilate adequately and where a vapour control layer would be necessary, for example a CDR (but equally a ventilated warm roof)
- roofs with a large ventilated roof space above the insulation, eg domestic pitched roofs in which vapour control layers are not normally required.

The IEA (International Energy Agency 1994, 4–11) states that it is very difficult to stop moisture moving into the roof cavity of a CDR, and the presence of water is very common. *Thermal Insulation: Avoiding Risks* notes the problems of underside condensation with metal-clad 'cold' roofs, and the importance of well-sealed vapour control layers. It regarded the CDR as 'a poor option in the temperate, humid UK climate' (BRE 1994).

BS 5250 (British Standards Institution 1989) also notes that:

- moisture should be extracted at source to reduce risk of vapour transfer to the roof
- water vapour penetration to the cold side of the roof construction should be minimized: constructional gaps and holes should be kept to a minimum and well-sealed
- vapour control layers should be adequately lapped and sealed, and their integrity maintained with puncturing avoided
- cross-ventilation openings should, if possible, be placed on the longer sides of the roof
- ventilation openings should be evenly spaced to avoid stagnant air pockets
- ventilation openings should be arranged so that they cannot be blocked, admit vermin or impair the weatherproofing. A 4 mm protective mesh is recommended
- the minimum free airspaces should be maintained past potential restrictions
- provision should be made to ensure moisture is not trapped and water vapour vented.

For pitched roofs:

- access doors should be heavy and clamped onto compressible seals
- high-level ventilation alone must not be used as it will suck moist air into the roof void
- materials which absorb condensate are preferred: they can re-evaporate it later when conditions are favourable. (However, some of this may end up under the lead.)

For both pitched and flat roofs, 25 mm ventilation gaps are recommended at the eaves along both long sides, while lean-tos should have a 5 mm gap at the top as well. The ventilation space should be at least 50 mm. For flat roofs over 5 m across, both the openings and the ventilation gap should be 'substantially increased' (though *Thermal Insulation: Avoiding Risks* [BRE 1994] suggests only a 20% increase for widths of 5 to 10 m). Attention is drawn to possible moisture attraction to thermal bridges where the insulation (and perhaps the vapour control layer) stops. This can easily happen at the eaves of refurbished buildings, and occasionally there have been outbreaks of timber decay after historic roofs have been upgraded with vapour control layers and insulation.

All the above recommendations are essentially based on the assumption that the roof is an inert structure which is subject to heat and moisture gains from below, and which must be protected from condensation damage by sufficient outside air ventilation to remove the moisture before it condenses. Recent research (for example, Cleary & Sherman 1987) casts doubt on this picture: there is a strong daily cycle in roof space dewpoint, which has been confirmed in RTL's studies, where on sunny days the dewpoint in roof spaces which are not generously ventilated can be well above those outside, and on cool nights well below. Such effects can potentially help to protect the lead: elevated daytime non-condensing dewpoints creating conditions more likely to provide passivation than in a generously-ventilated roof and the lower night-time ones avoiding some condensation events. There may also be seasonal effects: annual cycles in the moisture content of structural and decking timbers are well-known and the mass of water involved in these changes can be very large. For example if one tonne of wood increases its moisture content by 1% it absorbs 10 kg of water, which is sufficient to lower the relative humidity of 10,000 cubic metres of air at 10°C by over 10%. [19] A workshop on *Hygrothermal performance of the building fabric* at the Building Research Establishment on 21 January 1991 concluded that moisture movement and storage was poorly understood, current calculation methods did not necessarily describe the situation and further research was required. Subsequent work (for example, Jones 1993) has reinforced the importance of buffering effects and unventilated cold roofing systems are now being pursued in several countries (Shaw & Brown 1982, International Energy Agency 1994).

'Cold' roof design and condensation risks

Only the CDR, and its variant the ventilated warm roof, are now recommended for lead roofing. In essence they are variations on the same theme: a space under the lead and its immediate substrate, ventilated by outside air and from which water vapour and moist air from indoors are excluded by an AVCL. Paradoxically, Scottish Building Regulations prohibit CDRs but not ventilated warm or pitched roofs, probably because:

- for a CDR, with the ventilation normally within the structural zone, a good AVCL is very difficult to achieve and to maintain at ceiling level. People will always be putting in hatches and drilling holes for building services, which may easily destroy the action of the entire void. The zone itself is not easy to inspect and maintain in the way that a ventilated pitched roof is, and failures may threaten not only the weatherproofing but the structure
- for a ventilated warm roof, the vapour sealing, insulation and ventilation is restricted to a 'sandwich' on top of the structure. This permits a higher level of quality control: any failures will tend to be more localized, and if they occur they will tend to affect the roof finish and its supporting sandwich only, and not the primary structure. Vapour-permeable but waterproof sarkings may also be placed over the insulation to allow dispersal of any trapped moisture, and allow any condensation and water ingress that drips into the airspace to run out into the gutter
- ventilated pitched roofs, although in principle similar to the CDRs, perform more reliably in practice although their design has required some attention and improvement over the past two decades, as discussed below.

Condensation in roof spaces has tended to increase as a problem over the past 50 years owing to a number of mutually reinforcing trends:

- the change from coal fires to central heating has greatly reduced the amount of ventilation up chimneys, both hot and cold, and increased wintertime dewpoints
- the change from open-flued to room-sealed or electrical heating appliances, and from stoves to boilers in boiler houses has had a similar effect
- buildings without flues tend to carry more warm (and often moister) air into the roof space. Canadian tests on a two-storey house showed that a gas appliance with a chimney could reduce air leakage into the roof from the second storey of a house by 40% (Shaw & Brown 1982). Coal fires could easily have had a much greater effect and their sulphur-rich fumes may also have promoted passivation
- better sealed windows and doors tend to be opened less owing to changed habits, security requirements, noise control and energy saving
- more holes are made in the ceiling for building services (cables, pipes and ducts)
- heating is more controllable, and often operated intermittently
- in some buildings more internal moisture is generated, through increased tourism, catering, bathing and domestic appliances, and occasionally from humidifiers and unflued gas and oil heaters
- in some buildings lower occupancies, but with lower levels of heating and ventilation that can make them damper.
- progressively increasing insulation at ceiling level, which together with loss of incidental heating from chimneys in turn has tended progressively to reduce winter-time roofspace temperatures and consequently increase fabric moisture levels
- former roofspace ventilation paths are blocked, either deliberately or by insulation stuffed into eaves
- intermittent heating, particularly occasional heating of churches, can also increase roof space dampness: pulses of heat releasing pulses of extra moisture from the building fabric without creating enough of a continuous flow of heat and natural buoyancy ventilation to remove it (and the moisture from occupation) entirely (Bordass 1990).

When the present research began, it was felt that the above changes were the dominant causes of underside lead corrosion and that small alterations to heating and ventilation, perhaps only at critical times of the year, would make it possible to improve conditions and arrest corrosion. In practice, however, it appears that a 'golden age', where there was little or no underside lead corrosion, never existed. While the environmental changes outlined above have exacerbated the situation, they are contributory causes and not the sole reason, and adverse effects are difficult to reverse.

BRE Digest 270 (Building Research Establishment 1983) discusses condensation in insulated domestic roofs. It notes that in existing houses about 80% of the moisture enters the roof space with air rising from within the building, predominantly around roof hatches, via pipe routes and to a lesser extent through holes for electric cables and cracks at wall heads, and only 20% by diffusion through porous building materials. In a typical semi-detached house, 20-30% of the air dispersed via the loft, and in a single-aspect flat this became as much as 60%. Where chimneys were present, the proportions were reduced. Sealing hatches, access doors and holes and extracting air from moist spaces such as kitchens and bathrooms was found to be more effective at reducing moisture in roofs than adding a vapour control layer (which is both difficult to do retroactively, other than by paint, and as normally installed would tend to do little to reduce air leakage). To remove the moisture that did get through, roof space ventilation was recommended.

Current techniques for predicting condensation do not apply directly to constructions with ventilated air spaces. A recent laboratory study (Simpson, Castles & O'Connor 1992) of a flat timber 'cold' roof found that a vapour control layer was essential. It reduced the amount of moisture entering the roof space by a factor of 100.

With 0.01% of the polythene layer membrane's area perforated, the moisture gain increased by a factor of 10 but was still acceptable, but the authors noted that for specification purposes faultless sealing of the vapour control layer was imperative. Without this layer (but still with a plain plasterboard ceiling), moisture levels were high at distances more than 2 m from the air inlet, and in stagnant pockets across which the air did not pass. Under similar conditions, parts of a CDR tend to be damper than a ventilated pitched roof would be. This is because this type of roof contains a circulating body of air into which incoming air is blended while the CDR has more of a piston flow through the narrow gap.

In practice, ventilated air gaps in CDRs and ventilated warm roofs often fall short of good practice requirements. In particular:

- the ventilation does not run from bottom to top, as recommended, leaving dead spots above and below the ventilators
- sometimes other dead spots are not swept by the air path
- in complex geometries, and in particular at hips, valleys, rooflights, dormers etc, ventilation may be omitted entirely, or there is no through air-path
- occasionally gaps which should have been ventilated by outside air are instead ventilated, in whole or part, by inside air.

The UK's recommended air gap of 50 mm for a CDR (and implicitly for a ventilated warm roof) is smaller than that recommended by many other countries, at least for shallow roof pitches. To maintain the roofline in historic buildings contractors and architects have often been forced or tempted to use shallower gaps still. Unfortunately, however, the actual gap is sometimes even less than anticipated.

- In the test rig used by Simpson, Castles and O'Connor (1992), the researchers found that the nominally 100 mm-thick glass fibre quilt insulation had expanded to as much as 140 mm, so the designed 50 mm air gap was as little as 10 mm in places
- On ventilated warm roofs inspected we have found similar, though less severe, expansion. In one, a nominal 25 mm air gap became 20 mm owing to the effect of nominal timber sizes, and expansion of the 50 mm glass fibre batts had reduced this to 10-15 mm. RTL's studies indicate that 25 mm is probably a practical minimum (and then only allowable if the design and workmanship of the vapour control layer is extremely good)
- On several occasions we have also found air inlets and outlets wholly or partially blocked by projecting edges of the lead underlay or the vapour control layer.

Designers need either to allow extra space for fibre expansion (as is already noted in French-derived technical literature, see Eurocom 1993), to use more rigid insulation or to consider ways of stopping the insulation expanding (for example with a strong breather membrane on top and the air gap controlled by battens). [20]

Cold roofs are not the complete answer to 'no moisture, no corrosion'. Even if the building had an air and vapour control layer which was a perfect barrier to moisture migration into the roof space by diffusion and air movement, condensation is nevertheless likely in severe ambient conditions, particularly on still nights when radiation losses to clear skies takes the roof surface temperature well below ambient temperature and dew forms, or when a warm humid front arrives after a cold spell. Indeed, on dewy autumn mornings this condensation can often be observed on the underside of lead through gaps between the supporting boarding, but it is not necessarily accompanied by corrosion.

BRE Digest 270 (Building Research Establishment 1983) noted that while its recommendations suited most conventional roof constructions, under extreme overnight conditions more ventilation could actually increase condensation in lightweight sheeted roofs. However, it expressed the view that the extra ventilation would also clear the moisture more rapidly afterwards and prevent any long-term build up. However, this is not necessarily true if dripping or running condensation concentrates the build-up. For unpassivated lead, the resultant evaporation/condensation cycles can also be damaging, as already discussed in *Chemical properties* above.

Application to historic buildings

Few roofs in historic buildings comply with modern principles, except for very well-ventilated 'cold roof' situations, such as cloisters and bell-towers. Elsewhere, the underside of the decking often sees more air from inside the building than outside air. Even in nominally ventilated roof voids, the predominant air movement in winter (except on windy days) is often by natural buoyancy from below, with egress through both roof inlets and outlets.

Nevertheless, many such roofs have given good service, and their timbers do not get unreasonably damp. Modification to comply with CDR or ventilated warm roof principles is seldom easy, and often virtually impossible, taking into account technical, visual and historical constraints. Ventilated pitched roof principles may be easier to adopt, but where it is not possible to make good air seals between the roof space and the rooms below, additional roof-space ventilation may not only be unhelpful, it could be counter-productive, both for moisture levels (see Energy Design Update 1994) and in losing potentially useful buffering effects.

Roofs in historic buildings come in all shapes and sizes, but for convenience we have put them in four different categories (see Figure 4, A–D).

- Type A: direct onto occupied space, no intervening roof space
- Type B: underdrawn: a ceiling underneath but no distinct roof space
- Type C: domestic, with a roof space over the ceiling: this may or may not be ventilated
- Type D: stone vault, with a roof space above. A variant of C, but often more isolated from the building underneath and with more buffering capacity.

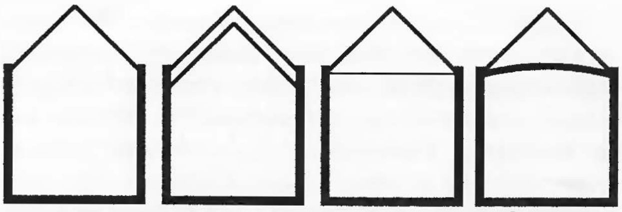

Figure 4. Four different types of roof.

Many historic buildings, particularly churches, have Type A roofs with no ceilings, which fly in the face of today's practice and in which the underside of the lead and its supporting decking experience the same environment as the building's interior. In winter, the inside air will tend to be both warmer and damper than that outside: the extra warmth will tend to dry out the timbers while the extra moisture will have the opposite effect. On balance, interior timbers are normally drier than air-dried ones in protected ventilated spaces outdoors, as shown in Figure 5. However, in winter many poorly-heated churches have relative humidities in the region of 80% when unoccupied, so interior timber moisture contents can easily rise to 15% and more. Owing to heat loss to the outside, the decking timbers under the lead are colder and damper than this, and condensation risks are high. The processes are discussed further in *Influence on moisture levels*.

Underdrawn roofs, Type B, (known as 'cathedral roofs' in North America) with no explicit ventilation appear to offer the worst of both worlds: little or no opportunity to lower the dewpoint by introducing outside air (though a ventilated warm roof sandwich could potentially be added on top), while the winter-time temperature is reduced by heat loss to the outside, hence increasing the condensation risk (though this is only weakly dependent upon outside temperature, see *Influence on water levels*. However, these roofs seem to perform better than they deserve to, probably because the moisture-absorbing effects of the additional timbers between the lining and the roof decking can reduce the uptake of moisture into the structure and the amount of condensation, particularly under transient conditions.

Many domestic-type roof voids, Type C, act as an outlet for air from below, with some additional moisture diffusion for good measure. While additional ventilation is often called for, if it is not extremely generous it may be unproductive unless the sources or ingress are properly attended to first, which is usually much more easily said than done.

Roofs over stone vaults, Type D, are often found to be in good condition, probably for five main reasons:

- they are often on relatively dry, and continuously (if not generously) heated buildings, such as cathedrals
- they are often steeply-pitched, which reduces the amount of radiant heat loss under still, clear night sky conditions and helps water to drain from the splashlaps
- the steep pitch allows gap-boarding to be used, which although prone to condensation on dewy nights can dry out rapidly and does not trap moisture from any source
- the roof space is more separate from the air in the building (though access doors and holes can be a problem), with a greater proportion of ventilation by outside air
- they tend to be large in scale, and buffered by relatively large amounts of material.

The large amounts of hygroscopic material, especially timber in the roof spaces of many historic buildings, particularly Type D but to some extent also C and B, may have a variety of potentially beneficial effects both for the roof space environment and for the lead, and may work best with only limited amounts of ventilation by outside air:

- *Drying effects*: high roof void temperatures in summer may eventually dry out the timbers to a greater extent than if they were in free air, when they would not get as hot and where they would be able to re-absorb moisture more rapidly on cooler days and nights
- *Seasonal storage*: if the ventilation of the roof space is limited, the rate of moisture uptake by the dried timbers will be slowed down, allowing them to stay drier and to exert a dehumidifying effect during the vulnerably dewy autumn period. After the exceptionally hot summer of 1995, unusually dry roofing and decking timbers were found in many buildings right through the winter, which was also dryer than usual
- *Diurnal fluctuations*: when the roof is heated by the sun during the day, moisture driven off from the timbers humidifies the air and slowly escapes. When the timbers cool at night, moisture is absorbed and the roof is dehumidified. These augmented swings in dewpoint (William Bordass Associates 1986, Cleary and Sherman 1987) and have been reproduced in the unventilated roof void section of RTL's test facility
- *Improved passivation and protection of the lead*: the elevated (but non-condensing) dewpoints on sunny days may help to passivate the lead by a mechanism which would be less available in a better-ventilated roof from which the water vapour would disperse more rapidly. Similarly, the depressed night-time dewpoints may protect the lead, particularly above the gaps in the boarding, from transient condensation under some conditions.

4 Patterns of corrosion

This section reviews some observed patterns of underside corrosion and relates them to the circumstances in which they are found. For ease of description, the initial classification is by the type of substrates and underlays used. For each of these, other influences are mentioned, in particular:

- the geometry of the lead
- roof configuration and orientation
- the effects of external and internal climate (with more in *Influences on moisture levels* below)
- chemistry (see also *Chemical properties* above).

The issues are brought together more strategically in *Discussion* below. The information has been collected

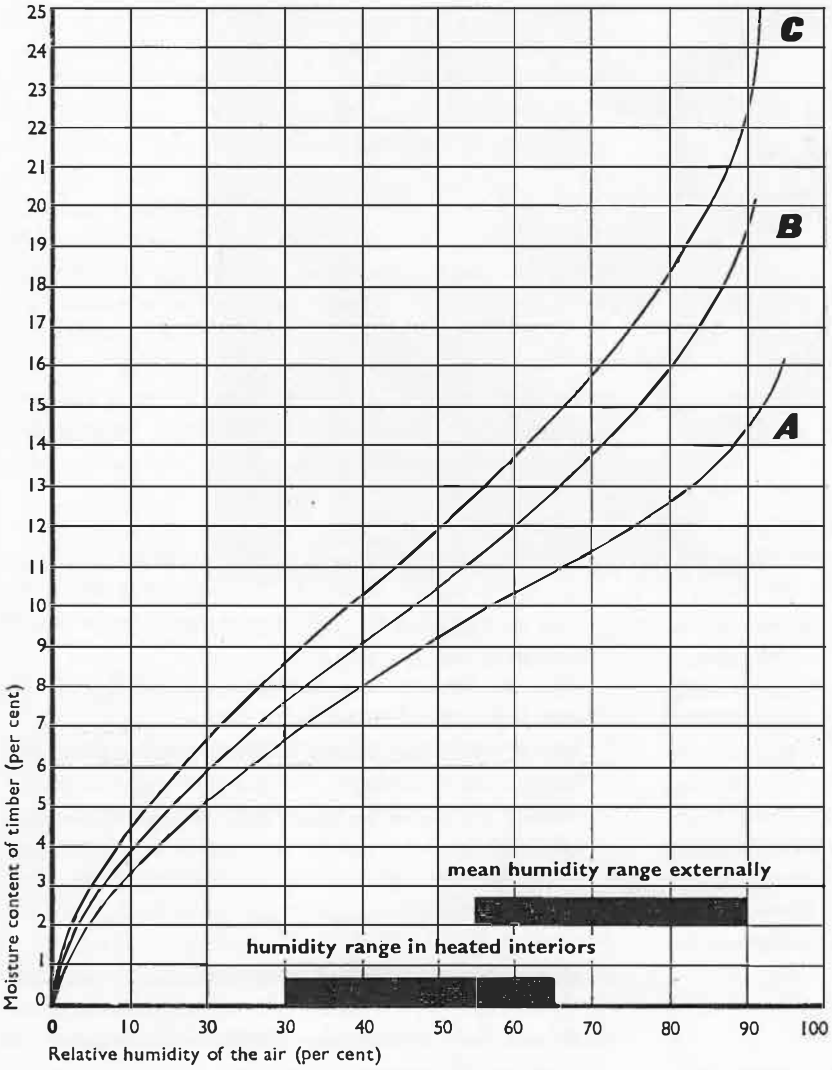

Figure 5. Relationships between equilibrium timber moisture content and indoor relative humidity (from Stillman and Eastwick-Field 1966, pp42–3). Many woods perform in the region of Curve B. Curve A includes teak, iroko, western red cedar and yellow pine. Curve C includes lime, sycamore and Corsican pine.

from nearly thirty sites visited, see Appendix D. Nearly two-thirds of these sites have received some monitoring and testing in this and associated studies. Most of the sites also contain a variety of roofs, of different pitch, construction and orientation, and sometimes with widely differing internal environments.

The underside surface of lead is often found in one (or usually several) of seven typical states:

- *State 1.* Type I corrosion (see *Chemical properties* above). A relatively hard, compact white scale, which confers some protection, unless it builds to such a thickness that it fails under mechanical stresses (often induced by thermal movement of the lead)
- *State 2.* Type II corrosion (see *Chemical properties* above). A looser, powdery or flocculent white scale. This tends to be formed in sustained condensing conditions. In more variable or gradually improving conditions it can sometimes 'harden up' and become more similar to Type I, although generally less protective
- *State 3.* Multi-layered flaky scales. Thick layers are often the consequence of prolonged Type II or Type I corrosion. While predominantly white, colouration by oxides may give them a yellowish tinge. Red oxide may also be found, particularly near the interface between the scale and the underlying lead. When they are particularly thick, organic acids are often present. Indeed, in most cases where corrosion has been sufficient to cause complete failure organic acids usually seem to be implicated.[21] Thin flakes are also sometimes found, probably the result of the roof being very damp to start with
- *State 4.* Localized streaks or spots of corrosion, often including brown as well as white areas. These are most often associated with the distillation of rainwater trapped in splashlaps into the adjacent roll or step. Corrosion only seems to occur in places where the two lead sheets are close enough together to trap condensate between them
- *State 5.* Dark and passivated. This tends to be found in environments which are sometimes moist but seldom fully condensing. These often occur in close proximity to highly corroded areas, even in acid-rich environments
- *State 6.* Dulled (sometimes with interference colours). This tends to be found either in dry environments where there is ample air (freshly-unrolled bright lead will dull down in a few weeks indoors), or in enclosed environments which are somewhat damper
- *State 7.* Bright and uncorroded. This normally occurs where the lead seldom if ever encounters moisture, for example when it is well-buffered by sound,

preferably low-acid, timbers in a dry environment. Usually access of air is also restricted.

Underside lead corrosion is seldom uniform, either on a single sheet or on different roofs over a building, and can vary tremendously between buildings, even where conditions are ostensibly similar. Many variables have both positive and negative effects: if the balance between them is slightly changed the outcome can be very different. If adverse physical effects occur (in particular where there is not only condensed or retained moisture but also frequent wetting and drying cycles), together with aggressive chemistry (in particular the release, generation and retention of organic acids), the results can be particularly severe.

Lead on close-boarded softwood deckings

Traditionally lead, particularly for low-pitched roofs, was often laid directly on sawn (or sometimes planed) softwood planks with 'penny gaps' between the boards.[22] While these gaps are prudent carpentry practice to allow for moisture movement of the timber, they also help to admit air to the underside of the lead, which in the right circumstances may assist passivation. However, the same route also allows moist air and water vapour to reach the underside of the lead rapidly, so increasing the risk and quantity of local condensation under adverse conditions, and providing a short-circuit path to the underside of the lead in contact with the boarding. On the other hand, the gaps also provide a path for any ingressed or condensed moisture to drip out, and for more rapid drying of the timber in the sunshine.

Corrosion under lead laid directly upon softwood boarding often reflects the patterns of boards, gaps and sometimes knots. Figure 6 is characteristic: on the nave roof of a church in Buckinghamshire, the lead is somewhat corroded (States 1 and 2) above the boards but above the gaps it is largely passivated (State 5). This passivation has occurred in spite of regular condensation above the gaps (at least in recent years). Freshly-cleaned lead samples placed above the gaps here also corrode.

However, as with the fresh lead samples mentioned above, one often finds more corrosion over the gaps than the boards, particularly for roofs laid in the autumn which can rapidly encounter condensation, if not from damp substrates, then merely from diurnal fluctuations in ambient conditions. For example, Figure 7 shows the ventilated warm roof section of the 1994–5 Donnington Castle tests in November 1994, about two months after these tests were started:

- over the top (leftmost) two boards of untreated softwood, which were laid in September 1994, the lead is only slightly dulled and shows interference colours (State 6)
- over the next two, preservative-treated, boards the lead is passivated (State 5)
- but at the joint between the preservative-treated boards there is a stripe of corrosion which widens out into the roll and at the top left licks into the uncorroded section.
- at the bottom (right) of the lower plank there is also some corrosion.

While the differences here may be influenced by chemicals in the timber preservative, evidence from computer modelling (see *Influences on moisture levels* below) and

Figure 6. Corrosion above softwood boarding. White and yellowish (States 1 and 2) corrosion product on the nave roof of a Buckinghamshire church, with dark passivation above the gaps between the boards. The photograph was taken after a cold, clear night, and the roof was particularly damp at the time. Note also the passivation over the rolls (with the odd spot of corrosion). The ridge is passivated on the far (right) side, probably by rainwater, which also seems to flow over the ridge from time to time (the lap is mean). Not surprisingly, there are signs of corrosion here, probably the result of a combination of condensation and refluxing of rainwater. In spite of this, and of the church being particularly damp (RTL 1993, Report 6, Appendix D), the corrosion is not yet serious. See also Colour Plate 2.

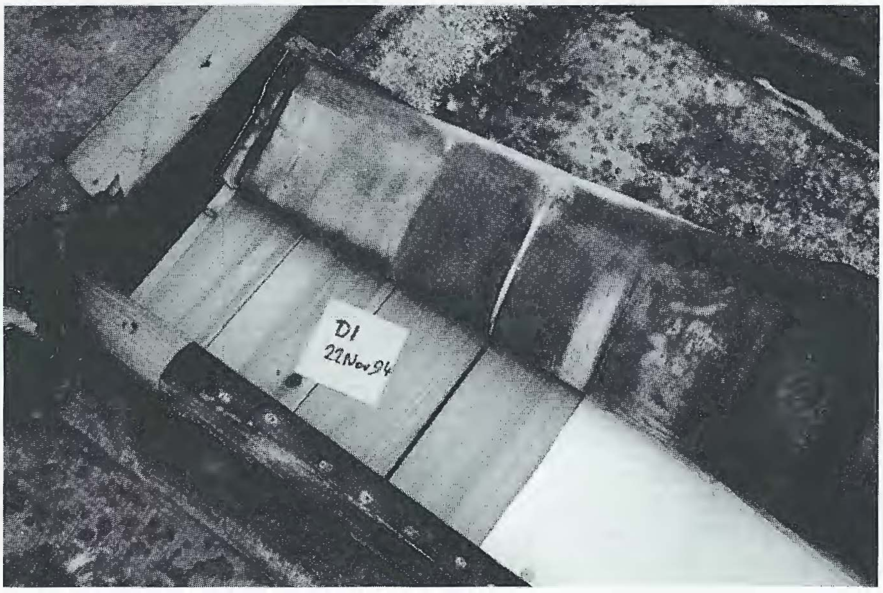

Figure 7. Lead after a two-month autumn test at Donnington Castle showing a wide range of surface states from passivation to corrosion. The two (untreated) boards on the left have kept the lead dry and its underside is only slightly dulled. The two to their right were preservative-treated and probably initially damper. This has assisted passivation over much of the boards, but corrosion around the perimeter. See also Colour Plate 3.

other sites suggests that initial moisture contents in the boards may be significant:

- the initial moisture content of the preservative-treated board may have been higher than in the plain board: here sufficient to assist passivation but not corrosion[23]
- when the lead was heated in the sun, moisture evaporated from the timber and passivated the lead more quickly
- the lead not in contact with the wood would not be passivated so well because the water vapour would disperse more rapidly
- however, this lead would be more at risk of condensation and corrosion when the temperature dropped (in the shade or at night), both from ambient moisture and from extra water vapour emission from the still-warm wood
- corrosion may have been exacerbated by volatile components of the preservative.

The church in Buckinghamshire also has an example of the high variability of corrosion patterns. White corrosion products are generally visible between the boards from inside the church below, while in the higher nave roof (above a clerestory) they are not (see Figure 6).[24] Figure 8

Figure 8. A church in Buckinghamshire: corrosion patterns on a slipped panel on the south aisle. See also Colour Plate 4.

shows a lifted sheet which is particularly informative because it has slipped at several stages during its life. Initially (when the lead was about one-third of a board width to the right of its current position) there seems to have been a strong tendency to corrosion over the gaps and passivation in between, but following the slippage some corroded areas have extended (as in the centre of the photograph) while to the right corrosion has been resisted by the passive layer. Indeed, it even appears that, in the lead's current position, one or two areas may actually have lost corrosion product and become more passivated by the present environment.

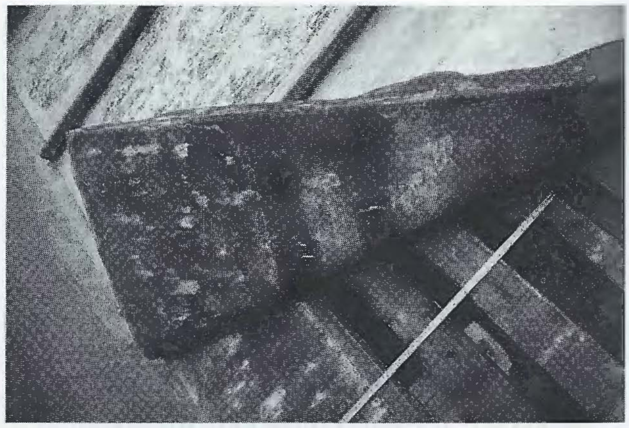

Figure 9. Lead over gap-boards at the Church of St Cross, Winchester. This lead, which dates from the 1880s, is generally passivated above the gaps and very slightly corroded over the boards. As in Figure 8, there has also been some slippage. To get some corrosion in the lap is not uncommon.

Lead on gap-boarded softwood deckings

Gap-boarding is commonly found in cathedrals and larger church buildings. The softwood supporting boards are often narrow (typically 50 to 75 mm wide, like tiling battens), with spaces of 15 to 25 mm between them. Since the lead has to span across the gap, they are most appropriate for the thicker codes of lead and for steeply-pitched roofs, for which there is also a possible advantage during construction as the sheets can be clipped over the battens at the top and intermediate clips used where necessary. They are usually installed without any underlays. Salisbury Cathedral used bitumen-cored building paper for a while but found that it made things worse.

Lead over gap-boarding in cathedral or similar roofs often seems to be in good condition, either passivated or with only small traces of corrosion (as at St Cross, see Figure 9; much of Salisbury Cathedral is similar), even though condensation can sometimes be found, for example on clear, still autumn nights. The effect is often attributed to good ventilation through the gaps alone, and certainly the avoidance of moisture traps and the ability to vent (or drip) away any excess moisture (and acids) will be helpful, shortening the time of exposure and potentially allowing passive layers to survive and regenerate. However, there appear to be other influencing factors, including gap-boarding's general associations with:

- more steeply-pitched roofs, which are not as subject to dew on still, clear nights because they cool less, owing to a diminished 'sky view'
- separate roof spaces, often over vaults, often well buffered and somewhat decoupled hygroscopically from the occupied parts of the building.

In turn the buffering may have other advantageous effects, particularly in more humid conditions when the roof is hot (which may enhance self-passivation), the ability of a buffered roof space to dehumidify itself after a warm period (which reduces the occurrence of condensation) and a slower transition into condensing conditions, which may assist passivation and absorption of carbon dioxide into the condensate (helping to avoid the unprotective Type II corrosion).

In an attempt to repeat the successes of past gap-boarded roofs, some new designs have reverted to gapped boards without underlays, for example in ventilated warm roofs. However, the results have been variable, probably because the buffering and passivating effects in a traditional situation are not necessarily present and the effects of any failure in the control of air and water vapour from the building below are more concentrated in the region of the failure.

For example, the foreground of Figure 10 shows a ventilated warm roof where the underside of the lead is in exemplary condition after two years. Above the softwood the metal is still bright, and above the gaps only dulled and perhaps slightly passivated. However, the bay immediately behind tells a different story of condensation and corrosion: not only above the gaps themselves, but spreading over the boards as well. The difference is that in the near bay the vapour control layer performed well, but in the adjacent one, and although the ventilated air space had been retained, faults in terminating the layer around the perimeter of a rooflight allowed moist air and water vapour from inside the building to leak into the ventilated airspace. [25]

This again emphasises the importance of meticulous attention to detail in design and workmanship of air and

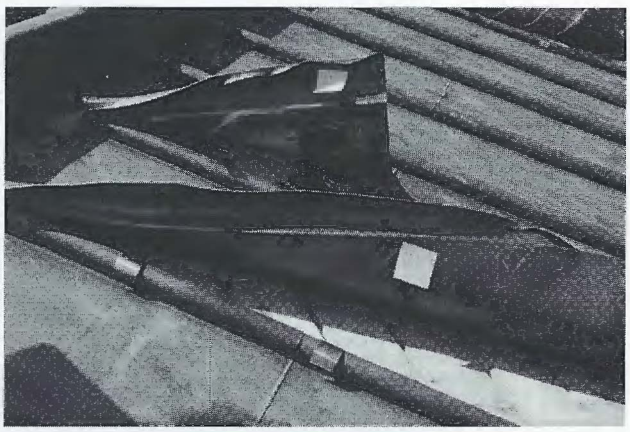

Figure 10. Variations in corrosion performance over the gaps in a ventilated warm roof. Small amounts of leakage of water vapour and moist air can make large differences to corrosion in a roof which has limited buffering capacity. For comparison with later illustrations, note also the good condition of the rolls, which here do not have splashlaps.

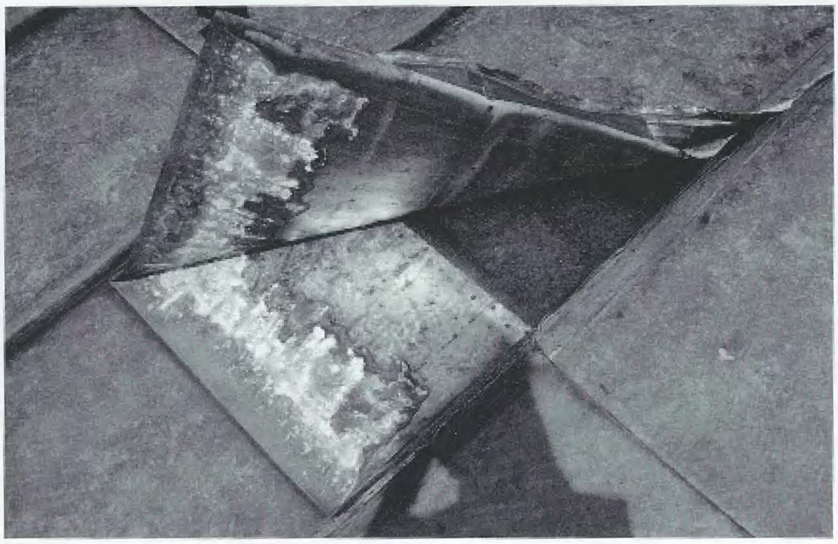

Figure 11. Lead over building paper on softwood on a relatively dry building. The lead is bright or only slightly dulled, though with a white haze between the boards. The pattern in the lap is not unusual: at the bottom a weathered area indicating capillary rise of rainwater, some corrosion (with a fringe of dark passivation) above that (where the rainwater distils) and the lead above that unaffected. The hollow rolls are free from corrosion. See also Colour Plate 5.

vapour control layers if the intended performance is to be attained. The same applies to ventilation of the ventilated warm roof's air gaps: owing to its complex geometry, parts of the roof in Figure 10 were not fully ventilated and these also suffered from corrosion. On another building, the upper ventilators were not at the very top of a lean-to ventilated warm roof and underside corrosion was found in the region above them. Ideally, some protection to new lead in such situations would also be furnished, either chemically (perhaps using chalk treatment if this proves successful in tests) and/or using suitable underlays.

The effect of underlays on softwood substrates

Often lead is separated from softwood by underlays, which tend to be of three kinds:

- a building paper, often bitumen-cored
- natural felt blankets, made of animal ('hair felt') or vegetable fibres. These tend to be permeable to air and can absorb moisture. 'Inodorous' felt (eg Erskine's) (made of flax and jute with resin and pitch binders) was used frequently in the past but less so now because the binders become mobile at about 50°C (a temperature easily reached by lead in summer sunshine), which not only stiffens the material but may also stick it to the lead, which can then lead to thermal fatigue. If it rots, the decaying jute may also harm the lead
- polyester geotextile felts, which have become increasingly popular. These tend to be very permeable to air but the fibres do not absorb much moisture.

These underlays can affect the corrosion observed, as discussed below.

On a relatively dry building, building paper underlays can help to isolate the lead from the environment underneath, and avoid the patterned corrosion discussed above. For example, the nave roof of a church in Northamptonshire has no void but just two layers of softwood boarding above (an older one underneath and a newer one on top). When re-leaded with cast lead in 1988, building paper was laid over the existing softwood. Two years later (see Figure 11), the lead was largely in bright condition, indicating little contact with either air or moisture. The softwood decking underneath was also relatively dry. However, at the time the church was unusual in being not only continuously heated but also in good condition and well cared-for by the churchwarden, who opened doors and windows on dry, sunny afternoons. All these measures helped it to be dryer than usual. Evidence of past condensation came from the architect's reports and from marks on the wooden ceiling underneath, suggesting that the situation might easily deteriorate if the heating and ventilating regime was to change.

In addition to the leaching discussed above, three main problems have been found with building papers:

- if bitumen-cored or polythene-backed building papers become wet on the upper side, from water ingress or condensation, the trapped moisture in the relative absence of air can exacerbate corrosion, particularly where acids are present. Even small amounts of water and acid may collect near defects such as laps and holes, causing severe localized corrosion damage and failure either by direct penetration or by increasing the lead's susceptibility to fatigue under thermal stresses
- condensation under the building paper cannot escape as readily under drying conditions, for example when the sun shines upon the lead, and so the risks of fungal or insect attack to the underlying timber may increase. The same applies to all unbreathable underlays unless they are carefully combined with additional insulation

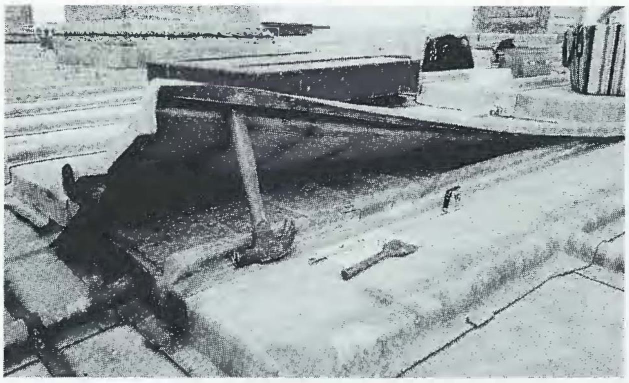

Figure 12. Underside of lead over Erskine's felt at a mansion in Dorset. The lead over the underlying boards above the public rooms is lightly and fairly uniformly corroded. Above the gaps there is a tendency to passivation. This corrosion is no longer active. Note also the corrosion in the roll above the splashlap caused by distillation of trapped rainwater: this recurs on a freshly wire-brushed surface. See also Colour Plate 6.

- the paper itself may rot, undermining its physical effect. Occasionally it has also provided a path for the rapid spread of fungus.

Natural felt underlays have three main effects:

- they provide some insulation, which in cold weather tends to make the wood warmer and the lead cooler. This can be significant in marginal cases (see *Influences on moisture levels* below).
- they allow air (and moisture) to permeate more uniformly to the underside of the lead, with mixed results
- they partially isolate the lead from the buffering effects of the wood underneath. However the hygroscopic fibres themselves also exert their own buffering effect.

Figure 12 shows some uniformly-corroded milled lead (laid in 1985) over Erskine's felt at a mansion in Dorset.

Figure 13. Underside of lead over Erskine's felt in a damper location at the Dorset mansion. The lead above the gaps is somewhat corroded, particularly towards the rolls in which there is also some corrosion. Note also the corrosion in the rolls above the splashlaps, as in Figure 12. The splashlap corrosion pattern varies with the distance apart of the sheets. Water is also trapped in the splashlap here by a slight backfall below the nosing. See also Colour Plate 7.

The corrosion product over the boards is thin, hard, compact and adherent Type I. Subsequent studies have shown that most of it was formed soon after the lead was laid, probably because the softwood decking (and perhaps the building) was relatively damp initially. In a few places where there was no Erskine's felt, the corrosion product was soft and flaky.

Over a warmer and somewhat more humid occupied flat in the same building, the lead above the boards shows similar Type 1 corrosion but over the gaps the corrosion product is whiter and less adherent, widening out into a 'fish-tail' as the roll is approached, and spreading into the roll and nosing (Figure 13). Wire-brushing patches (some can be seen in Figure 13) showed that lead freshly exposed in September was liable to further corrosion over the winter in the fish-tail areas only, where moist air rising from within the building could most easily con-

Figure 14. Corrosion over geotextile in a ventilated warm roof. While not serious, the underside lead corrosion is considerably greater than where the lead is placed directly on low-acidity softwood boards in ventilated warm roofs which are properly vapour-sealed from the building below.

Figure 15. Rapid initial corrosion at a mansion in Buckinghamshire. Four weeks after this sheet was replaced in the autumn, fish-tails were already very evident.

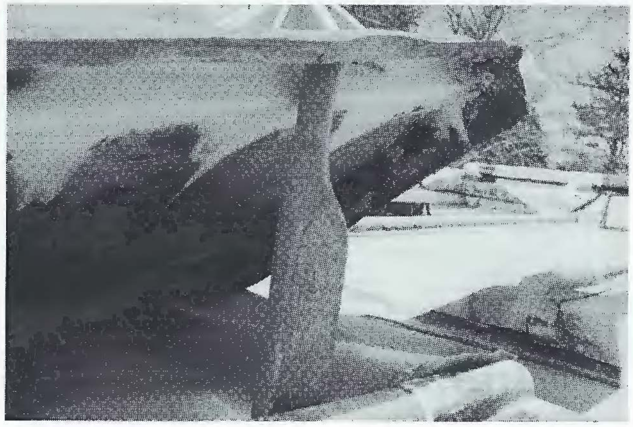

Figure 16. A year later in the same position the corrosion has now spread more widely.

dense. Corrosion did not occur in these positions (at least over a three-year test) in areas where the lead was cleaned and pre-treated with patination oil or linseed oil.

When geotextile underlays are used, corrosion above the gaps generally seems to be more pronounced in all but the driest environments. For example, Figure 14 shows some hazy corrosion where geotextile was used over a well vapour-sealed ventilated warm roof. This did not occur over plain softwood boards on other sites (see Figures 7 and 10).

Figure 15 shows a more dramatic example from a mansion in Buckinghamshire, where pronounced fish-tailing was evident under a replacement sheet only one month after laying in the autumn and continued thereafter (Figure 16). Interestingly this pattern is the reverse of that shown by the original sheets laid in 1905 over hair felt (Figure 17). Nevertheless, fresh (or freshly-cleaned) lead placed over the gaps corroded here too. However, lead laid in the early summer was much less affected as it had built up some passivation before encountering dewy winter conditions.

Three effects, all working together, appear sometimes to increase the likelihood of initial corrosion over geotextiles:

- the high permeability of the geotextile to air and water vapour
- the partial isolation of the lead from the moisture-buffering effect of the timber
- the non-absorbent nature of the geotextile fibres.

The effect of oak boarding

If any condensation or water ingress ever occurs (and even without liquid water), lead laid over oak boarding

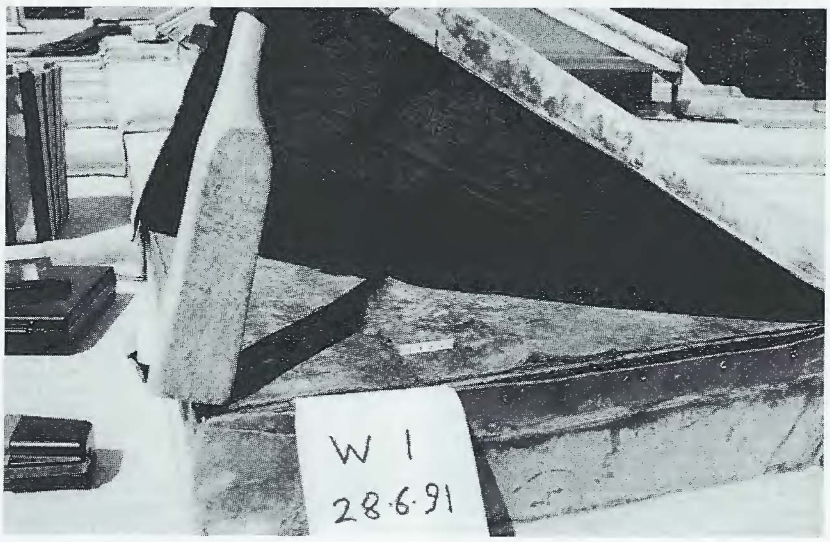

Figure 17. The original roof at the mansion in Buckinghamshire. Most of the roof was laid over Erskine's felt and was passivated between and corroded above the boards (the opposite of the current pattern). A few sheets, which did not have the felt, showed a similar pattern but with worse corrosion over the boards, probably because any moisture accumulating within this region would be trapped for longer than over the more permeable felt, and possibly there might have been some acidity. The longitudinal stripe was made by wire-brushing for tests and is not part of the original pattern. See also Colour Plate 8.

Figure 18. Norwich Cathedral cloisters, showing lead distress and repairs. The pattern here is characteristic of acid attack, with not only weakening along the gaps between the boards, but also failure at the perimeter, at rolls and laps. See also Colour Plate 9.

tends to corrode much more extensively than in any of the examples yet shown, though nevertheless it may take 20 to 50 years before noticeable failure begins to occur. Figure 18 shows the pattern of repairs in the cloisters of Norwich Cathedral, and Figure 19 the very heavy corrosion underneath.

On several sites visited in mid-winter we have found the underside of lead laid over oak boards to be damp while over nearby softwood boards it is dry. Computer simulations by BRE Scottish Laboratory also predict this effect (see *Influences on moisture levels* below). The reasons for increased corrosion over oak may therefore be physical as well as chemical.

The literature suggests that lead may be protected from oak by interposing an impermeable layer such as bituminous felt.[26] On the sites studied we have found a variety of techniques, none of which has been entirely successful, at least for roofs directly over occupied spaces, with no intervening roof space.[27] Examples include:

- bitumen paper bedded in hot bitumen at church 1 in Yorkshire
- hardboard at Donnington Castle

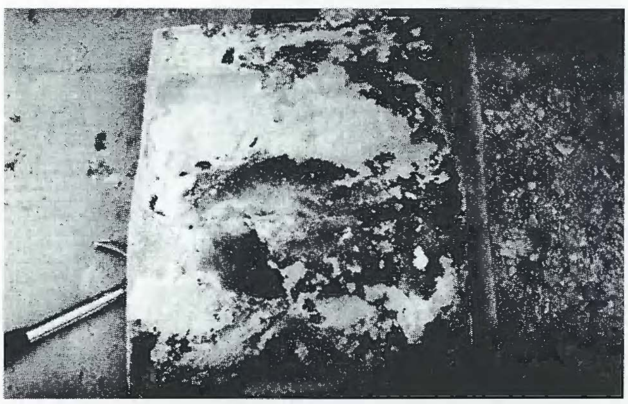

Figure 19. Underside corrosion over oak at Norwich Cathedral cloisters. The patch removed, on the left, failed at the perforation in the middle. The characteristic red/brown oxide can be seen near the interface with the metal, with the thick, flaky and granular corrosion product remaining underneath (on the right). See also Colour Plate 10.

- hardboard over bitumen-cored building paper at the Great Hall, Hampton Court
- Erskine's felt over polythene-backed building paper at St Mary's, Stoke-by-Nayland.

In the first three buildings the protective measures have failed, typically after about 40 years, and replacement is now imminent. Stoke-by-Nayland, where the re-leading dates from 1967, is in much better condition but nevertheless shows some signs of distress. At a very damp church near Sheffield, lead laid on bitumen-cored building paper over timber boarding was also suffering acetic acid attack, probably arising from moist air and acetic acid vapour egress from the oak ceiling and the closely-spaced oak rafters underneath.

In simple terms, the failures could be attributed to 'an absence of ventilation under the lead', though as we have seen, ventilation by no means guarantees the absence of moisture or corrosion. However, all these sites share a relatively sealed environment between the lead and its substrate. Any water or acid which happens to get there by whatever mechanism will be trapped and available to hydrolyse timber products, dissolve adhesives and binders and distill with changes in the weather and sunshine. Even though barrier layers may restrict the total amount of underside corrosion, the remaining pockets of local corrosion can still be severe enough to require the whole sheet to be scrapped.

At church 1 in Yorkshire much of the underside of the lead surface is only lightly corroded, but there is severe corrosion, and penetration in places, where the lead rises into the hollow rolls and at the top of the laps (as in Figure 18). Essentially moisture and acid seem to have accumulated and distilled near the potential exit points from the roofing sheet. Here the atmosphere would also be richer in atmospheric carbon dioxide, to convert lead acetate into basic lead carbonate, and regenerate the acetic acid.

At the church near Sheffield moisture ingress was noticeable at the laps between the sheets of building paper, which were also uniformly wet. Since the laps ran down the slope of the roof, moisture also trickled down by gravity, as seen in Figures 20 and 21. Although the lead was corroded right through in places, and especially above gaps between some of the underlying boards (perhaps because condensation could collect here most), there were passivated areas nearby (dark shade), as in the lap in Figure 20 and in the frond-like pattern under the lead at the top right. The dark lines of the fronds coincide with the ridges in the puckered building paper underneath, suggesting that lead in close contact with the substrate was less corroded. These at first curious findings apply to many of the very badly-corroded roofs inspected:

- highly-corroded and well-passivated lead are often closely juxtaposed
- lead touching the substrate is often less corroded than where there is an air gap.

Donnington Castle gatehouse was one of the most corroded sites found. The roof of this unheated tower

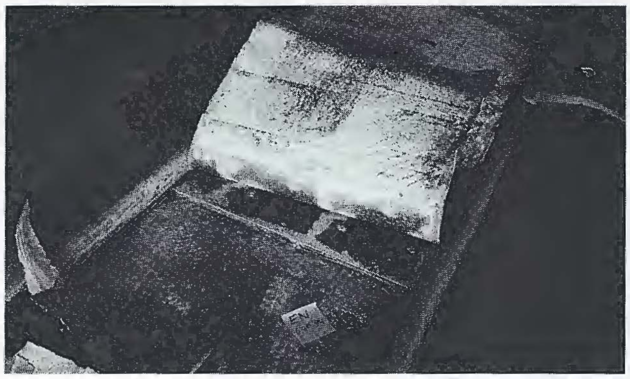

Figure 20. Underside corrosion at the church near Sheffield. This roof over the NE chapel was very wet owing to a damp building, poor ventilation and a heating system which had been turned up, releasing more moisture into the atmosphere while the building slowly dried out. Some of this made its way through the construction and condensed under the lead where acetic acid was also present.

was completely replaced in the mid-1950s by a new oak structure with oak rafters and purlins and an oak-boarded ceiling with hardboard over, presumably intended as a protective layer and to form a level surface for the lead. The lead began to fail in the late 1980s, and Figure 22 shows the heavily-corroded underside (average thickness loss 25%: (Lowe et al 1994), with patterning which coincides with the gaps between the underlying boarding (slightly less corroded above the gaps) and with the rafters and purlins (also less corroded over these). There is also some corrosion on the inside of the roll, but interestingly with a stripe of passivation at its base.

Across several bays near the southern eaves at Donnington there is a stripe of largely-passivated lead, see Figure 23. When the hardboard was taken up over this, a softwood fillet of approximately the same width as the stripe was found between two oak boards. There was also less corrosion above butt joints in the hardboard.

Chemical tests of the timber and hardboard showed that while the oak had a relatively low acetate content (for oak) of 80 ppm, acetate had accumulated in the hardboard (both original, from the oak and probably by hydrolysis) to a very high level of 600 ppm (Lowe et al 1994). Over the softwood strip, the hardboard's acetate content was only marginally smaller at 587 ppm, suggesting that the difference in corrosivity was likely to be primarily related to the physical (hygroscopic) properties of the softwood, and probably its higher absorbency. The

Figure 21. Valley gutter at the church near Sheffield. The lead from the gutter and roof has been removed in preparation for replacement by a ventilated warm roof. Products of corrosion at the oak rafter ends are very evident.

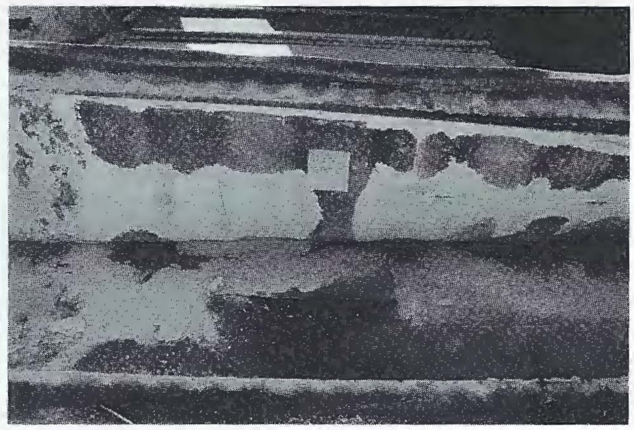

Figure 22. Typical underside corrosion patterns at Donnington Castle. A rafter underneath in the foreground coincides with the less-corroded area at the top.

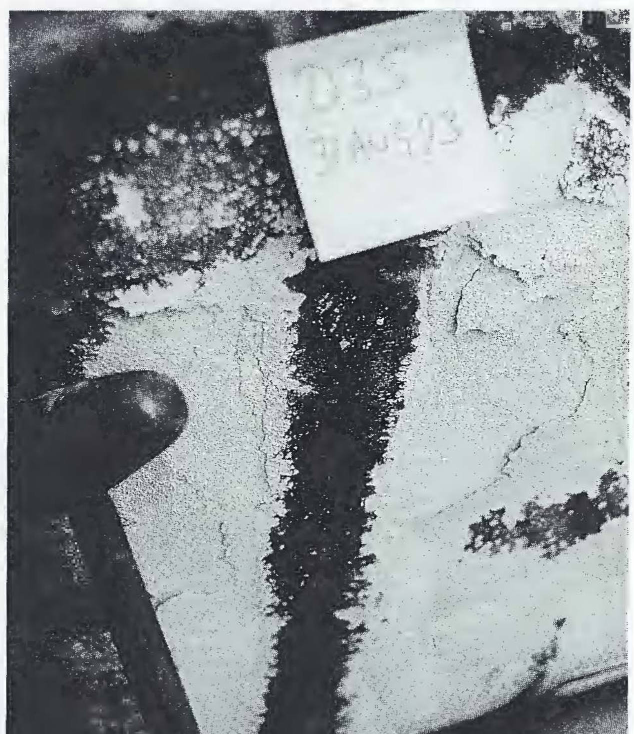

Figure 23. Passivated stripe at Donnington Castle. 3 mm hardboard separates the lead from the oak boarding underneath. The lead is badly corroded except for this dark passivated stripe, beneath which a softwood fillet was found under the hardboard. Since the acid content of the hardboard was found to be high (600 ppm) and similar throughout, the contrast is likely to be the consequence of different hygroscopic properties of the two woods.

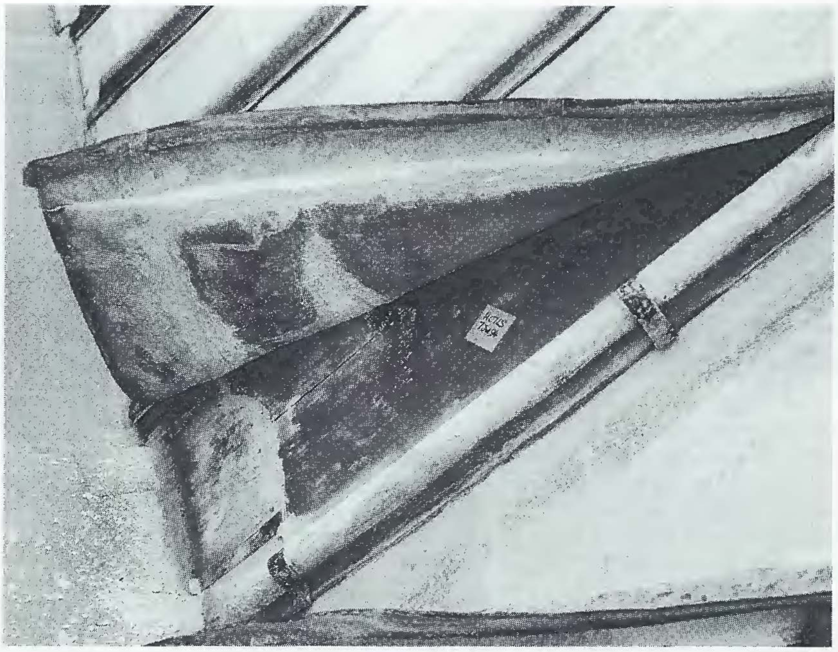

Figure 24. The south-facing roof of the Great Hall at Hampton Court. Corrosion is greatest around the perimeter and in places where the lead has bulged away from the substrate. The corrosion in the rolls varies from place to place and from sheet to sheet, presumably depending upon the precise geometry and its propensity to trap moisture.

lighter corrosion over the rafters may also be an effect of their greater hygrothermal inertia.

From September 1993 to April 1994, RTL left a number of prepared lead samples sandwiched between the existing lead and the hardboard. The one over compacted fibre geotextile underlay was highly passivated. In contrast, at Hampton Court lead over geotextile was severely corroded, more so than over Erskine's felt. RTL's test rig work (RTL 1995, Report 6) also showed a reduced level of corrosion after the oak had become wet. As with pure concentration corrosion, there seems to be a fine, surprising and even more distinct boundary between passivation and severe corrosion when acetic acid is present.

The lead at the Great Hall of Hampton Court was relaid over hardboard in the 1950s, at much the same time as Donnington. On this much more steeply pitched roof, the hardboard has bitumen-cored building paper underneath. It too is heavily corroded, but the corrosion is more localized than at Donnington. Acetate in the

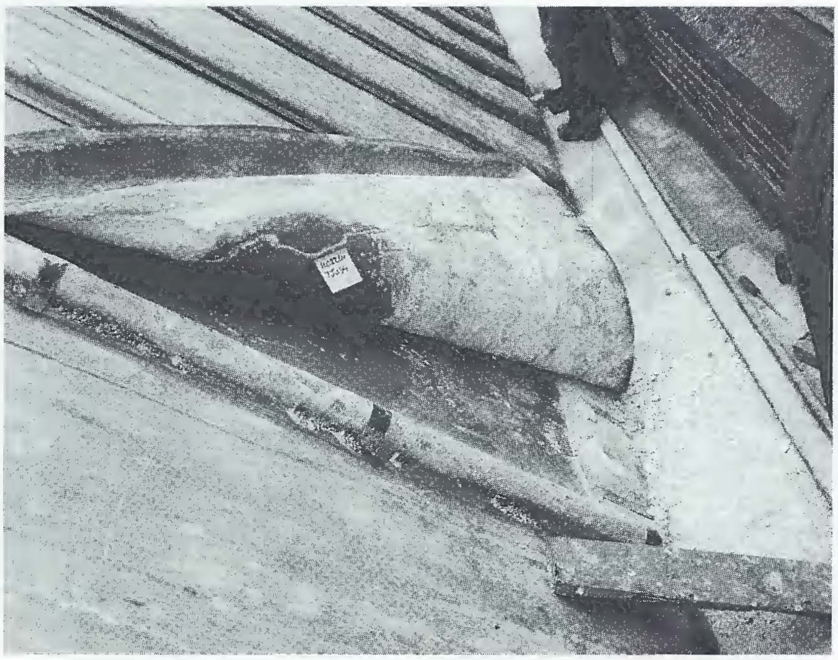

Figure 25. The north-facing roof of the Great Hall at Hampton Court. While this sheet generally exhibited more corrosion, it has a highly passivated area in the middle. Contrasts like this also occur on the south side.

corrosion product varied from 40–100 ppm in the lap to 450 ppm in the roll and 3700 ppm in the centre of the panel (ibid, Report 4, Appendix E).

Figure 24 shows a typical sheet on the south-facing slope. The corrosion is greatest around the perimeter, both just above the lap and beside and over the roll. Note also the tongue of corrosion a short distance above the lap, which coincides with a 'blister' formed in the lead sheet by restrained movement. Underside lead corrosion is also found under similar blisters further up the sheets (see also Figure 25). What these all have in common is that the lead seems to be worst corroded where it is least in contact with the acid and often moist substrate. There could be several contributory reasons:

- distillation of moisture and acid across the gap with changing weather and sunshine
- greater availability of carbon dioxide in the gap to regenerate acetic acid
- concentration of acetic acid during drying-out, although in the laboratory lead is less corroded by glacial acetic acid than dilute (Hoffman & Maatsch 1970)
- electrolytic effects (corrosion cells) creating anodic and cathodic areas.

Lead over plywood

In the recent past, plywood was often used as a substrate for lead. Today softwood boarding is again becoming more popular for all types of continuously-supported metal roofs, and the present study tends to support this choice. Plywood's performance can be acceptable if it is subject to little condensation or water ingress. However, if it becomes wet underside corrosion failure can be rapid, with severe symptoms occurring within typically 5 to 20 years. This seems to be the consequence of combined chemical and physical effects:

- the material is commonly made from acid timbers such as birch, Douglas Fir and some less well-known species, plus aggressive components such as formates in the glues
- the layered structure of the material, with vapour checks in the glue lines and generally poorer-quality and more porous timber in the middle lends itself to trapping moisture in the centre cores
- the trapping is exacerbated because the permeability of plywoods increases unusually quickly with moisture content, as illustrated in Figure 26. This means that in damp conditions plywood can take on large quantities of water, but if the surfaces of the plywood then dry out, water remaining in the core can be trapped, as we found at an educational building at Cambridge. BRE Scottish Laboratory are currently attempting to model this process
- any trapped moisture is then potentially available both to hydrolyse the core, releasing more aggressive chemicals, and also to move relatively quickly to the underside of the lead when the weather changes.

The flat-roofed extension of the conference/training room in a converted stables has lead on bitumen-cored building paper over a plywood deck, with glass fibre insulation underneath in the structural zone. The polythene vapour control layer beneath this is somewhat imperfect, owing to difficulties of making good seals to an inter-penetrating steel structure and at the perimeter. In a domestic situation the plywood would be at severe risk of condensation dampness. However, the occupation of the room is neither intensive nor dense, while its air-conditioning system provides good heating, ventilation and cooling when necessary but is not humidified. Consequently the internal moisture gains are relatively low.

Figure 27 shows one bay where the building paper was partly omitted. The pattern of light streaks and spots of corrosion is continuous across the edge of the building paper and so the lead may well have already been stained like this at the time of laying, or before. However, the background lead is darker in colour (and similar to fresh lead) above the building paper, while over the plywood there is a whiter haze. Corrosion on the outside of the roll may well be related to rainwater distillation from the splashlap, but the light corrosion at the inside of the roll

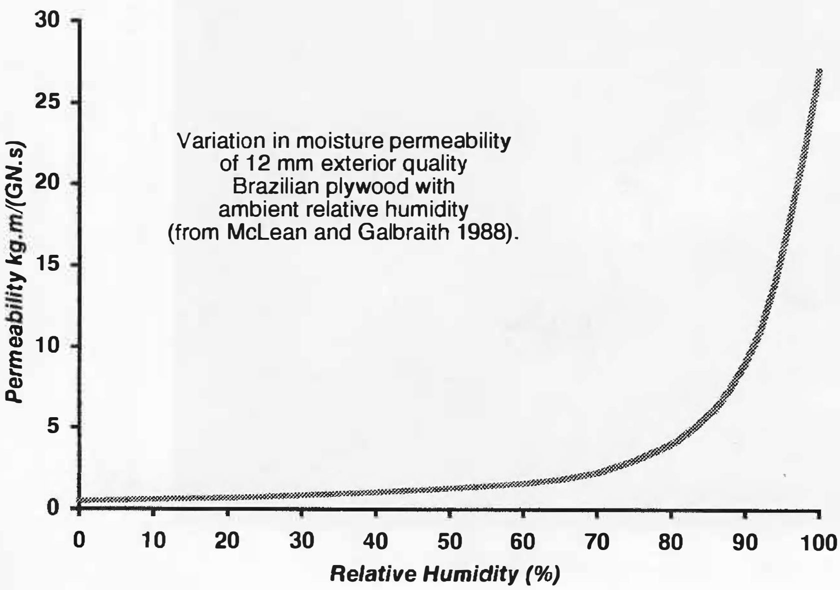

Figure 26. Graph illustrating relative humidity and permeability of plywood (McLean & Galbraith 1988).

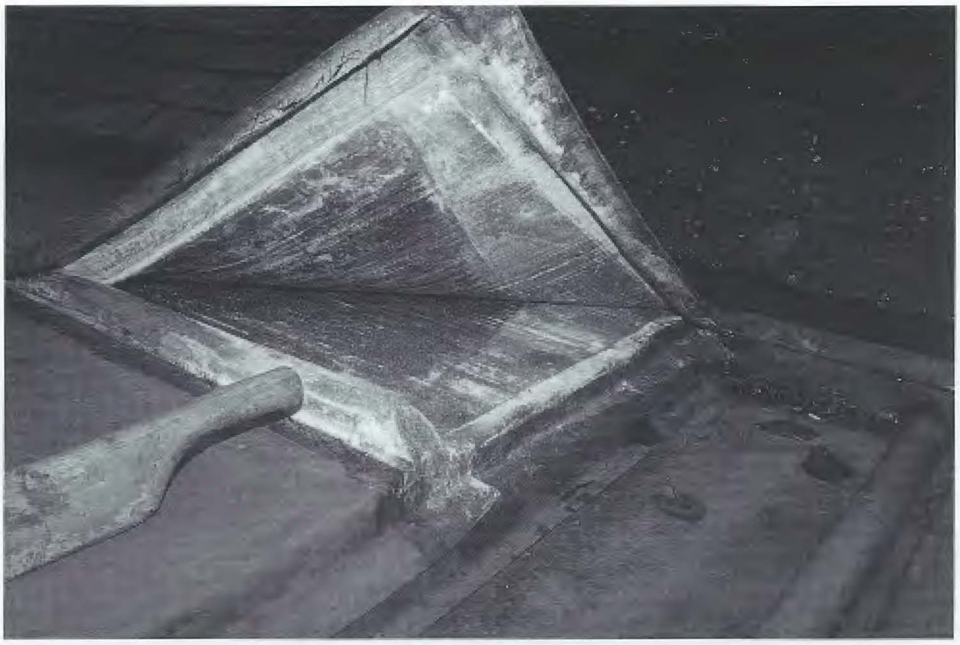

Figure 27. Lead over plywood at a converted stables.

could be acid in origin, as might that above the step (which incidentally looks rather low). Further investigation is planned.

Figure 28 shows the underside of lead laid over a plywood gutter sole, where it was first subject to condensation corrosion and later to some water ingress. While badly corroded over the plywood, on both sides of this, where the substrate was woodwool cement slab, the lead is passivated. Theoretical calculations suggested that the lead over the woodwool would be at more risk of condensation: while this was not physically evident, the architects for the remedial work reported that when removed it had lost some mechanical strength, a symptom of moisture-related deterioration. Owing to their open structure, these slabs may have carbonated rapidly and protected the lead by pH control and carbonate availability in the same way that chalk coatings have now been found to do.

Concluding points on corrosion patterns

This section has reviewed how different substrates and underlays can modify the effects of roof space environments and other variables upon the performance of the lead. Some key points are summarized in Table 2. Some characteristic patterns have been identified, including the fine line which often separates corrosion from passivation. Some things have been demonstrated unequivocally, such as the undesirability of acid substrates, including many wood-based panel products. Other things are highly equivocal: for example all underlays, and indeed ventilation itself, have both positive and negative effects which in practice often seem to be very finely balanced.

Figure 28. Lead over plywood in a gutter, with woodwool slabs to each side.

Table 2. Some physical influences on the underside corrosion of lead.

ITEM	POSITIVE EFFECTS	NEGATIVE EFFECTS	COMMENTS
ROOF SPACES			
1 Roof space ventilated to outside air	Can help to remove moist air and avoid condensation	May instead increase transfer of moist indoor air to outdoors via roof vents	May be of little or no net benefit if the roof space does not act as a theoretical cold roof and is poorly sealed to air and water vapour transfer from below
		Removes heat from the roof space and lowers its temperature	If there is still a high moisture flux from underneath, the roof may get little drier Near egress points, outlets and dead spots it can even be damper
	Conditions in the roof space are closer to those outdoors	Reduces hygrothermal stability of roof space	Hygrothermal buffering can enhance passivation, because the roof space becomes hotter and more humid (but not wet) when warmed by the sun
	Helps accumulated moisture to disperse when conditions allow	Introduces moisture with the outside air in dewy conditions	Hygrothermal buffering can also provide some protection against condensation in dewy conditions, with night-time dewpoints below ambient recorded on several sites
SUBSTRATES			
2 Underside of lead ventilated via air gaps	Introduces potentially passivating carbon dioxide	Carbon dioxide can enhance corrosion in some environments	Beneficial if condensation seldom occurs, particularly early in the life of the lead Once passivated, occasional later condensation may be tolerable
	Evaporates moisture quickly	Condensation is more rapid	Beneficial provided ventilation is 100% outside air; otherwise variable
		Faster evaporation/condensation cycles	Slight or occasional condensation may enhance passivation: heavier condensation may not Site location can be important
3 Lead laid on substrate of sheet material (no gaps)	Dry material helps to protect lead from condensation and corrosion	Wet sheet material promotes corrosion, particularly if acid, or becomes acid	Lead over sheet materials can perform well in relatively dry environments, but fails more rapidly in wetter ones, as effects of trapped moisture and acids combine
	Moist material may be passivating	But see above	Corroded and passivated areas are frequently found close together
UNDERLAYS			
4 Impervious underlays	Can protect lead from moisture and chemicals underneath	Can trap ingressed moisture and chemicals and partly exclude carbon dioxide	Can be very effective in relatively dry environments With water, vapour or acid present corrosion often severe, though sometimes localised
5 Highly air- and vapour-permeable fleece underlays	Introduces air and carbon dioxide and assists drying-out	Introduces more moisture in condensing conditions and lowers hygrothermal stability	More condensation; more evaporation/condensation cycles; and often more corrosion In marginal conditions corrosion is often worse if the underlay is non-absorbent
	Separates lead from potentially acid timber	Partly separates from buffering effect of timber, but acids may still diffuse across	Normally disadvantageous but can be useful reservoir for chalk powder, which not only enhances passivation but provides some hygroscopicity
6 Slightly permeable underlays (eg: plain building paper)	Provides buffer reservoir for overnight condensation	Not resistant to more sustained condensation and may occasionally rot	Useful to protect lead over well-ventilated and vapour sealed airspaces (efor example in ventilated warm roofs) against corrosion on dewy nights In some conditions, may also help to assist passivation
	Can disperse ingressed moisture	Reduces contact of air and carbon dioxide	On balance, seems beneficial in the circumstances described above
ROOF PITCH, ORIENTATION AND LOCATION			
7 Flat and low-pitched roofs	More consistently warmed by the sun, whatever the orientation	Get colder on clear, still nights, owing to radiation losses to night sky	As a rule more condensation, more retained moisture, more wet/dry cycling and more corrosion
		Roof spaces less easily ventilated	Moisture levels tend to be higher, generally or locally, increasing corrosion risk
		Any ponded water will cool the roof while it is evaporating	The outdoor test rig, with 100% outside air ventilation, showed corrosion under ponded areas, indicating how sensitive results can be to small variations
		Any corrosion product is vulnerable to damage by trampling	This can initiate spalling, open up cracks, and reveal fresh surface and traps for moisture, potentially increasing corrosion rates
8 Steeply-pitched roofs	Moisture can drain by gravity	This may sometimes be beneficial	Provided the water does not accumulate where it can do harm
	More likely to have roof spaces	Likely to be better ventilated or buffered	Normally beneficial
	Permits use of gap-boarding	Not good in humid environments	But can perform well in reasonably-ventilated and buffered ones
	South roofs may be drier	But may nevertheless be more corroded if the consequence is more wet/dry cycles	South roof performance tends to be the most variable
	North roofs may be damper	But not necessarily more corroded as there may well be fewer wet/dry cycles	Where acids are present, variations between different orientations often seem to be smaller (cycling may be less important than average conditions)
	Better air circulation in roof space	Sometimes moister near apex	Better buffering and more uniform conditions generally seem to be beneficial
9 Relative position	Lower roofs act as air inlets	Upper roofs act as outlets	Upper roofs are sometimes more corroded, but depends on heat distribution too
	Gutter area acts as air inlet	Upper areas act as outlets (but they are not necessarily more corroded as hot weather passivation can be greater too)	Gutters usually corrode less than one might expect, unless they trap moisture (e.g: running down from above) or are laid on acid timber or fresh concrete or lime Gutters may also suffer less because they are less exposed
LEAD DETAILING			
10 Splashlaps	Help reduce uplift and rainwater ingress in exposed positions	Trap rainwater (particularly at steps and near the bottoms of low-pitched sections) and inhibit drying of wet substrates	Promote thermal pumping and distillation at rolls & steps, particularly if tightly-dressed Corrosion may occur in the outer part of the roll May also inhibit drying of wet substrates, increasing corrosion on the inside of the roll

The illustrations have also shown the variability in patterns of corrosion at rolls, laps and steps. Some of this, particularly corrosion near splashlaps on low pitches, is related not to the internal environment or to substrate conditions but to the distillation of rainwater. Where distillation from splashlaps occurs, the corrosion on both the over- and under-cloaks usually matches and tends to occur in streaks or patches where the two sheets are sufficiently close together to trap condensate between them. Often the corrosion tends to be only cosmetic: where removed, it can re-establish itself quite rapidly but then settles down, perhaps because once the corrosion product forces the sheets apart distillate is less easily trapped. However, more such corrosion can occur near the roll-end nosings in low-pitched roofs, which sometimes need repair even where the rest of the roof is in good condition. In these positions the reservoir of water lasts for longer (particularly if there is a backfall), the water distilled into the nosing has nowhere else to go, and of course the nosings will often have already been thinned or otherwise weakened by bossing. However, on one site we have recently found more extensive splashlap corrosion, for reasons which are not yet clear.

Where moist air emerges from the buildings through gaps in boards, characteristic 'fish tails' are often seen, rising into the rolls. In new roofs, these are more often corroded: in older roofs areas of passivation are also found, though quite frequently with corrosion above the boards themselves.[28] Site investigations and RTL's test rigs also indicate that such different behaviour can be triggered by very small changes in environmental conditions. With the more permeable underlays (such as geotextiles) corroded fish-tailing increases, probably because with less resistance to the passage of air through the gaps between the boards, more condensation can occur under adverse conditions.

However, the heaviest corrosion in roll, lap and step positions is usually found where the lead is laid over sheet materials and over acid substrates such as oak and plywood. Here corrosion is often greatest at the perimeter, probably because trapped moisture, often by this stage containing acetates etc, will distill repeatedly before it finally emerges, in an atmosphere in which acetic acid can be regenerated rapidly. Acid-induced underside lead corrosion also tends to be worst where there are splashlaps, which will tend to inhibit the release of moisture, and sometimes provide some water vapour inputs of their own.

5 Influences of moisture levels

Moisture, particularly condensed and trapped moisture containing organic acids, is the principal agent in the corrosion of lead. The previous section has shown how sensitive lead can be to even small additional amounts of moisture, for example

- at the gaps between the decking boards
- in the parts of a well-ventilated 'cold' roof in which the lead surface is sometimes slightly cooler owing to evaporative cooling from puddles above
- in sections of a ventilated warm roof which are not fully through-ventilated or in which there are small imperfections in the vapour control layer under the insulation
- with a change in underlay.

On the other hand, one can also find lead in good condition and well-passivated in some situations which are manifestly damp.

This section outlines some mechanisms of evaporation, condensation and buffering which may affect the state of the lead and the underlying substrate, and how they may differ in different buildings with different construction, different levels of heating, ventilation and moisture generation, and at different times of the year. This work is not complete: more analysis is needed of the temperature and relative humidity data collected. There is limited availability of theoretical techniques which can describe the situations of interest, and little available information which could be used to calibrate them. Further investigation and analysis is strongly recommended.

The external environment

Figure 29 is a psychrometric chart of water vapour pressure versus air temperature. The darker line at the top, marked 100% RH, is the saturation curve, showing the maximum vapour pressure that can be sustained in air at the appropriate temperature: air can contain no more moisture than this (unless in a fog of dispersed droplets). The family of curves 80%, 60%, 40% and 20% RH shows a series of relative humidity levels, where the moisture content of the air is the given percentage of the saturation value. Figure 29 also includes the average vapour pressure and temperature for each of the 52 weeks of a typical year, using the most representative months from Kew Meteorological Office data for 1959–68 compiled by the Polytechnic of Central London (Loxsom 1986). In examining Figure 29, the following points are of interest:

- in general, the warmer the weather, the higher the vapour pressure, so air in the summer typically contains a lot more moisture by weight than in the winter. At a typical winter time vapour pressure of 650 Pascals (Pa) [29], air contains about 0.4% by weight of water, in summer 1300 Pa, twice this much
- in spite of this, in the warmer months the RH is lower because the air's moisture content is a relatively smaller proportion of the saturation value
- hence, in sheltered outdoor conditions, materials tend to be drier in summer. For example, using Curve B in Figure 5, timber in equilibrium with air at typical summer RH of 65% would reach a moisture content of about 13% and in winter at 85% RH, about 17%. However, it can take a long time for equilibrium to be reached, particularly for large, dense timbers in poorly-ventilated spaces. On the other hand, summer heating by the sun can cause extra drying, with structural timbers in warm roof spaces falling to perhaps 10–12%, and boards immediately under the lead to

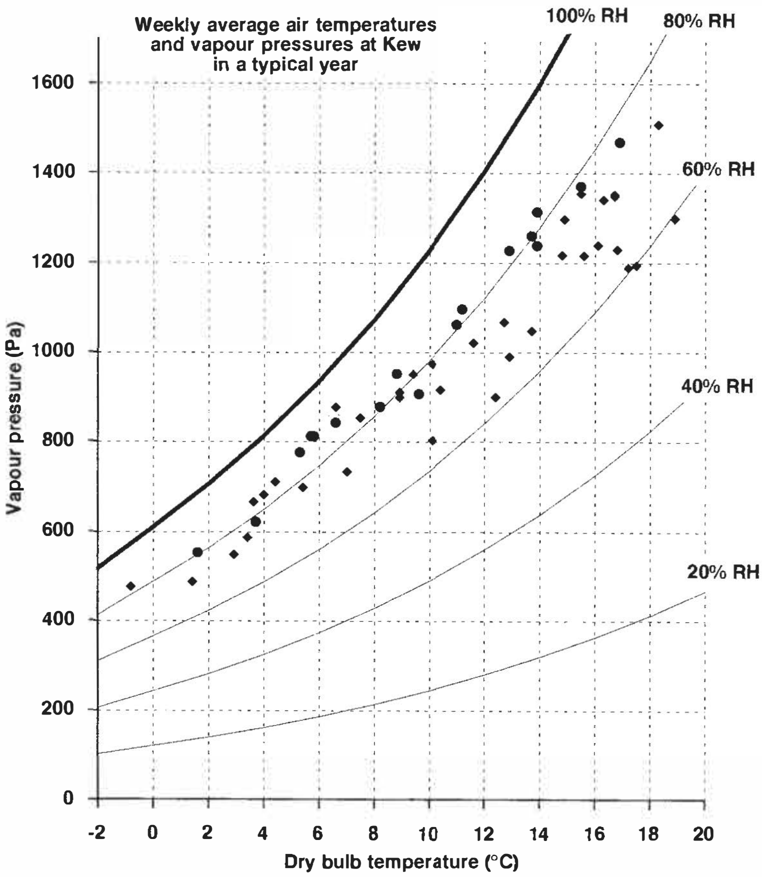

Figure 29. Psychrometric chart showing weekly average outdoor temperatures and vapour pressures. The points marked as diamonds show conditions in the months January to August while the solid circles show those from September to December, when the relative humidities tend to be higher, as is the likelihood of condensation arising from fluctuations in external temperatures and from further cooling of the roof by radiation heat losses on still, clear nights.

around 8%. In winter, some timbers can get damper, as discussed further below.

The points for each week are shown as diamonds for the months January to August and as dots for September to December: the four months in which RHs tend to be at the high end of the range. The high RHs in autumn arise essentially because the ocean has warmed up during the summer and stays relatively warm into the early part of the winter, humidifying the air which is carried over the country by the prevailing south-west winds. In this season, condensation arising from fluctuations in ambient temperature and from radiant heat losses from roofs on clear, still nights tends to be the most common: fresh, unpatinated lead can be particularly vulnerable to corrosion then.

The indoor environment

On average, and particularly during the heating season, the indoor environment will tend to have both a higher temperature and a higher vapour pressure than that outside. Even where there is no explicit heating, trapping of solar heat and heat from occupancy, lights and equipment tends to raise the internal temperature. Moisture is also added by the metabolism of occupants and often plants, by activities and equipment, in particular cooking, washing and bathing, and by evaporation from the building itself, for example from any rising or penetrating damp. Heating itself may also humidify the air through three main mechanisms:

- by warming up the fabric the rate of evaporation is increased. While in a dry building this moisture will eventually leave, if there are semi-infinite sources of moisture (for example from the ground outside), it may be continuously replaced
- if the building is heated intermittently, moisture will be given off by the fabric and contents into the air as it warms, giving additional transient humidification
- flueless gas and oil heaters also humidify the space directly by emitting their products of combustion, which include a lot of water vapour, directly into it.

Figure 30 shows a section of the psychrometric chart, with points plotted on it for the typical test situation as used in BS 5250:1989, the British Standard Code of Practice for the control of condensation in buildings for 'dry/moist' occupancy (British Standards Institution 1989). The RH curves here are plotted at 10% intervals. The outside air is at a typical wintertime state of 5°C 95% RH (in Figure 29 temperatures below 5°C occurred for nine weeks) and the inside air averages 15°C 65% RH.

If the outside air is cooled somewhat, its condition travels to the left along the horizontal arrow until it hits the saturation curve at its dewpoint of 4.25°C (see drop arrow). Any exposed surface any colder than this will attract condensation even from the ambient air: this can happen on clear nights (and indeed on bright winter mornings for lead not directly in the sun) when the lead loses heat by radiation to the clear sky. On clear nights, the lead can fall 5°C or more below outside air temperature, particularly for flat roofs, over a cold building or a well-insulated roof void, and in still conditions where the lead picks up less heat from the outside air.

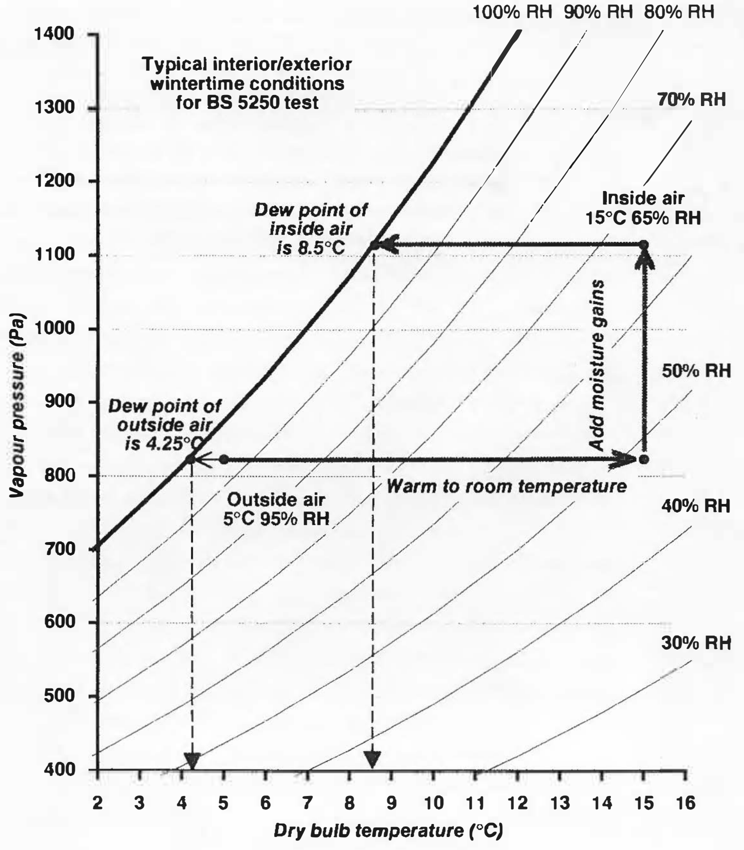

Figure 30. Psychrometric chart showing BS 5250 test conditions. External conditions are 5°C 95% RH (dewpoint 4.25°C). Internal conditions for 'dry/moist' occupancy are 15°C 65% RH (dewpoint 8.5°C), a vapour pressure gain of 285 Pa.

If outside air coming into the building is warmed to 15°C, its condition travels to the right along the horizontal shaded arrow, maintaining the same moisture content and vapour pressure but reducing in RH because the saturated vapour pressure of the warmer air is higher. In this example the RH falls to 48%. However, moisture gains within the building add to the vapour pressure, increasing it by some 300 Pa in this example, and raising the RH to the 65% test condition. The actual amount of water vapour pressure gain in practice will depend upon:

- the rate of evaporation of moisture into the air by the mechanisms outlined above
- the ventilation rate of the building, in the course of which more moist inside air is displaced by drier outside air (in terms of percentage by weight)
- (to a lesser extent) diffusion of moisture through the fabric of the building.

With high rates of ventilation or low moisture gains, the inside air will be drier, with low ventilation rates and high moisture gains it will be damper.

Dampness levels in a building, and in different parts of it, can vary greatly with heating, ventilation and construction. For example:

- with generous heating and ventilation, the horizontal displacement to lower RHs is much greater than the vertical displacement by added moisture, leading to a drying effect. For example, at 15°C 48% RH caused by the heated and unhumidified outdoor air in Figure 31, the equilibrium timber moisture content would be about 10%, and if the air were further heated to living-room temperatures of 20°C the RH would be in the low 30s and timber moisture content 8%. Again, these are limiting values subject to time lags (frequently measured in weeks or months) as conditions change
- with generous heating but with poor ventilation, moisture may build up internally, as in the example in Figure 31. If this moist air then rises into the roof space, it may then cool, say to a temperature of 10°C, and if not diluted by outside air its RH would approach 90%, when the equilibrium timber moisture content would be nearly 20%. With a dewpoint of 8.5°C, condensation is also likely under the lead
- with poor heating and ventilation, the atmosphere will be cold and damp, particularly if structural dampness adds additional moisture. With occasional heating, as in churches, the pulse of heat evaporates some of this moisture and raises the dewpoint further.

For a given amount of heat and moisture input, there is an optimum amount of ventilation to minimize RH. As the ventilation rate increases from zero, the RH first drops sharply as moist air is displaced from the building or roof space. However, with too high a ventilation rate the heat is removed too rapidly, the temperature falls and the RH rises again: to reduce RH further either requires more heat, less moisture input or moisture removal at source. In domestic circumstances, optimum ventilation rates tend to be between 0.5 and 1 air changes per hour: beyond this additional ventilation is usually counter-productive because the additional heating required is seldom regarded as necessary or affordable.

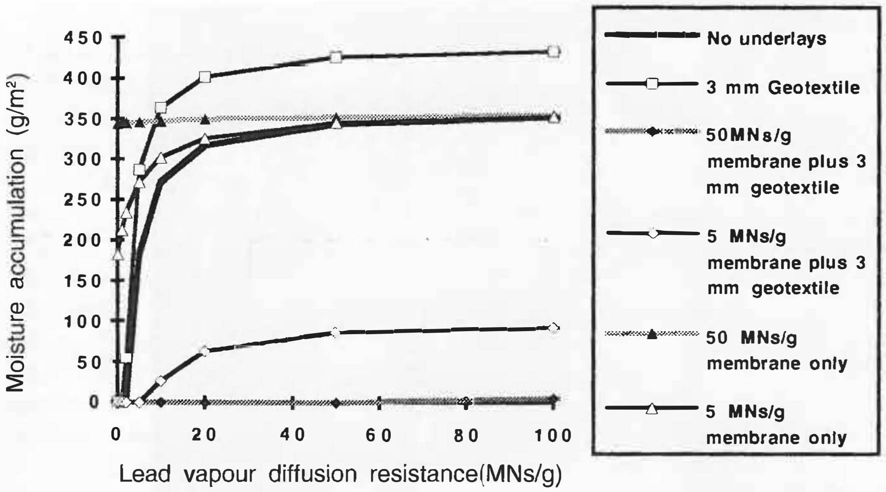

Figure 31. BS 5250 calculations for a variety of lead/underlay combinations. The six traces show the calculated accumulation of moisture in grams/square metre over a 60-day period averaging 15°C 65% RH inside and 5°C 95% RH outside, which is deemed characteristic of the build-up in a typical winter. The vapour resistance of the lead is varied to account for water vapour escape through rolls and laps.

Condensation risk

Condensation may occur on the surface of a material (as with dewdrops on the outside or the inside of a lead roof), or within constructions which remain superficially dry but inside which interstitial moisture accumulates.

Most conventional condensation calculations consider diffusion of water vapour in one dimension through homogeneous materials with constant levels of resistance to the passage of heat and water vapour, and under steady-state conditions of fixed internal and external temperatures, RHs and exposure levels. The BS 5250 calculation (*op cit*) works as follows:

- the types and thicknesses of the various layers of materials are determined.
- material properties are obtained from the tables in the BS, or from suitable references
- the thermal and water vapour diffusion resistance of each layer is calculated
- the temperatures and dewpoints at each interface between materials are determined
- if condensation planes are identified, then the rate of moisture diffusion to that plane is calculated by dividing the vapour pressure difference by the vapour resistance between the source of moisture and the condensing plane
- the moisture build-up in grams per square metre is assessed, over a 60-day period.

For lead roofs these calculations have many shortcomings:

- they consider moisture transfer by diffusion only, while air movement is important for lead, which is often laid upon discontinuous boarding, with permeable underlays and with opportunities for ventilation at the perimeter joints of each sheet
- they do not take account of dynamic wetting/drying effects with changing internal and external conditions, including sunshine and clear skies
- they do not take account of the ways in which properties of materials vary with moisture content, normally becoming more permeable the damper they are

Nevertheless, they are very helpful in giving an initial 'feel' for the important variables.

A series of of BS 5250 calculations have been undertaken using BRE's computer program BRECON II under the standard conditions (outside 5°C 95% RH, inside 15°C 65% RH) for Code 7 lead on 25 mm softwood boarding, assumed to be a homogeneous material with no air gaps between the boards. The underlay specifications are as follows:

1 no underlay
2 3 mm geotextile
3 a reasonable vapour control membrane of water vapour diffusion resistance 50 MNs/g (MegaNewton seconds per gram), equivalent to about ten metres of still air
4 a poor vapour control membrane of water vapour diffusion resistance 5 MNs/g
5 as 3 with 3 mm geotextile between it and the lead
6 as 4 with 3 mm geotextile between it and the lead.

While lead itself is impermeable to the passage of water vapour, moisture will escape through the joints between the sheets. To illustrate the influence of this, the lead was given a range of water vapour diffusion resistance values from 0 to 1000 MNs/g.

Figure 31 shows the results of the calculations for a sheltered exposure. For all combinations, once the lead's diffusion resistance rises over 20 to 50 MNs/g (probably a reasonable average value in practice) there is little increase in the total amount of condensation over a 60-day period:

- the geotextile alone shows the most condensation because it offers little water vapour resistance but its insulating properties lower the temperature of the lead
- at high lead vapour resistances, the lead alone and the three membranes show similar amounts of condensation. At low lead resistances, condensation under the membranes is higher owing to their relatively lower permeability. Note that in these examples the condensation is under the membranes. While potentially this may protect the lead it could be dangerous for the membranes and for the underlying timbers
- the geotextiles over the membranes perform best, particularly with the more resistant membrane. How-

ever, this result has not been supported in site tests where ingressed and trapped moisture was troublesome in what amounts to a miniature 'warm' roof.

Figure 32 shows the effect of changing the indoor RH on moisture build-up and on BRECON II's calculated moisture content of the substrate boarding, again at 5°C outside and 15°C inside:

- at 15°C 50% RH the dewpoint is 4.8°C, and so there is no condensation
- as the RH rises, so does the timber moisture content and the amount of water accumulation below the lead
- the flattening-off at 85% arises because by this stage condensation is taking place not only below the lead but also under the timber decking: a similar situation occurs at a damp church in the Yorkshire Dales, after a cold, clear autumn night, and particularly under the colder tips of the copper fixing nails.

Although any moisture accumulation under the lead can be troublesome as far as corrosion is concerned, initially it will not appear as free water but will be absorbed by the wood. 25 mm thick substrate boarding with a specific gravity of 0.5 will weigh 12 kg/m^2. If its moisture content by weight were to increase from 10% to 20% from summer to winter, in principle it could absorb all the predicted condensate without entering the dangerous levels of over 20% moisture content. In fact, the situation is not this benign, because:

- moisture will be absorbed from the ambient air without condensation in any event
- moisture can get directly to the lead via the gaps between the boards. In completely still air, the amount transferred by diffusion is relatively small: water vapour only diffuses through still air about ten times as fast as through softwood; so if there are 3 mm wide gaps in 150 mm wide boards, the additional moisture accumulation under the lead would only be about 20%
- however, a much greater amount of moisture will normally get through by movement of moist air between the boards and out of the building via the rolls, accounting for the fish-tailing discussed in *Patterns of corrosion* above.

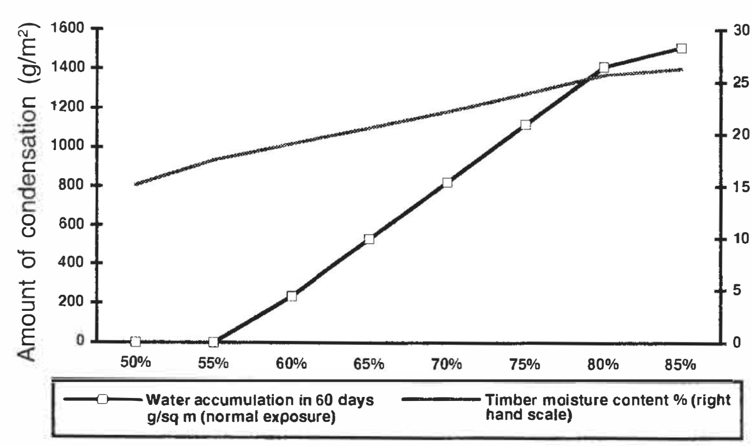

Figure 32. Amount of condensation over 60 days as a function of interior RH. At 50% RH the dewpoint of the indoor air is below 5°C and there is no condensation. The levelling off over 80% occurs because surface condensation also takes place under the boards: the calculated amount at 85% (1500 grams) is very similar to that taking place under the lead.

Dynamic modelling of moisture movement

The passage of moisture across the grain of wood can be a slow process; along the grain it can be a hundred times faster. Conversely, saturated wood takes a long time to dry out. In order to obtain a better idea of the importance of buffering by the substrate timbers, EH commissioned BRE Scottish Laboratory to undertake some test runs with the MATCH computer model. Like the BS 5250 method, this is also one-dimensional, diffusion-only. However, it models moisture movement through the timber more accurately by using different isotherms for adsorbtion and desorption and by having variable water vapour permeability. It also takes account of external climate changes: both air temperature and solar radiation on a time step basis, typically hour by hour.

Unfortunately, MATCH does not simulate indoor and roof space conditions. For the runs undertaken to date, a range of constant temperature and pressure rises above external ambient were assumed, typically 4°C and between 50 and 200 Pa (but restricted to a maximum roof space RH of 100%): above 200 Pa the lead was too damp for too long. At present the model does not take account of time lags between the interior and exterior environment or of the buffering and self-humidification and dehumidification processes which have been observed in roof spaces and discussed in *Roofs and roof space environments* above. It also does not simulate the drying of roof spaces by the sun in summer, although the effect of solar heating of the lead and the substrate boarding is included. It also does not appear to model accurately the effect of self-humidification when the sun shines upon the lead. Future modelling plans aims to improve these aspects by calibrating the model with roof space environment data from monitored sites.

The initial investigations looked at the variations in moisture movement for lead laid directly over oak, pine and plywood deckings, both for flat roofs and for pitched roofs inclined to the four points of the compass, and with different starting moisture levels in the boarding: 10% to represent dry timbers and 30% for wet timbers. The simulations ran for two years, starting either on 30 June (which from site tests appeared to be a good time to complete a lead roof) and 30 September (a bad time as it would rapidly encounter the autumn dews).

The most significant results were for the boards which started dry at 10% moisture content (M/C) on 30

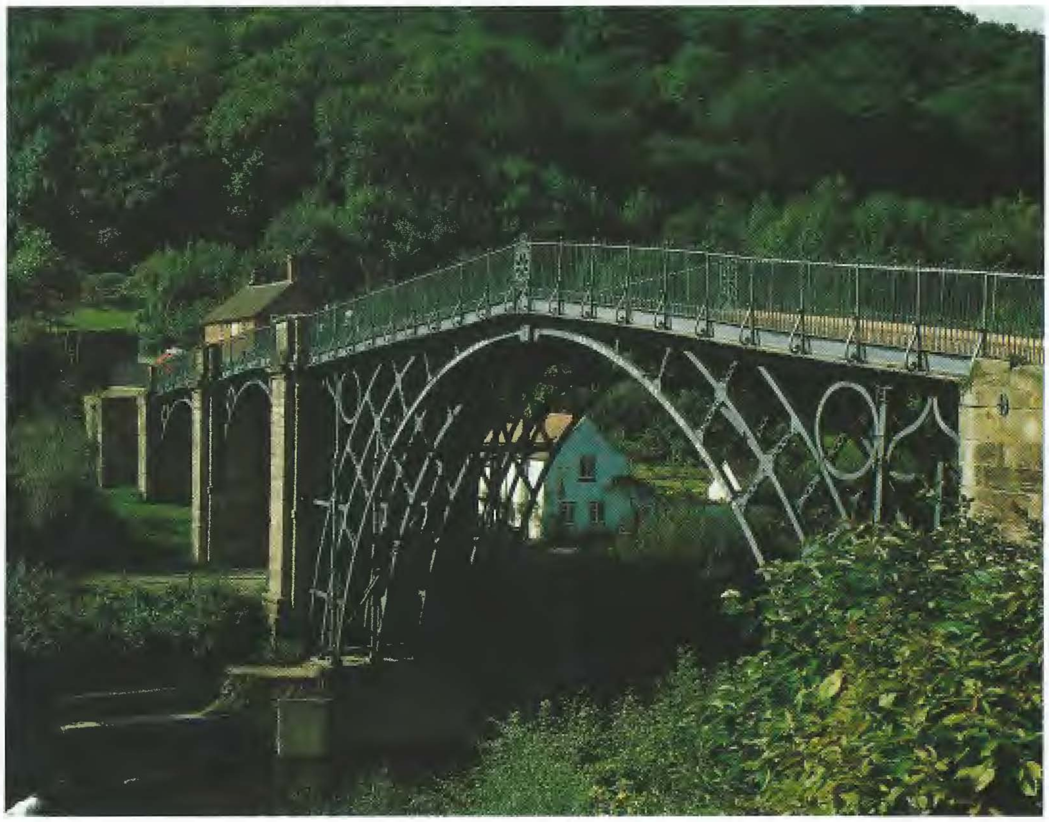

Plate 1. Abraham Darby's Iron Bridge at Coalbrookdale (1777–81) is a notable early example of the structural use of cast iron. From such precedents, cast iron warehouses, mills and factories were developed, many designed to be of fire proof construction.

Plate 2. Corrosion above softwood boarding. White and yellowish (States 1 and 2) corrosion product on the nave roof of a Buckinghamshire church, with dark passivation above the gaps between the boards. The photograph was taken after a cold, clear night, and the roof was particularly damp at the time. Note also the passivation over the rolls (with the odd spot of corrosion). The ridge is passivated on the far (right) side, probably by rainwater, which also seems to flow over the ridge from time to time (the lap is mean). Not surprisingly, there are signs of corrosion here, probably the result of a combination of condensation and refluxing of rainwater. In spite of this, and of the church being particularly damp (RTL 1993, Report 6, Appendix D), the corrosion is not yet serious. See also Figure 6, p 38.

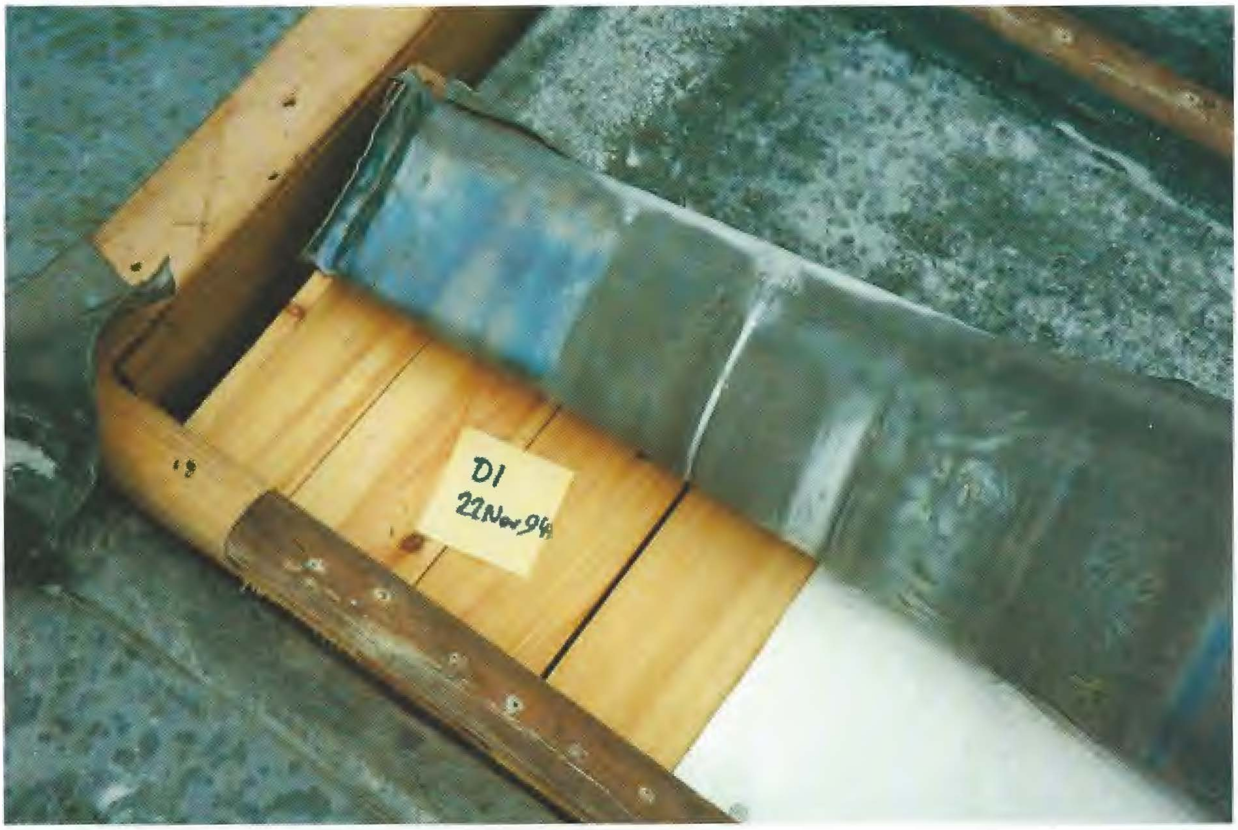

Plate 3. Lead after a two-month autumn test at Donnington Castle showing a wide range of surface states from passivation to corrosion. The two (untreated) boards on the left have kept the lead dry and its underside is only slightly dulled. The two to their right were preservative-treated and probably initially damper. This has assisted passivation over much of the boards, but corrosion around the perimeter. See also Figure 7, p 39.

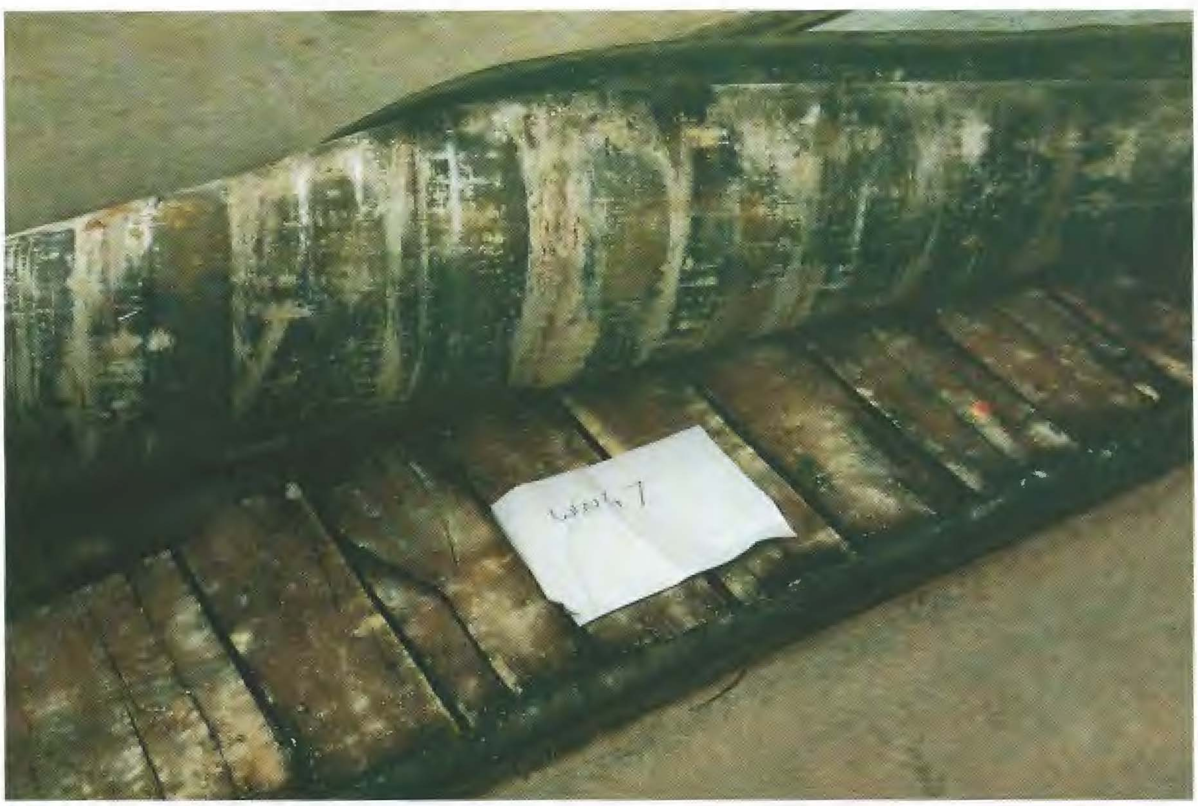

Plate 4. A church in Buckinghamshire: corrosion patterns on a slipped panel on the south aisle. See also Figure 8, p 39.

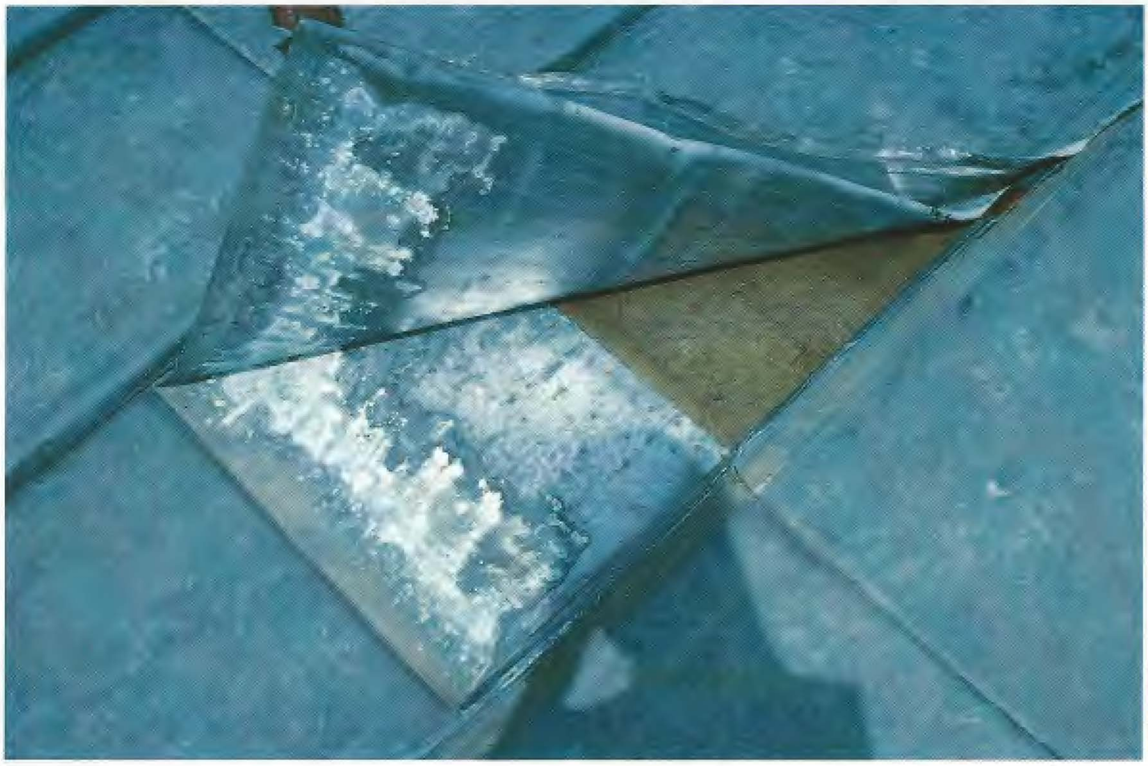

Plate 5. Lead over building paper on softwood on a relatively dry building. The lead is bright or only slightly dulled, though with a white haze between the boards. The pattern in the lap is not unusual: at the bottom a weathered area indicating capillary rise of rainwater, some corrosion (with a fringe of dark passivation) above that (where the rainwater distils) and the lead above that unaffected. The hollow rolls are free from corrosion. See also Figure 11, p 41.

Plate 6. Underside of lead over Erskine's felt at a mansion in Dorset. The lead over the underlying boards above the public rooms is lightly and fairly uniformly corroded. Above the gaps there is a tendency to passivation. This corrosion is no longer active. Note also the corrosion in the roll above the splashlap caused by distillation of trapped rainwater: this recurs on a freshly wire-brushed surface. See also Figure 12, p 42.

Plate 7. Underside of lead over Erskine's felt in a damper location at the Dorset mansion. The lead above the gaps is somewhat corroded, particularly towards the rolls in which there is also some corrosion. Note also the corrosion in the rolls above the splashlaps, as in Figure 12. The splashlap corrosion pattern varies with the distance apart of the sheets. Water is also trapped in the splashlap here by a slight backfall below the nosing. See also Figure 13, p 42.

*Plate 8. The original roof at the mansion in Buckinghamshire. Most of the roof was laid over Erskine's felt and was passivated between and corroded above the boards (the opposite of the current pattern). A few sheets, which did not have the felt, showed a similar pattern but with worse corrosion over the boards, probably because any moisture accumulating within this region would be trapped for longer than over the more permeable felt, and possibly there might have been some acidity. The longitudinal stripe was made by wire-brushing for tests and is not part of the original pattern.*See also Figure 17, p 43.

*Plate 9. Norwich Cathedral cloisters, showing lead distress and repairs. The pattern here is characteristic of acid attack, with not only weakening along the gaps between the boards, but also failure at the perimeter, at rolls and laps.*See also Figure 18, p 44.

Plate 10. Underside corrosion over oak at Norwich Cathedral cloisters. The patch removed, on the left, failed at the perforation in the middle. The characteristic red/brown oxide can be seen near the interface with the metal, with the thick, flaky and granular corrosion product remaining underneath (on the right). See also Figure 19, p 44.

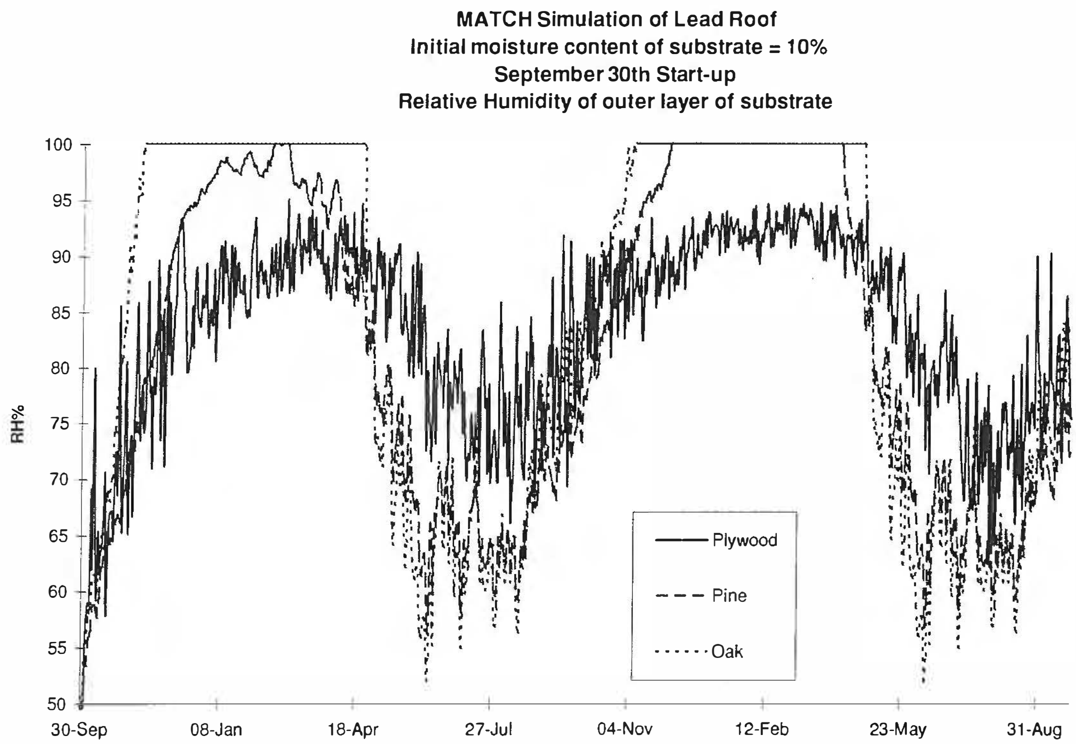

Figure 33. MATCH modelling of moisture content at lead/substrate interface.

September. Figure 33 shows plots of daily readings for a flat roof for two years, expressed in terms of RH at the outer layer of the substrate, immediately under the lead. The x-axis is the day number, starting on 30 September and running to 29 September two years later. With a 200 Pa/4°C vapour pressure/temperature gain, the lead/oak interface becomes saturated after some 40 days, while the pine gathers moisture more slowly with only a brief period of potential condensation after about 140 days, and the plywood never reaches saturation. Results for a north-facing roof were similar. For a south-facing roof starting at 10% M/C, for the roof completed on 30 September there was no condensation at all during the first winter and very little for one completed on 30 June.

In the second year, however, the pine never dries out to 10% over the summer and the interface becomes moist around Christmas and stays there until Easter. In practice, however, it seems that the model underestimates drying-out in summer: the 200 Pa vapour pressure gain is usually too high then because buildings are better-ventilated and drying in sunshine may not be adequately simulated. Certainly site measurements of the moisture contents of substrate boarding in September often show them to be in the region of 10%, and after a dry summer (as in 1995) sometimes considerably less.

The differences between pine and oak concur with findings on site, where in the first quarter of the year we have found visible water under lead over oak boarding and little or none over pine in the same building. Such differences in hygroscopic performance also help to explain the passivated stripe over the softwood fillet at Donnington Castle (see Figure 23). This is a consequence of oak having a higher water vapour permeability than pine when dry and a very much higher one when wet, so allowing moisture to accumulate faster in the hardboard above.

For plywood, however, it is not easy to relate the simulation data to site experience. Although we have found that over relatively dry buildings lead on plywood can perform well, in damper situations severe hygroscopic problems can occur, leading to the chemical problems discussed above. However, inspection of the source data showed that the MATCH database for plywood had only a 4:1 difference in permeability between wet and dry, while in the tests shown in Figure 25 the range was ten times greater! The plywood was also simulated as a homogeneous material: different results would be obtained by modelling it as porous timber separated by less pervious glue lines. In addition, a lot depends on the source and batch of the plywood. Further studies are recommended.

In a second batch of studies, BRE looked at the number and duration of wetting/drying events for an oak roof, starting with a 30% moisture content on 30 June, for vapour pressure differences (overpressures) between 50 and 200 Pa. The statistics shown in Table 3 are interesting.

Essentially, for overpressures between 50 and 150 Pa the number of annual condensation events is similar at about 30: what changes is their duration. Little significance should be read into the precise numbers, which fluctuate rapidly with small changes in overpressure, as events separate or merge. At 50 Pa there is a rapid succession of very short events, typically in late December. Above this overpressure the average duration ceases

Table 3. Results from dynamic modelling.

OVERPRESSURE (pascals)	50	100	150	200
Percentage of year condensation is present	1.4	14.3	26.5	47.3
Number of events per year	32	37	25	10
Average hourly duration of wetness period	4	34	126	415

to be very meaningful owing to a long period of winter wetness with most of the events taking place in the autumn (as the roof moves into wetness) and in the spring (when it moves out again). For example at 100 Pa, there are six cycles in late November, as the roof begins to get wet, none during December or early January, a rapid succession of 25 cycles over a fortnight in late January and the final few in late February. At 200 Pa the events associated with wetting occur in late October, with drying-out events not until April.

Although only preliminary work was done, and with some reservations about the results, the MATCH modelling does support the evidence from sites that differences in the material properties of the substrate timbers can have major effects on wetting, drying and corrosion/passivation processes immediately under the lead. In addition, in particular for the pine, the time of laying, the initial moisture content and summer drying-out processes can significantly influence the dampness under the lead in the autumn, and perhaps for the whole of the subsequent winter. Where pine starts dry or has been dried out in the summer, a slow transition from dry to wet may also allow passivation to occur during the intervening moist, non-condensing conditions. More detailed investigation is about to start, including some full-scale laboratory tests.

The wetting/drying events analysis is also of interest. RTL's work suggests that in a neutral environment with little organic acid, passivated lead surfaces can withstand some 50 or more cycles events before they begin to break down. If the preliminary MATCH results are substantiated, then there may seldom be this many cycles in a year. If therefore:

- the lead is passivated initially
- the substrate material has suitable hygroscopic and chemical properties
- the substrate material starts out dry
- the environment allows passive films to repair themselves when conditions change

the prospect of lead being able to resist some wintertime condensation is offered. This supports the evidence from a number of sites.

Conclusions

This section has only scratched the surface of the problem but offers some interesting avenues for future investigations and analysis. It confirms the importance of the substrate material and its initial condition and suggests possible methods of minimizing the underside corrosion risk to lead in situations where condensation may occur from time to time. However, one must remember to protect not only the lead but the building as a whole. At present it seems unlikely that the right combination of substrates, underlays, chemical treatments and conditions at the time of laying would be able to provide suitable protection from winter-time over-pressures much in excess of 150–200 Pa. Beyond this, explicit attention to heating, ventilation, moisture removal or roof construction may well be necessary.

Promising future work would include:

- further modelling of hygrothermal properties of the lead/underlay/substrate system
- detailed consideration of the different relationships between indoor and roof space environments, for the four different roof types
- modelling of hygrothermal buffering in roof spaces and the benefits or otherwise of outside air ventilation
- more timber moisture measurements, if possible including continuous recording of seasonal changes
- review of the adsorption/desorption, water vapour transmission and acidity characteristics of a variety of timber products, both theoretically and in the laboratory, to identify which are most appropriate as substrates
- analysis and interpretation of RTL's monitored temperature/RH data, in particular to understand typical overpressures
- theoretical and laboratory review of the beneficial and adverse effects of different boarding types, gap sizes and underlays on condensation, corrosion and passivation
- further review of suitable underlays.

6 Discussion

The sections above have outlined some aspects of the chemistry of lead, roof construction, heat, air and moisture movement in roof spaces, and site evidence of underside corrosion. All of them reveal a capricious system, with a high variability which often depends upon small differences between larger, and often unknown quantities.

Underside corrosion in context

Underside corrosion is nothing new. It has been known for centuries to be a contributor to the decay processes which cause lead roofs to need replacing from time to time. Although some lead roofs last 80–200 years, and occasionally even more, records for some churches visited suggest that on occasions only 40 years or so passed between major re-leadings: so some problems they have now may well have occurred in the past too. [30] Since we are examining them more now, we are also more alert to early underside corrosion (some of which is only cosmetic) and to incipient failures which would previously have gone un-noticed.

Lead is durable, but not infinitely so, a feature it shares with nearly everything else. But in these days where many things claim to be maintenance-free (although in practice this may mean 'impossible to maintain', we may be expecting more of lead than we did. While lead lasts longer than many alternatives, its properties need to be respected, just as glass, a much more fragile material, can give a long and largely maintenance-free life if properly specified, handled, installed and used.

While condensed water is enough to cause underside corrosion, where the lead has actually failed rapidly, aggressive chemicals have nearly always been involved. Many timbers, and the vapours from them, can harm lead, particularly if they get wet. Today this may be exacerbated by preservative treatments (if only through increasing the timber's initial moisture content), by kiln-drying, and by a wider range of timber sources. In historic buildings the most common offender is oak, whose aggressive effects have been known for millennia. Nevertheless, this sometimes seems to be tacitly ignored, occasionally for new oak and more often for old, on the assumption that it will have lost its aggressiveness. This is not necessarily so, particularly where conditions have become moister. The studies to date also indicate that barrier layers intended to separate lead from such timbers are seldom totally effective, and that the potential aggressiveness of modern wood-based sheet materials is not always realised.

Is underside lead corrosion getting worse?

Over the past 50 years or so, changes in the heating, ventilation, occupancy and insulation of buildings have tended to make roof spaces damper, and the 1939–1945 war no doubt helped through shortages and neglected repair and maintenance. However, the study has shown that the relationship between these environmental changes and increased corrosion is not as direct, or as reversible, as was thought. [31] While there is good reason to think that the number of failures, and not just the awareness of them, did increase during the 1970s and early 1980s, these seem to have been as much due to new substrate materials and details as to altered environments, though increased dampness has certainly not helped. However, actions already taken have brought some of the problems under more control.

Ten years ago it became known that the 'warm' roof principles widely applied to roofs with continuous membranes did not suit continuously-supported metal roofs. The main reason is that moisture entering from any source becomes trapped. This trapped and refluxing moisture, which also tends to pick up organic acids and other chemicals, can affect many metals but is particularly aggressive to lead. It is now widely known that this form of roof construction should not be used for lead, and so this source of severe underside lead corrosion will be progressively eliminated.

While the physics of thermal pumping can affect any roof, the use of splashlap details on 'warm' lead roofs, and particularly low-pitched ones, made them particularly susceptible to sucking in rainwater. Rainwater can both cool the roof rapidly, causing the trapped air to contract, and also seal the splashlaps by capillary attraction, closing air paths via the joints which would otherwise have provided pressure relief. The ventilated warm roof now recommended avoids this problem.

Another cause of early underside corrosion failure was the use of has been deckings of wood-based panel products such as plywood. Their raw materials are often more acid than the traditional softwood and resins, glues and processing can make them more acid still. While they can perform well in dry environments, in damper ones failures may be much more rapid. Their physical properties may also increase the incidence of moist, corrosive conditions at the lead/substrate interface. For a while these materials were also used in composites under very thin lead, and these were subject to corrosion, thermal fatigue and combinations of the two. Although these composites are no longer sold, and in historic buildings there has been a trend back to softwood boarding, manufactured boards may still sometimes be used in inappropriate circumstances.

By avoiding 'warm' roof construction, and using ventilated warm roofs where appropriate, the circumstances that led to the most severe corrosion failures (apart from those in very humid and/or aggressive environments such as swimming pools and some industrial processes) are being eliminated. However, the classic problems in historic buildings still remain, sometimes exacerbated by damper environments under the roof. The research has also found that ventilated warm roofs and well-ventilated roof spaces are not always immune from some underside corrosion.

Improving the situation

Laboratory, field and theoretical studies have all shown that the state of the lead's surface when it first encounters moisture can have a major influence on its long-term corrosion behaviour, particularly in marginal circumstances. Contact of fresh, clean lead with rain, condensation or a damp substrate must be avoided and the early formation of a protective film should be encouraged. In the past, some protection may have been provided by one or more of:

- leaving the lead lying around for some time (not tightly-rolled) before fixing. However, this gives only limited protection. Slight protection may also be offered to the rough side of cast lead by being steamed on the sand bed
- applying linseed oil to the lead either deliberately (by wiping) or incidentally (as a lubricant in the rolling-mill)
- laying the lead on a relatively dry substrate at an appropriate time of the year, preferably between May and July. In the past plumbers would have tried to re-roof when the weather was better, now with project approval often tied to financial years, contractors report that this can be their slackest time for lead roofing work.

In the laboratory the simplest and most durable means of pre-passivation found to date has been to paint the lead with a slurry of chalk powder in water: and this may allow higher initial timber moisture levels to be tolerated. Site tests must continue, which look not only at simple flat specimens but also at the wide range of geometries and details that can occur.

Ventilation is often proposed as the cure-all, but its function and purpose is often misunderstood and consequently mis-applied. There are three main ways in which ventilation may be beneficial:

- ventilation of the building as a whole helps to remove moisture by displacing inside air by outside air, which on average will tend to have a lower dewpoint. However, the same air also removes heat in the colder weather when condensation and dampness is more likely. Unless this heat is put back, the temperature will drop and the relative humidity will increase, undoing much of the benefit. Indeed, if the source of moisture remains but with little or no extra heat, in spite of a reduced dewpoint the building may actually become damper, as has been found in many attempts over the past twenty years to improve conditions in low-income housing by ventilation alone. Alternatively, if the temperature is maintained and the ventilation is increased too much, then in cold weather the intense atmosphere may become too dry, which although perhaps good for the roof may well cause problems with shrinkage and cracking of organic materials such as timber and efflorescence and crystallization damage to masonry. In general, occupiers will not pay to heat what they regard as excessive amounts of ventilation and so a compromise will often fall short of what might be seen as best for the roof. While an adequate level of heating and ventilation should be aimed for, this level will seldom be sufficient to keep the roof dry enough to be out of danger. The traditional combination of high fuel consumption, high ventilation rates and relatively low air temperatures obtained with many open fires is no longer sustainable.
- ventilation of the roof space under the lead and its decking. The ideal of the 'cold' roof, in which there is so much ventilation by outside air that all moisture gains from within the building are borne away with no significant increase in dewpoint, is most closely approached in generously-ventilated roofs such as bell-towers (provided that rain does not blow in and air leakage from the church through the floor is very much less than the cross-ventilation through the louvres), and with less but well-distributed ventilation in well-detailed ventilated warm roofs with effective air and vapour control layers. The moisture content of the timber will depend on the climate, the time of year, the hygroscopicity of the timber species, its size and shape, the heating and ventilation of the roof space, and so on, and with variations for the individual sample. Owing to its lower temperature, 'air-dry' timber here will be relatively damp in winter (see Figure 5), so any small amounts of additional moisture may be sufficient to wet the underside of the lead. At 90% relative humidity, a hygroscopic species such as Corsican Pine typically has an equilibrium moisture content of 22% by weight [32], European Redwood (and European Oak) 20% and Yellow Pine 15% (Stillman and Eastwick-Field 1966). RTL suggests that underside corrosion can start to occur at timber moisture contents over 20%, so it may be worth evaluating timbers of different hygroscopicity and vapour permeability
- Ventilation to the underside of the lead itself. This often occurs through the gaps (penny or larger) between the underlying boarding. It can be a mixed blessing, as we have seen in *Patterns of corrosion* above: sometimes the lead here is corroded, sometimes passivated. From the ventilated warm roofs studied and the 'Dutch Barn' external test rig it seems that in a fully-ventilated situation as outlined above, the underside of lead exposed to the open air often falls slightly below the dewpoint and only just avoids corrosion in ambient conditions: small increases in vapour pressure (as with an imperfect vapour control layer) or small decreases in temperature (as by evaporative cooling from a puddle in a slight depression in a dead flat section of roof), and possibly even a somewhat colder or damper climate, are sufficient to initiate underside corrosion. Unless the roof space ventilation corresponds to near-ideal conditions, its effectiveness in protecting the lead must be questioned, and alternative or supplementary measures may be required. RTL find that a layer of plain building paper under the lead can give useful physical protection against transient diurnal condensation, without trapping ingressed moisture. Chalk treatment may be able to provide additional chemical protection. Tests are continuing.

Laying the lead on a gapped substrate has one very important advantage: even though condensation corrosion may occur in adverse conditions, the worst situations associated with trapped, refluxing and acid-containing moisture may be avoided. If chalk treatments prove to be successful, they can create more opportunities for substrates which restrict the access of air and moisture to the underside of the lead. Further studies are recommended, both theoretical and practical, of material properties, moisture movement and whether underside corrosion can be prevented both on site and in the laboratory.

While chalk coatings have been promising, they need further testing and development for reliable use on site. In particular this includes:

- Testing of suitable, low-cost commercial supplies of powdered chalk in the laboratory and on site
- developing reliable guidelines and procedures for coating the lead on site
- consideration of additives which might reduce the risk of attack by carbonyl compounds etc. Chalk itself provides some initial protection from acetic acid, but cannot resist high concentrations, as from fresh oak, and its long-term performance is not known
- developing and testing suitable underlay specifications (see below)

- considering and developing pre-loaded underlays. Site tests indicate that these would be additional to, and not instead of, the chalk slurry coating
- reviewing how well lead can be protected where it is not in direct contact with the substrate boarding, especially where it turns into the rolls where fish-tailing can occur over gapped boarding and acid/distillation-related corrosion in more sealed environments
- longer-term tests of durability and self-repair in a chalk-rich environment.

CAUTION: chalk treatments look promising, but are not yet commercially available for use by specifiers because their performance has not yet been proven at full scale. Full-scale tests are being undertaken in 1996-97 on some English Heritage and Historic Royal Palaces Agency sites where areas of roofing are being replaced or repaired. Pre-treated underlays (the concept is already subject to a patent by English Heritage) are being promoted by some suppliers, but whatever they may say these have not been developed, approved or tested by or in association with English Heritage and have not been endorsed by the research.

To date underlay investigations have been disappointing: in moist situations permeable ones let water vapour in, impermeable ones trap any moisture going, which is worse, and double-layer underlays have been dissappointing. More work is required on suitable underlays to carry the chalk layers, including possible composites, in which the upper part is sufficiently open to carry the chalk while the lower part both stops it falling through and controls to some extent the ingress of too much water vapour and moist air.

The literature review and theoretical analysis has shown that outside-air ventilation of roofs to which sources of moist air and water vapour from the building underneath have not been stopped (or at least very severely restricted) can be of little use, or worse, in avoiding condensation. Indeed, where gains are not too large, roof spaces with limited ventilation may sometimes be useful reservoirs in which moisture accumulates only slowly. In the summer, even where ventilation is restricted the roof may dry out effectively while in the process the buffered environments may help to passivate the lead (or repair partly-eroded passive films), and protect it from transient condensation. It is not yet clear how these mechanisms can be used reliably to positive effect. Further investigation and analysis should continue.

Much data has been collected in the buildings already visited. While partially interpreted, it could yield more information. To avoid too much dispersal of effort, it would be better to continue analysis and testing on some of these sites than to introduce new ones.

Giving preliminary guidance to specifiers

A separate document is being prepared to update architects and surveyors. It will:

- outline the findings of the research to date
- re-state the principles of the ventilated warm roof and draw attention to the need for meticulous attention to detail in air and vapour sealing and to providing effective through-ventilation
- caution against the use of inappropriately damp or acid substrate decking
- identify an approach to diagnosis of underside lead corrosion problems and testing possible solutions.

While there is clearly a strong need and demand to move some of the findings from the research into full-scale pilot application, to date this has proved troublesome owing to:

- the absence of definitive guidelines, other than for ventilated warm roofs
- excessive enthusiasm by some in the industry about the use of chalk coatings and underlays
- issues of professional indemnity in making use of ideas which inevitably have not yet been thoroughly tested in practice.

A standard approach to such cases needs to be developed, including:

- acceptance of some of the technical risks by the client
- a clear statement that any unusual specifications are for testing and development and not definitive new practice. A standard letter to this effect has now been agreed by English Heritage, the Historic Royal Palaces Agency and the Lead Sheet Association.

APPENDICES

A: Carrying out sample tests

If a roof has not been subject to significant underside lead corrosion, past advice has been that, provided nothing else changes, it would be reasonable to re-cover it in a similar manner, perhaps with some additional ventilation. However, the research has shown that even direct replacements do not always perform in the same way. There are several possible reasons for this:

- the environment now may be more aggressive than it was, but the existing lead has become passivated during its life, and this is now protecting it
- the new lead may be laid in unfortunate conditions (for example in the autumn, or on a wet building), which predisposes it to corrosion
- small changes (eg in substrates, underlays, detailing or ventilation) may be critical.

The research suggests that, for freshly-prepared samples, the type of lead has very little influence on the initially-observed corrosion. [33] Some tests are therefore possible merely by wire-brushing patches of the underside of the existing lead, taking appropriate safety precautions against ingestion or inhalation of the resultant dust (Lead Sheet Association 1993c), to expose a clean surface. The sample areas should include as wide as possible a range of conditions, and in particular:

- any locations showing systematic evidence of some underside lead corrosion (but also locations which do not, these may not necessarily be inert now)
- in the centre of a bay and at the edge
- over gaps and other weaknesses in the underlying decking (if present).

Photographs of typical underside corrosion patterns and sites can be found in *Patterns of corrosion* above.

If new lead, or lead with alternative pre-treatments, is to be tested, a simple procedure is merely to lift the existing lead, lay the samples, typically about 100 mm square, underneath in positions as outlined above, and re-lay the lead as a capping sheet. Ideally, thermally-conducting paste would be placed on the top of the sample to give better heat conduction to the outside, but in the research it was found not to be necessary. Alternatively, a whole bay or bays can be replaced: this may be a sensible option where a sheet has failed anyway and needs urgent replacement, or where the substrate is also to be renewed.

For either existing or new lead samples, different substrates and underlays can be placed underneath as required. However:

- larger samples will normally be necessary to permit all conditions to be monitored
- if underlays are intended to be vapour-resistant, steps must be taken to avoid water vapour getting around the sides.

As a general rule, lower-pitched roofs are more prone to corrosion than steep ones, very well-ventilated roofs (such as in bell towers) are less prone than elsewhere, roofs with roof spaces (ventilated or not) are less prone than those without, and for those without, roofs at high level are more prone than those at low level. Sometimes there are also significant variations with position and orientation, see *Patterns of corrosion* above.

Ideally samples should be first set up in May. An inspection in late September will then reveal whether any corrosion or passivation has occurred in the summer. At this time, half the area of each sample (or one sample where pairs are being used) should be wire-brushed (and this area re-coated, for example with chalk slurry, if this was done in May). The autumn is often the worst time for underside corrosion and the samples should be checked again around Christmas: sometimes the September ones will be corroded and the May ones not. Finally, at around Easter the two parts of each sample can be compared. If no samples of a particular type are corroded (one hopes that chalk treatment may often do this), then one can proceed with caution, though care will still need to be taken to keep the site dry during laying. Otherwise, more thought will be required.

B: Members of the Condensation Corrosion Forum

The Condensation Corrosion Forum has met annually during the project to review the conclusions and to coordinate them with other research and expertise.

- Professor Geoffrey Allen, University of Bristol, Interface Analysis Centre: conducting research into fundamental processes in the corrosion of lead (joint project with SERC and The National Trust)
- Dr Paul Baker, Building Research Establishment, Scottish Laboratory: conducting research into moisture movement and condensation in buildings and roof constructions
- Leo Biek, chemist: consultant and former head of the Ancient Monuments Laboratory at English Heritage
- Leon Black, University of Bristol, Interface Analysis Centre: conducting research into fundamental processes in the corrosion of lead (joint project with SERC and The National Trust)
- Stephen Bond, Historic Royal Palaces Agency: involved in the maintenance, repair and replacement of a large number of lead roofs, co-client for RTL's research
- Dr Bill Bordass, William Bordass Associates: chairman and coordinator of English Heritage programme
- Dr James Charles, University of Cambridge, Department of Materials Science: conducting research into the differences between milled and DM cast lead
- Dr Rob Edwards, Department of Chemistry, Liverpool John Moores University: conducting research into corrosion of archaeological lead and providing analytical support to the English Heritage project
- Dr David Farrell, Rowan Technologies Ltd, Manchester: main contractor for English Heritage site and laboratory tests
- David Farrington, Historic Royal Palaces Agency: involved in the maintenance, repair and replacement of a large number of lead roofs, co-client for RTL's research
- Paul Frost, Calders Industrial Metals Ltd: expert on the performance of lead, providing scientific and analytical support
- Neil Lewis, Lead Sheet Association and Calders Industrial Metals Ltd: lead industry representative and technical liaison with LSA
- Chris Sanders, Building Research Establishment, Scottish Laboratory: conducting research into moisture movement and condensation in buildings and roof constructions
- Dr Nigel Seeley, The National Trust: chief scientist
- Chris Wood: client for English Heritage's work
- John Woods, Lead Sheet Association representative

Contributors to earlier meetings of the Forum:

- Iain McCaig, initial client for English Heritage
- Ray Cox, Building Research Establishment, Metals Section: expert in the performance of metals in buildings
- Brian Day, University of Bristol, Environmental Engineering Studies Unit: conducting research into moisture movement and storage in building materials
- Philip Forshaw, University of Bristol, Interface Analysis Centre, Research student on lead corrosion
- Professor Jack Harris, University of Bristol, Interface Analysis Centre

- Dirk Janssen, Rheinzink: providing information on continental European practice for continuously-supported metal roofs

C: Research projects

- Laboratory tests of corrosion under intermittent wet/dry cycles: Rowan Technologies Ltd
- Outdoor full-scale test rig: Rowan Technologies Ltd
- Site investigations, sample tests, and overall reporting: Rowan Technologies Ltd. Computer modelling, site studies and test rigs at BRE Scottish Laboratory

Support and advice received from Dr Bill Bordass (William Bordass Associates), The Lead Sheet Association, The Historic Royal Palaces Agency, The National Trust, Borough of Preston, SAS Software Ltd, Bickerdike Allen Partners, Follansbee Ltd, Ove Arup Partnership and Vis Williams Partnership.

D: Sites visited (see table 4 for key characteristics)

- *Church 1 in Yorkshire: observation and tests*
  The nave has oak boarding which is both the ceiling and supports the lead. It was re-roofed in 1938 with a separating layer of bitumen-cored building paper, which appears also to have been bedded in bitumen over the oak. The Code 8 sand-cast lead in some areas, especially on the apexes and at the edges of the rolls (a typical weak spot where acid-related corrosion is involved), has now corroded through. In these positions the building paper had also tended to fail.
  Conclusions: An example of the difficulty of protecting lead from the effects of acetic acid in the long term. Chalk coatings, which have been found to give some protection in the laboratory, are now being tested here.

- *Church in Buckinghamshire: observation, monitoring and testing*
  Lead on the roofs to the tower and the two aisles date from the nineteenth century, the nave was re-leaded in 1939. The sheets on the aisles have slipped over the years and are now admitting water in places. All roofs are laid on softwood boarding with gaps averaging some 5 mm. As in many village churches the underside of the boarding forms the ceiling of the church. The underside of the lead on the well-ventilated tower roof (now also used as the air intake chamber for the heating) is in good condition. The other roofs showed some underside corrosion, related to the gaps between the boards but which had varied over the life of the roof, in places passivating and sometimes corrosive. Monitoring has shown that the atmosphere in the church is currently very damp, and condensation events frequent, even in summer. Sometimes condensation drips onto the pews, particularly in the nave: probably owing to the stratification of moist air. Given the amount of dampness, it is surprising that underside corrosion was not more severe.
  Pressurised direct gas-fired heating was installed in the late 1980s. It is likely (though not entirely certain) that combustion moisture from this may have exacerbated the condensation and corrosion: some corrosion, particularly to the nave roof, appears to have started within the past few years. Tests and environmental monitoring are continuing.
  Conclusions: Confirms that there is no direct relationship between the amount of moisture and the amount of corrosion. As a general rule, flueless heating should not be used where there are lead roofs. The south aisle roof is currently being used both as a test site and for environmental monitoring: more information will be available from RTL in due course.

- *Brightling Observatory, Sussex: observation*
  Domestic background heating. A house on an exposed hilltop which has slate roofs with lead flat tops, gutters and window cills. 'Cold' uninsulated roof spaces quite well isolated from rooms underneath by thick lath and plaster ceilings with little cracking and few holes for services, hatches etc. No explicit ventilation but adventitious ventilation via slates, particularly when windy. Underside of lead directly on softwood close boarding in good condition, even over rotted timber in gutter. Some corrosion under window cills and flashings where lead had been stuck down with dabs of acrylic (?) sealant after it had been lifted in gales (1987?).
  Conclusions: Probably no need for explicit ventilation when the slate roof is repaired, provided no sarking felt is added under the slates, and if patination oil or chalk pretreatment is used. A separate roof on the tower should be of ventilated warm roof construction.

- *Caerhays Castle, Cornwall: observation, monitoring and tests*
  Domestic background heating. The lead dates from the 1850s and is now in poor condition from thermal fatigue. Underside corrosion present on some sheets but relatively thin in spite of damp roof space, timbers and external environment. In a few places, the softwood boarding had been replaced by elm when repaired in the 1970s (?): lead over some of these boards (typically with acetate content of 80 ppm or more) has corroded. The mild, moist microclimate could well be passivating at times. The roofs get extremely hot in the sunshine, owing to shelter from the hillside and trees behind and absorption by a dark brown topside patina (probably an effect of the microclimate and possibly sea salt).
  Tests showed that:

  - lead wire-brushed in September corroded over gaps and holes but over one cracked sheet, which let water in, the wire-brushed lead had passivated, even some distance away where there was visible condensation from the refluxed moisture
  - lead wire-brushed in September and treated with chalk paste did not corrode, over softwood, the

Table 4. Lead roofs inspected in the UK.

				DATE:		OCCUPANCY AND HEATING:			ROOM CONDITIONS:				TYPES OF ROOFS:				ROOF VOID VENTILATION:			
NAME	Variant	Location	Building Type	First built	Lead dates from	Building usage	Heating type	Heating schedule	TEMPERATURE: when heat on. Scale 5=warm to 1=chilly	TEMPERATURE: at other times. Scale 5=warm to 1=chilly	VENTILATION: Scale 5= liberal to 1= limited	DAMPNESS: Scale 1=dry to 5 = very damp	Classification	Ceiling	Extra vapour control layer	Added insulation	Void	To room air	To outside air	Likely main origin of roofspace ventilation
Brightling Observatory	Typical	Sussex	House	1810	1900s	Domestic	HW rads	Domestic	4	2	4	3	Domestic	Plaster	None	None	Crawl	Adventitious	Via slates	Outside?
Caerhays Castle	Typical	Cornwall	Mansion	1808	1850s	Domestic	Night storage	Background	3	3	3	4	U'drawn	Plaster	None	None	Shallow	Adventitious	Via loose lead	Indoors
	Elm boards																			Indoors
Cathedral in North West	Existing	Northwest	Cathedral	>500 yrs	1980s	Cathedral	Radiators?	Daily	4	3?	3	2	??	Wood?	No	No	No	Not known	Adventitious	Outside
	New VWR												VWR	Wood?	Hyload	50 mm	50 mm	Vapour sealed	Top and bottom	Outside
Church in Bucks	Aisle	Bucks	V church	> 500 yrs	1930	V church	Direct gas	Occasional	4	2	3	5	Direct	None	None	None	None	Complete	Outlet via gaps only	Inside
	Nave				1939								Direct	None	None	None	None	Complete	Outlet via gaps only	Inside
Church in Northants	Nave	Northants	V church	>200 yrs	1988	V church	HW radiators	Continuous	4	4	4	1	Direct	Timber	None	None	Shallow	Complete	Adventitious	Inside
Church near Sheffield	Existing	S Yorks	Church	>200 yrs	Varies	V church	Floor trench	Continuous	4	4	1	5	U'drawn	None	None	None	None	Complete	Outlet via gaps only	Inside
	New VWR		NE chapel		1995		HW radiators						VWR	Wood	Yes	Yes	50 mm	Vapour check	Top & bottom	Outside
Church in Shropshire	Aisle	Shrops	V church	>500 yrs	1982	V church	HW pipes & rads	Daily	3	3	2	2	U'drawn	Plaster	Bit felt	none	Shallow	Adventitious	Adventitious	Minimal
Church 1 in Yorkshire	Nave	S Yorks	V church	>500 yrs	1988	V church	HW fan conv'rs	Occasional	3	2	2?	3?	Direct	None	Bitumen fel	None	None	Complete	Outlet via gaps only	Minimal
Church 2 in Yorkshire	All	North York	V church	>500 yrs	1990	V church	HW pew rads	Occasional	3	1	3	5	Direct	None	None	None	None	Complete	Minimal	Inside
Church 3 in Yorkshire	Chancel	S Yorks	V church	>200 yrs	?	V church	HW radiators	Occasional	3	1	3?	4	Direct	None	None	None	None	Complete	Outlet via gaps only	Inside
	Aisle												Direct	None	None	None	None	Complete	Outlet via gaps only	Inside
Civic building	Typical	Herts	Amenity	1980	1991	High	HW rads	Daily	5	4	3	3	VWR	Timber	Polythene	50 mm	15-20 mm	Vapour check	Top and bottom	Outside
									5	4	3	3	VWR	Timber	Polythene	50 mm	15-20 mm	Vapour check	Top and bottom	Both
Donnington Castle	Existing	Berks	Monument	>500 yrs	1955	None	None	None	1	1	4	4	Direct	NA	NA	NA	NA	Complete	Outlet via gaps only	Inside
Educational building	Typical	Cambs	Common Rm	1966	1966	Meeting	HW convectors	Daily	4	3	4?	2	U'drawn	Timber	Slaters felt	25 mm	Shallow	Via cracks	Adventitious	Both
	Facia												Facia	Timber	Slaters felt	25 mm	Shallow	Via cracks	Adventitious	Outside
Hampton Court	Gt Hall	London	Great Hall	500 yrs	1955	Visitors	Underfloor	Continuous	3	3	3	2	U'drawn	Wood	None	No	Shallow	Via timber joints	Adventitious	Inside
Manchester Cathedral	Aisle	M'chester	Cathedral	>500 yrs	1984	Cathedral	HW radiators	Daily	3	3	3	2	U'drawn	Wood	None	none	Shallow	Loose fit ceiling	Adventitious	Inside
Mansion in Bucks	Original	Bucks	Mansion	1906	1906	Office	HW radiators	Daily	5	4	3	1	Domestic	Plaster	None	50 mm	Crawlable	Adventitious	Adventitious	Inside
	New				1988	Office	HW radiators		5	4	2	1	Domestic	Plaster	None	50 mm	Crawlable	Adventitious	Adventitious	Inside
	Separate		Stables	1906	1986	Training rm	Air conditioned	Daily	4	4	5	1	U'drawn	C/tiles	Polythene	50 mm?	Shallow	Poor vap check	Adventitious	Inside
Mansion in Derbyshire	Existing	Derby	Mansion	>200 yrs	1900?	Museum	HW radiators	Constant	4	4	2?	2	Domestic	Plaster	None	None	Walkable	Adventitious	Adventitious	Inside?
	Renewed				1992	N Trust hse	Dehumidified	Conserv'n	2	2	3	4	Cold	Plaster	Yes,poor	Slabs	Walkable	Adventitious	Eaves and apex	Both
Mansion in Dorset	West end	Dorset	Mansion	>200 yrs	1984	N Trust	HW radiators	Domestic	5	4	3	2	Cold	Plaster	None	100 mm	Walkable	Adventitious	Hatches+tubes	Inside
	East end							Conserv'n	3	3	3	2	Cold	Plaster	None	100 mm	Walkable	Adventitious	Hatches+tubes	Inside
	Mansard							Domestic	5	4	3	2	Cold	Plaster	None	100 mm	Varies	Adventitious	Tubes	Inside
Mansion in Northants	Renewed	Northants	Mansion	200 yrs	1994	Medium	HW radiators	Domestic	?	?	4	2	Cold	Plaster	Foil back?	100 mm?	Shallow	Adventitious	Via new turrets	Mixed
	Chapel'								3	3	2	3	U'drawn	Plaster	Bit felt	none	Shallow	Adventitious	Adventitious	Minimal
Metal store		London	Castle	>500yrs	1930s	Metal store	Radiator?	Constant	4	4	3	2	U'drawn	Plaster?	None	None	Shallow	No explicit	No explicit	Inside
Museum		London	Castle	>500yrs	1967	Museum	HW fan conv'rs	Constant	5	5	4	2	U'drawn	Timber	None	None	Crawlable	Exit route	Fan louvres	Inside
Norwich Cathedral	Choir sch	Norwich	Cloister rms	>500 yrs	1953	Daily	HW radiators	Daily	3	3	3	2	Direct	None	None	None	None	Complete	Outlet via gaps only	Inside
	Refectory		Refectory	>500 yrs	1956	Daily							U'drawn	Plasterbd	Foil back	25 mm?	Shallow	Adventitious	Swan necks	Not clear
Preston Guild Hall	Phase 1	Preston	Events	1970	1991	High	Central warm air	Daily	5	3	4	1	VWR	Concrete	Bituthene	50 mm	50 mm	Vapour sealed	Top and bottom	Outside
	Phase 2				1992								VWR							Outside
	Phase3/4				1993	Phase 4 1995							VWR							Outside
Salisbury Cathedral	Typical	Salisbury	Cathedral	> 500 yrs	Varies	Cathedral	HW radiators?	Continuous	3	3	3	2	Vaulted	Vault	None	None	Walkable	Via 100 mm hol	Small windows	Outside
	SW corner																			Outside
St Cross, Winchester	Typical	Winchester	Church	>500 yrs	1880s	Daily serv	Direct gas	Short bursts	3	2	3	3	Vaulted	Stone	None	None	Walkable	Via doors etc	Small windows etc	Both
	Tower							daily	2	1	5	3	Cold	Timber	None	None	Walkable	Via floorboards	Belfry openings	Mostly O/S
St Mary's, Hadleigh	New VWR	Suffolk	V church	>500 yrs	1988	V church	Gas plaque+pew	Occasional	4?	2?	3?	2	VWR	NA	Polythene	50 mm?	50 mm?	Vapour check	Side-to-side	Outside
St Mary's, Stoke-by-N	Typical	Suffolk	V church	>500 yrs	1967	V church	Electric pew	Occasional	3	2?	2?	4	Direct	None	None	None	None	Complete	Outlet via gaps only	Inside
St Mary's, Stratford	S aisle	Suffolk	V church	>500 yrs	1986	V church	Warm air+pew	Occasional	4?	2?	3?	2	U'drawn	Timber	None	None	Shallow	Via cracks/gaps	Via slate area	Inside?

Table 4. Lead roofs inspected in the UK (continued).

NAME	Variant	PITCH: 1= <3° 2=≤6 3=≤15° 4=≤30° 5=>30° 6=90	SUBSTRATE	LEAD TYPE	CODE	VERT JOINTS^	HORIZ JOINTS	SPLASHLAPS	UNDERLAYS Lower layer	 Upper layer (if any)	UNDERSIDE CORROSION ASSESSMENT Over boards	 Over gaps	 At laps or steps	 At rolls	 COMMENTS	POSSIBLE FUTURE WORK
Brightling Observatory	Typical	2	S/W	Mill?	6	B/R	Step	Yes	None		Slight	Some streaks	Slight	Modest	Some corrosion where sealants used	None, currently on market
Caerhays Castle	Typical	2	S/W	Cast	8	B/R	Step	Loose	None		Slight	Passivated	Some	Slight	Brown topside patina in warm damp climate	Phase I re-roofing with chalk just completed
	Elm boards		Elm	Cast	8	B/R	Step	Loose	None		In some areas	Some	Slight	Slight	Chalk coating test sgive some protection	Phase I re-roofing with chalk just completed
Cathedral in North West	Existing	5	S/W	Cast	6	H/R	Lap	No	None		Some	Not inspected >>>>>>>>>>>>>>>>>>>>			Water ingress main cause?	Test chalk samples in corroded areas?
	New VWR		S/W	Cast	7	H/R	Lap	No	Geotextile		In "dead" areas	Significant	Some	Slight	Most in flat areas above upper vents	Test chalk samples in corroded areas?
Church in Bucks	Aisle	2	S/W	Cast	6	B/R	Step	Small	None		Slight	Significant	Limited	Limited	Slippage shows past corrosion above gaps	Tests and monitoring continue
	Nave	2	Gap S/W	Cast	6	H/R	Lap	No	None		Significant	Varies	Largely passivated		Pressurised direct gas-fired heating might be increasing corrosion now	
Church in Northants	Nave	2	S/W	Cast	7	H/R	Lap	No	420 B paper?		Bright	Bright	Some	Minimal	Particularly well heated and ventilated	Check autumn 1996
Church near Sheffield	Existing	3	S/W	Cast	7	B/R	Lap	No	420 B paper		Severe, failing	Worst at laps	Yes	Yes	Drying-out problems with constant heating	Chapel was very damp: sealed+gas htrs!
	New VWR	3	S/W	Mill	7	B/R?	Lap	Yes	None		Little	Some at edge	Slight	Slight	Vapour check not well sealed at edge	Lead stolen. Improve details when replacing
Church in Shropshire	Aisle	1	S/W	Mill	6	B/R	Step	Tight	Insul bd 13 mm	420 B paper	Significant	N/A	Substantial	Substantial	Thermal pumping and ingress likely	Check performance of closed cell insulation
Church 1 in Yorkshire	Nave	3	Oak	Cast?	7	H/R	Lap	No	Hot bitumen	420 B paper	Significant	Significant	Severe	Severe, failing	Bad just above lap, likely acid attack	Chalk gives useful protection to samples
Church 2 in Yorkshire	All	3	T&G S/W	Mill	6	H/R	Lap	No	None		Some in middle	Ditto	Slight	Slight	Exposed site, top lap has more corrosion	Consider installing small dehumidifier
Church 3 in Yorkshire	Chancel	3	Oak	Mill?	7	B/R	Lap	Yes	None		Substantial	Passivated	Passivated	Slight	Oak very wet when inspected March 1994	Test remedial underlays
	Aisle	3	S/W	Mill?	7	B/R	Lap	Yes	None		Minimal	Minimal	Minimal	Minimal	Only one sheet lifted, much drier	
Civic building	Typical	4	S/W	Mill	7	B/R	Lap	No	None (diagonal boards)		Not normally	No	Slight	No	Excellent where vapour check (VC) good	Check autumn 1996
	Leaky VCL	4	S/W	Mill	7	B/R	Lap	No	None (diagonal boards)		Not normally	Yes	Slight	No	Poor where ventilation or VC faulty	Check autumn 1996
Donnington Castle	Existing	2	Oak	Mill	7	B/R	Step	Yes	Hardboard		Severe: failing	Less	Steps passiv	Yes	Large set of test samples in place	Revisit to check samples.
Educational building	Typical	3	Plywood	Mill	7	B/R	Lap		Insul board	Plywood	Extensive	N/A	Extensive	Varies	Passivated over adjacent woodwool slabs, though slightly corroded at some joints	
	Facia	6	Plywood	Mill	7	Welt	None		None		Disastrous	N/A	Disastrous	N/A	But passivated nearby! Welts trap rain	Inspect renewed roof
Hampton Court	Gt Hall	5	Oak	Mill?	7	B/R	Lap	Small	Hardboard		Severe in places	N/A	Severe	Severe	High acid content in hardboard	Monitoring and testing continues
Manchester Cathedral	Aisle	3	Ply?	Mill	7	B/R	Step	No	420 B paper		Slight corrosion	N/A	Some	Not known	Monitored in 1988-89	Inspect autumn 1966
Mansion in Bucks	Original	2	S/W	Mill?	7	B/R	Step	Yes	Hairfelt		Extensive	Passivated	Passivated	Limited	Many nosings have been repaired	Chalk treatment looks promising: continue
	New	2	S/W	Mill	7	B/R	Step	Yes	Geotextile		Minimal	Substantial	Substantial	Substantial	Fish tails rising from gaps into rolls	Chalk treatment looks promising: continue
	Separate	2	Plywood	Mill	7	B/R	Step	Yes	420 B paper		Slight	N/A	Substantial	Some at s/laps	Polythene seals poor but A/C not humidifie	Test coatings including chalk
Mansion in Derbyshire	Existing	2	S/W	Milled	8	B/R	Step	Yes	Erskine's felt		Patinated	Patinated	Slight	Slight	Buffering effect seems helpful here	Monitoring and testing continues
	Renewed	2	S/W	Cast	8	B/R	Step	Yes	None		Spread from gap	Significant	Slight	Slight	Reduced buffering has caused corrosion	Test coatings and blocked ventilation
Mansion in Dorset	West end	2	S/W	Mill	7	B/R	Step	Yes	Erskine's felt		Initial corrosion	More now	Slight	Some at s/laps	Samples of treated underlays left	Return to inspect in 1997
	East end	2	S/W	Mill	7	B/R	Step	Yes	Erskine's felt		Initial corrosion	Less	Slight	Some at s/laps	Samples of treated underlays left	Return to inspect in 1997
	Mansard	5	Gap S/W	Mill	7	B/R	Lap	Yes	None (diagonal boards)		Little	Some	Not inspected >>>>>>>>>			Return to inspect in 1997
Mansion in Northants	Renewed	2	Plywood	Mill	7	B/R?	Step	???	Bldg paper	Geotextile	Not known				Not visited since re-roofing	Inspect renewed roof
	Chapel	1	S/W	Mill	6	B/R	Lap	Tight	Insul bd 13 mm	420 B paper	Some	Some	Local	Some	Lap mean: some ingress suspected	Check other locations
Metal store		1	Plywood	Cast	7	B/R	Step	Yes	Erskine's felt		Slight	N/A	Heavy	Severe	Step at bottom (into gutter) had no splashlap and was not corroded	
Museum		2	S/W	Cast	7	B/R	Step	Yes	Various B papers		Slight	N/A	Slight	Locally heavy	V well H&V roofspace; foil faced insulating board under softwood deck	Investigate origin of acid causing localised roll corrosion
Norwich Cathedral	Choir sch	3	Oak	Cast?	8	H/R	Lap	No	None		Severe; failing	Similar	Severe	Severe	Failing, many repairs	Consider installing coated test samples
	Refectory	2	Oak	Cast?	8	H/R	Lap	No			Only inspected from above				No signs of failure from above but no sheets lifted	
Preston Guild Hall	Phase 1	4	S/W	Cast	7	B/R	Lap	No	420 B paper		None	None	Slight	Slight	Some leaching by organic solvent	
	Phase 2	4	S/W	DM	7	B/R	Lap	No	234 B paper		Minimal	None	Slight	Minimal	Slight yellowish corrosion over tanalised boards, not serious	
	Phase 3/4	4	S/W	Cast	7	B/R	Lap	No	234 B paper		None	None	Slight	Minimal	Performance seems good	Check
Salisbury Cathedral	Typical	5	Gap S/W	Cast	8	S/S	Lap	No	None		Little	Slight, varies	Not known		Early gap corrosion sometimes occurs but settles down	
	SW corner			Cast	8	S/S	Lap		B paper 420						Small part of roof only, some problems but origin unclear	
St Cross, Winchester	Typical	5	Gap S/W	Cast	8	B/R	Lap	No	None		Minimal	Passivated	Slight	Slight	Fresh samples in church corrode at gaps	Revisit and install remedial test samples?
	Tower	3	S/W	Cast	8	B/R	Lap	No	None		Slight	Some	Significant			
St Mary's, Hadleigh	New VWR	4	S/W	Mill	7	B/R	Lap	Loose	Geotextile		Significant	Significant	Minimal	Some	ULC worst in dead spot, centre bottom	Inspect test samples?
St Mary's, Stoke by N	Typical	2	Oak	Mill	7	H/R	Step	No	Bitumen/Erskin	420 B paper	Small	N/A	Significant	Some	Water ingress path at foot of hollow roll	
St Mary's, Stratford	S aisle	2	S/W	Mill	7	B/R	Step	Yes	Slaters felt	Breather paper	Some	N/A	Occasional	Some at s/laps	Some ULC patterning with ridges and furrows of breather paper	

^ B/R=Batten Roll; H/R=Hollow Roll; S/S=Standing Seam.

corrosive elm or gaps but there was some corrosion where chalk-loaded geotextile underlay was used underneath.

Conclusions: Demonstrates the usefulness of a chalk coating retained in place, but the benefits of chalk-coated geotextile are questionable. Confirms passivation in some humid environments. A section has been re-roofed more or less to the original specification with the sheets reduced in width and a chalk coating applied. This will be examined in 1997.

- *Cathedral in North West: observations, plus some monitoring by BRE*
  Reasonably heated. Various roofs upgraded to ventilated warm roof specification when re-laid, with softwood gap-boarding and geotextile. BRE monitoring shows no significant moisture entering the air gap from inside the building. Nevertheless, some cosmetic corrosion was found, particularly above the outlet vents on lean-to areas and at laps.
  Conclusions: Corrosion seen in the laps is almost certainly caused by distilled rainwater. Important to have through-ventilation in a ventilated warm roof, with no dead spots. Geotextile might not be the best underlay. Comparison tests are desirable.

- *Chester Cathedral, Cheshire: observation*
  Several lead roofs here have recently been replaced using DM lead, but concern was expressed at their appropriateness and appearance. The material has one rippled face and one flat face: its appearance is normally satisfactory with the flat face outermost; see Preston Guild Hall.
  Conclusions: If DM lead is used, for appearance it should have the flat side upwards. It would be worth undertaking studies of whether any patterning effects are associated with the ripples in corrosive situations (as puckered building paper sometimes has had on flat lead).

- *Donnington Castle, Berkshire: observation, monitoring and tests*
  No heating. Lead laid in the 1950s over new oak with hardboard underlay is badly corroded over much of its area. High acetate contents (600 ppm) in the hardboard, in which acetate seems to accumulate. Less corrosion (and some passivation) where there is softwood (rather than oak) under the lead, in spite of similar hardboard acetate content, probably the result of hygroscopic buffering by the softwood. Similar, but less marked, effect over rafters and purlins, and some passivation in parts of rolls. Wet gutters uncorroded, possibly owing to the effect of carbonated concrete. Roof used by RTL in 1994–6 for full scale tests.
  Conclusions: Beware accumulation of organic acids in certain materials. Chemical effects of acetate seem to be greatly influenced by local hygrothermal conditions. Recent tests with chalk coatings and underlays are promising.

- *Educational building in Cambridge: observation and tests*
  This roof on a late 1960s building had failed badly, owing to a combination of underside corrosion, water ingress via a fascia welt detail which had become a water-trap, and with cracking elsewhere from thermal movement. There may also have been some condensation. When opened up, the corrosion was found to be restricted to lead either laid on plywood, or in the distillation zone above areas of damp plywood. Although corrosion was very severe, with the lead paper-thin in places, passivated areas were found in close proximity to corroded ones, even over the plywood. Sharp boundaries between the two states have also been seen in particular at Donnington Castle, Hampton Court and a church near Sheffield. Lead over woodwool cement slabs here was also well passivated, in spite of evidence that it had been subject to condensation from time to time.
  Conclusions: An example of the severe corrosion caused by the hydrolysis products of damp plywood. After a hot dry month, the plywood here was also found to be very damp in the middle although its surfaces were dry. Conversely, the carbonated cement in the woodwool appeared to have had a passivating effect.

- *The Great Hall, Hampton Court Palace, Surrey: observation, monitoring and tests*
  The steeply-pitched roofing of the mid-1950s has a hardboard underlay (now with a very high acetate content) over oak decking, similar to Donnington Castle. However, unlike Donnington the Great Hall has background (underfloor) heating and also has bitumen-cored building paper under the hardboard. Both north- and south-facing slopes are badly corroded, particularly around the edges of the sheets and in places where the lead has arched away from the substrate owing to constrained slippage (the lead is nailed to the rolls from top to bottom) and thermal movement. Such patterning appears to be widespread where organic acids are involved, and may be related to distillation across the air gap, greater local access of carbon dioxide to regenerate acetic and formic acids, and electrochemical differences. The building paper also appears to have helped to trap ingressed moisture in the hardboard layer. Although the internal environment is relatively dry, removing the hardboard and building paper in a sample area led to visible evidence of condensation. This may result from the sustained egress of moist air via natural buoyancy in this tall, single-volume building which has no openable windows and a timber ceiling with joints readily permeable to the passage of air.
  Conclusions: Confirms the particular acidity problems of hardboard, probably exacerbated by nearby oak. Suggests that the building paper was an ineffective barrier and may have made things worse by trapping moisture. Illustrates that corroded and passivated areas can be in close proximity, even in a highly acid environment.

- *Mansion in Northamptonshire: observation only*
This house was visited while lead was about to be installed on geotextile over a plywood deck. While it was too late to change this, to reduce the risk of problems better air and vapour sealing of the ceiling and better ventilation of the roof space was recommended, together with building paper under the geotextile. The renewed roof will soon be inspected.

- *Church in Shropshire: observation, tests and monitoring*
In the early 1980s, the south aisle roof was renewed, as recommended at the time, with a vapour control layer bedded in hot bitumen over plywood, 12 mm wood fibre insulation board and bitumen-cored building paper under the lead. Five years later the insulation board was found to be wet and the underside of the lead corroded, particularly at the perimeter near laps and rolls. At the time the problem was attributed to a faulty vapour control layer, and possibly water ingress at the steps which did not have the specified anti-capillary grooves (although the Lead Sheet Manual does not require them for the 50 mm steps used here, but only for shallower ones). Battens at the bottom of the sheets above a step could also trap moisture at the foot of the insulation boards.
Environmental monitoring is still in progress with tests on moisture-resistant non-porous insulation, and different anti-capillary and water run-off systems but none seems to have been successful. Results to date suggest that the church is well-heated and relatively dry (reducing the risk of condensation) and that vapour control layer is effective. It is therefore likely that the moisture in the insulation board originates from outside, not inside. This moisture is effectively trapped: it did not even dry out in the prolonged hot dry summer of 1995. Water ingress paths have been identified via poor rendering above the top flashings and sub-atmospheric pressure ('thermal pumping') at the foot of the rolls just above the steps.
In the laps of the more steeply-pitched chapel roof, there is also some local evidence of water ingress (probably by thermal pumping, but it could be a wind effect) via nail holes which have become elongated owing to movement against the soft insulation board. However in the chapel bays inspected there was little underside corrosion.
Conclusions: Since 1986 'warm' lead roofs like this have not been recommended. Low-pitch roofs with splashlaps (such as this) are particularly susceptible to thermal pumping because rainwater retained in the splashlap creates a water seal which permits high negative pressures to develop under the lead when it cools, and a reservoir of water to be drawn in.

- *Mansion in Dorset: observation, monitoring and tests*
When restored in the early 1980s, roof space ventilation was improved using ventilated access hatches and 15 mm copper tubes at regular intervals around the eaves. The lead was laid directly on softwood gap-boarding on the mansards and close boarding with Erskine's felt underlay on the top. At the first quinquennial inspection, underside corrosion of the flat-roofed areas was virtually universal, though generally thin, compact and quite protective. Studies indicated that most of this had formed early in the life of the lead. In sample areas where the lead surface was cleaned, new corrosion only occurred above the gaps between the boards over the occupied flat on the top floor (in which additional moisture was generated by the occupants and their activities) and not above the exhibition rooms (which today have conservation heating). The additional roof ventilation openings did not seem to have been particularly helpful, often working as outlets for air rising from within the building. In some places where felt had been omitted the lead was covered with a loose, friable, dusty or flaky corrosion product: when cleaned off, no further corrosion occurred, indicating that this probably resulted from initial contact with damp and/or freshly preservative-treated wood. In active corrosion sites, corrosion could be reduced by applying linseed oil or patination oil to the underside of the lead: this was only fully effective if the oil was given sufficient time to cure before laying. Patination oil was generally better in practice because it cured more quickly. Some corrosion was also found on the outer parts of the rolls towards the splashlaps: this was thought to be from distillation of rainwater trapped in the splashlap, and has since been found on many other sites with low-pitched roofs.
Conclusions: Visible corrosion may have occurred early in the life of a roof and might no longer be active, so it is important to check before taking action which could be unnecessary. Linseed oil, which was sometimes applied to lead in the past (both in some rolling mills and on site), could have conferred some resistance to underside corrosion, at least initially. Pre-coating with patination oil may be helpful (but chalk treatment may be preferable, subject to further tests). Additional roof space ventilation may not always be effective or necessary.

- *Manchester Cathedral: observation, tests and monitoring*
The original test site for electrochemical monitoring of condensation corrosion of lead. The tests showed that on a sample arranged to be susceptible to condensation and corrosion, most of the corrosion occurred in the periods during which the condensate was drying out. The renewed nave roof, laid on building paper on softwood decking, only had a small amount of underside corrosion.
Conclusions: Important initial site. Worth re-visiting to check the current condition of the lead.

- *Hotel in the Midlands: observation*
The mansard roofs on this 1970s building were formed from Codes 4 and 5 lead sheet bonded to plywood and with a central metal clip driven into the wood and welded to the lead. Thermally-induced cracking had occurred (especially on the south and

east faces), with ridges formed by compressive expansion turning into cracks and ingress of moisture then causing corrosion damage. Even before this, some condensation and corrosion might well have happened. The lead was both over-sized and over-fixed, being secured to the plywood right around the edge and with clips in the middle. The corrosion had been greatly accelerated by acetic and formic acids from the plywood.
Conclusions: Some suppliers have argued that bonded lead can be used in larger panel sizes than recommended in freely-suspended situations because the loads are spread and buckling is restricted. However, we have found no firm evidence for this and bonded sheets are not covered by British Standards and LSA recommendations. Expansion and over-fixing was a bigger problem here (at least initially) than corrosion. It is also possible that, even using LSA size and fixing recommendations, bonded lead might ultimately suffer tensile fatigue because the adhesive (which stiffens as it cools) would restrict thermal movement and particularly contraction. Great caution must also be exercised in the choice of manufactured timber-based substrate boards owing to their potential acidity, particularly in environments in which there is any risk of dampness.

- *Norwich Cathedral cloisters: observation*
The quadrangle of cloisters has first floor rooms above, containing a choir school, a library, a restaurant and an audio-visual room, all with oak substrate boarding of some antiquity, which also forms the ceiling. New lead was laid in phases during the 1950s and 1960s. A lowered ceiling with vapour control layer and roof space ventilation was added above the restaurant only. The choir school roof, immediately beside the cathedral and subject to egress of moist air up the connecting stair, is the earliest and the worst corroded. Owing to the hollow roll construction, inspection of the underside of the lead was difficult, and sheets were only lifted on the worst-corroded part. Corrosion here was widespread, and worst along the joints between the boards and around the edges: this is characteristic of situations in which organic acids are involved. An inspection from above and below suggested that there was less corrosion in the newer roofs above the library (which was drier at the time) and even less above the restaurant. The roof of the audio-visual room (adjacent to the restaurant, affected by moisture emerging from it and without a lowered vapour-checked ceiling) was more suspect.
Conclusions: Oak, even if well-seasoned, may still promote underside corrosion. These roofs were inspected several years ago. A fresh and more detailed inspection, plus possible tests, would be desirable.

- *Preston Guild Hall, Lancashire: observation and tests*
The roof has recently been replaced with ventilated warm roof construction. Ventilation rates have been checked in relation to wind direction and solar heating, and the underside of the lead inspected. The Phase 1 roof (sand cast Code 8 lead) showed some adhesion between the lead and the substrate (Sisalkraft 420), owing to leaching of bitumen from the building paper's core by residual solvents for the wood preservatives. The Phase 2 roof (DM Code 8 lead on Sisalkraft 234 plain reinforced building paper) had been installed the correct way (flat side of the lead up). An initial yellow corrosion product indicated some reaction with the water-based softwood preservatives, or with the damp treated wood, but this corrosion appears to be cosmetic only. In the recent Phases 3 and 4, Code 8 sand-cast lead was used, with Sisalkraft 234 and a requirement that the treated timber should be dry. These roofs have not yet been inspected.
Conclusions: Well-detailed ventilated warm roofs appear to work well but there need to be precautions against damp or freshly preservative-treated substrate boarding.

- *Civic building in Hertfordshire: observation, tests and short-term monitoring*
A lead roof laid on a plywood deck with insulation underneath and poor vapour check details failed within a few years. Its replacement with a ventilated warm roof performed well generally, but with condensation and underside corrosion in a few places. In some of these, the airspace did not have through-ventilation from eaves to ridge. Where there was through-ventilation, tracer gas tests revealed that corrosion occurred in the bays in which there were faults in the sealing of the vapour control layer. These included junctions to brickwork and penetrations such as roof windows, where moist air and water vapour from inside the building could rise into the ventilated void.
Conclusions: The original roof was replaced before this project started and we have no records of it. However, the research indicates that it could only have failed as fast as it did if condensed and trapped moisture had activated the acids in the plywood. While the best parts of the new roof demonstrate the effectiveness of ventilated warm roof details, the weak spots makes it clear that the whole of the airspace must be ventilated by a through-flow of outside air (with no dead spots). The vapour control layer must also be meticulously detailed and jointed so that it is both vapour-resistant and airtight: ventilated air spaces cannot be guaranteed to bear away any moist air or water vapour with no ill effects. Adding a layer of plain reinforced building paper (such as Sisalkraft 234) under the lead can be helpful (see Preston Guild Hall), as can chalk treatments, but these need further testing.

- *Church near Sheffield: observation only*
A damp and poorly ventilated church, with ventilation further reduced in the north-east chapel owing to a modern enclosure. Although it had been intermittently heated, some months before our visit there had

been a change to continuous heating. This had increased evaporation from the walls and caused some efflorescence, but had not dried them out, partly owing to the poor ventilation and possibly to abundant sources of moisture. The raised internal dewpoint had also made it very wet under the lead roofing. The chapel roof had probably been wet before, owing to its enclosure and past use of flueless bottled gas heaters: it had corroded through in places, and was being replaced by ventilated construction. The decking was softwood (with lapped bitumen-cored building paper over), the building paper was very wet (though not decayed) and there was evidence of water vapour (and acid?) egress via the laps. The oak rafters and purlins underneath appear to have contributed to the corrosion, and had locally corroded the lead in the gutters near the exposed rafter ends.
Conclusions: Dampness and insufficient ventilation had exacerbated any problems. The increased heating, without attention to ventilation and drying-out, had made matters worse. The renewed chapel roof will soon be inspected.

- *St Mary's, Hadleigh, Suffolk: observation only*
Eleven bays at the north-east corner of the nave were re-covered in 1988 with an early version of the ventilated warm roof, with lead laid on geotextile over softwood boards with penny gaps. Unusually, the ventilation was not from eaves to ridge, but from side to side, with two ridge-like vents running up the pitch. The lead here shows some underside corrosion, with a white product which is friable and non-protective. The corrosion is greatest in the middle and particularly at the bottom, where ventilation is likely to be poorest. There is also evidence of condensation having trickled down from time to time. The effectiveness of the vapour control layer is not known.
Conclusions: This further supports the requirement for meticulous detailing and 100% through-ventilation in a ventilated warm roof. It also seems that the use of geotextile as an underlay may have increased the amount of corrosion, at least initially.

- *Church in Northamptonshire: observation only*
This was visited two years after the nave had been re-leaded, with hollow rolls and bitumen-cored building paper over the existing softwood boarding (there is a wooden ceiling immediately below this). The underside of the lead panel lifted was in very good condition. This was thought to be because the church was continuously heated, well-ventilated (with the churchwarden providing additional ventilation by opening doors and windows on warm, dry afternoons) and consequently reasonably dry.
Conclusions: Although such a detail is potentially at risk, it appears to have been protected by the benign environment and an assiduous churchwarden. Changes to the environment could alter this situation, and indeed internal staining indicated that there had been moisture problems in the past. A re-visit is planned.

- *St Mary's Church, Stoke-by-Nayland, Suffolk: observation only*
This church has oak ceilings throughout. All roofs were reportedly re-covered in 1967 with Code 6 milled lead, laid on bitumen-cored building paper (probably Sisalkraft 420), with what looks like Erskine's felt with a high bitumen loading under that. The underside was difficult to inspect owing to the hollow rolls, but on the south aisle it appeared to be passivated, except for some faint stripes of corrosion. The nave roof, however, was more corroded, though it was not clear whether the oak or rainwater ingress was the prime cause (a possible leakage route was identified beneath the nosings). If moist air and acid egress was to blame, to find more corrosion over the nave than the aisles is not unusual, because both wind and natural buoyancy forces tend to cause more air to leave at the top.
Conclusions: An interesting variant on the double-layer theme (where the less permeable layer is normally underneath) and one which has performed reasonably well. However, the detail does not have a clean bill of health, and small amounts of trapped moisture, whether from ingress or condensation, are still problematic.

- *St Mary's Church, Stratford St Mary, Suffolk: observation only*
The south aisle of this church was re-leaded in 1986, with steps formed and new plywood decking over, covered with an impervious layer of slater's felt underneath and breather paper on top. Joints in the slater's felt had been sealed with hot bitumen and some of this had partly been absorbed into the breather paper, which nevertheless still formed a good slip layer. In spite of the plywood (and an oak ceiling and oak structure underneath), the underside of the lead was generally in good condition, although in a few places there had been rainwater ingress and underside lead corrosion (although still cosmetic) had started. As at the Museum building in London there was also some corrosion above areas where the building paper had become impregnated with the bitumen, and no longer had an absorbent upper surface. As at the house in Dorset there was also some corrosion in the rolls above the splashlaps. There had also been some movement in the felt which was showing signs of cracking in places: perhaps this would not have happened had it been fully bonded to the deck.

Conclusions: While confirming the potential for double-layer underlays, evidence from this site supports other tests which suggest a vulnerability to corrosion by any ingressed and trapped rainwater.

- *Church 2 in Yorkshire: observation and monitoring*
A very damp village church in the Yorkshire Dales. The pitched roof was renewed in 1990 directly over the existing tongued-and-grooved ceiling/substrate boarding. At the same time the central heating was

changed from column radiators to under-pew skirting heating. Occasional dripping condensation was then reported: initially thought to be emerging from under the lead, but calculations indicated that it was surface condensation after still, clear nights in the harsh microclimate. Droplet formation is concentrated beneath the tips of the nails used to fix the lead: these go nearly all the way through the ceiling boards, and today's use of longer, stouter, highly-conductive copper nails probably exacerbated the problem. The new heating, although more efficient, may well have made condensation more likely by heating the underside of the roof less: column radiators often make the air highly stratified, while with the under-pew system the measured temperature gradient was small. The church may also have become damper generally for several reasons. The average ventilation rate measured by BRE was 0.7 air changes per hour, somewhat above the CIBSE Guide's rule of thumb of 0.5 ac/h for a small church.
Conclusions: Detailed changes to heating and to lead fixings can significantly affect the outcome in marginal circumstances, and in this particular climate the condensation risk is high too. So far the problems are mainly the dripping condensation, but there is also some underside corrosion and RTL are undertaking tests. Steps should be taken to reduce moisture levels in the church, preferably at source by attention to pointing and rainwater systems, and additionally by heating or dehumidification. A dehumidifier was tested for a few weeks and had a visible effect although part of this could have been related to the unusually dry 1995–6 winter. However its operating cost of about £2.50 per winter day was deemed high by the church.

- *Church 3 in Yorkshire*
  Another very typical church with the same boarding forming the ceiling and supporting the lead. The chancel roof has an oak ceiling, over which the lead was badly corroded, particularly above the boards (there was some passivation over the gaps). Over the softwood boards in the aisle, however, the lead was in reasonable condition. Although subjected to the same internal atmosphere, the oak boards were very wet and the softwood boards were not, a consequence of their different hygroscopic properties.
  Conclusions: The difference in corrosivity of different woods is related to both their physical and their chemical properties. This is a potentially useful site for testing remedial underlay and/or coating specifications for oak.

- *Salisbury Cathedral, Wiltshire: observation, testing and monitoring*
  All roofs inspected were relatively good condition. Temperature and humidity monitoring was carried out in several places. The buffering effects of the large volumes of air and hygroscopic material (particularly timber) in the roof spaces are thought to have helped to protect the lead from severe underside corrosion.
  Conclusions: Such roofs appear to be protected by three mechanisms:
  - moisture-stabilization by large volumes of absorbent material
  - a degree of isolation from the atmosphere in the building underneath
  - passivation of the lead by moisture which emerges from the wood when the sun heats the lead and the roof space.

Good ventilation via the gap-boarding also helps, where the roof space is relatively dry. However, the mechanisms and their interactions are not yet completely understood.

- *Mansion in Derbyshire: observation, testing and monitoring*
  The lead here covers both the top and the sides of some mansard roofs. During refurbishment of one roof, the opportunity was taken to improve outside air ventilation (using 'cold' roof principles) and to add fire barriers. At the same time, to avoid the ingress of driving rain and snow, copper flaps were added which closed when air velocities through the ventilators were high.
- The new roof shows more corrosion than a similar existing roof, which was also not so well ventilated. There are four likely reasons for this:

  - moist air and water vapour are entering the roof void from below, and with the lower roof space temperature the timbers have become moister and the likelihood of corrosive conditions has increased
  - the flaps are not working as intended and moisture is being trapped
  - the additional ventilation has undermined the buffering mechanisms which occur, for example at Salisbury Cathedral. This could have increased the number of evaporation/condensation cycles and at the same time have made it more difficult for the lead to self-passivate spontaneously in warm, sunny weather
  - unfortunate starting conditions, leading to unprotective initial corrosion.

Monitoring is currently being undertaken and shows that the roof space is very cold, the local microclimate very damp and the potential for condensation is high. Future tests are planned with variable amounts of ventilation.
Conclusions: Increased ventilation is not necessarily desirable unless one can attain ideal 'cold roof' conditions, in which there is a highly effective air and vapour seal at ceiling level and 100% outside air through-ventilation of the roof space. This is very difficult to achieve in any existing building, let alone a historic one, other than by means of well-detailed ventilated warm roof construction.

- *Metal store in London: observation*
  A brief inspection here has revealed heavy corrosion around the perimeter of lead laid on Erskine's felt on plywood. This is characteristic of attack by acetic and/or formic acids. The environmental conditions have not yet been characterized, but being over a metal store, they are unlikely to be particularly humid.
  Conclusion: Beware plywood in all but the driest conditions.

- *Museum in London: observation*
  The main roof was replaced in 1966–7 with a completely new steel structure, from which the original oak beams, purlins and boarded ceilings are suspended. The lead is laid on good quality 30 mm softwood boarding with penny gaps, with an intervening layer of building papers of various grades, sometimes bitumen-cored and sometimes not. The main pitches of the roof and upstands (but not the gutter soles) have a layer of aluminium foil-faced insulation board, with the foil face upwards (touching the underside of the decking boards). The roof space is ventilated by warm, relatively dry air rising from inside the building via gaps between the ceiling boards and out through louvres in the upstands to the valley gutters. [34] The underside of the lead is generally in very good condition, although with some traces of corrosion in places, either associated with water ingress, joints in the insulation board and places in which bitumen has leached out of the building paper above knots and resin pockets. Corrosion on the outer parts of some of the rolls, above the splashlaps, is quite severe and is being investigated. There is a high organic acid content in these locations.
  Conclusions: The main reason why most of this roof has performed well is because the building and the roof space is relatively dry, well-heated and well-ventilated. Even though there are condensation risks at times, in warmer conditions the constant, warm ventilation will have helped the timber to dry out well, making it able to absorb considerable amounts of moisture during adverse conditions. The main roof construction with the aluminium foil vapour control layer (which was still in excellent condition where we inspected it) approximates to that of a 'warm' roof and might have been expected to be susceptible to thermal pumping. We suspect that this did not happen in practice owing to:

    - the relatively small volume of air which is trapped in the timber boards, at least in relation to open-cell insulating materials
    - pressure-relief via the joints in the insulation boards, which are not taped.

  However, the entrapment of the timber may be the reason for the high organic acid content in the slash-laps. There has recently been a proposal to humidify the museum to improve conditions for exhibition display. We have expressed strong reservations about this, and we understand that humidification may now be restricted to some basement areas.

- *Mansion in Buckinghamshire: observation, testing and some monitoring*
  An early twentieth-century mansion which had a variety of uses before converted to its current use as an office and training centre. The roofs have void spaces which are not deliberately ventilated. The lead, thought to be largely original, is mostly laid on hair felt over softwood boarding. The original lead is usually significantly corroded above the boards, with a compact but sometimes flaky layer of yellowish corrosion product, but the corrosion product is relatively thin (5% or less of total thickness) and has not affected the life of the roof. Above the gaps between the boards, the original lead is passivated. Many nosings have been repaired and a few sheets replaced.
  A small number of sheets were renewed in the late 1980s and laid over geotextile in October. These immediately began to corrode above the gaps between the boards. Since then the corrosion has continued, and also spread into the rolls. Sample tests however, showed that lead laid in the early summer was much less susceptible to this type of corrosion. Environmental monitoring indicated that the building was relatively dry.
  Conclusions: These were the first tests to show that, at least in marginal situations, the time of laying and the underlays used might have substantial effects upon corrosion behaviour. It would be worth returning to this site to undertake more inspections and tests, including tests of specifications (such as chalk treatments and underlays) which the research now suggests could be really helpful in situations such as this.

ENDNOTES

1 The original paper recommending ventilated warm roofs (Murdoch 1987) and current guidance (LSA 1993a) draws attention to some of these detailed issues. However, experience in practice suggests that there would be no harm in underscoring these more strongly, and probably including some drawn details of do's and dont's, as in the BRE publication *Thermal insulation: avoiding risks* (1994). Murdoch (ibid) also stated that the ventilated layer would help to disperse any moisture that did penetrate the vapour barrier: while this is correct, site experience indicates that any weakness to the passage of water vapour, and in particular moist air, may initiate underside corrosion.

2 Solubility of the oxide and hydroxide is lowest at pH 9.5 and increases rapidly with rising acidity or alkalinity (Pourbaix *et al* 1966). Protection will therefore be best at pHs between about 8 and 11.

3 In the 1970s patination oil was developed to control initial weathering and avoid white staining of brickwork subject to run-off. Its effect is primarily physical, as a barrier layer to keep water and lead apart while the lead has time to develop its own patina underneath under the influence of light and chemicals able to diffuse through the oil layer.

4 The higher atmospheric concentrations of sulphur in the age of coal-burning may be significant here.

5 Underside corrosion is not restricted to lead. Some of the physical principles also apply to other roofing materials, particularly zinc and aluminium (Farrell et al 1992).
6 Excess moisture and condensation may also affect the roof structure, whether or not the covering material is resistant to underside corrosion. As a general rule, decay fungi only become active if wood has a moisture content above 20%. Wood-boring insects also prefer moist timber, typically over 15%: at lower moisture levels their activity diminishes and below about 10% they cannot survive (Oxley & Gobert 1994, Ridout 1995).
7 However, on a roof, if this hard, compact film becomes too thick, stresses from thermal movement of the lead cause it to crack and spall, leading to multiple layers of a dense, flaky corrosion product.
8 If so, since lead oxide is slightly soluble in water it may help to explain why passive films have only a limited life in continuously condensing conditions, or after many condensation/evaporation cycles in the test rig, as these would tend to wash away some of the oxide. With more occasional condensation, dissolved oxide might crystallize out again, and in any event there will be more time for self-repair to occur. It is also possible that the oxide is covered by a less soluble layer (for example containing carbonate or even sulphate), which confers increased initial corrosion resistance.
9 Some modern sealants, including some silicones, also emit acids when curing, with similar corrosive effects.
10 However, the oak used in RTL's external test facility was found to have a pH of 4.2, putting it in the high rather than the severe category (RTL 1995, Report 6)
11 With the exception of wood fibre insulation board which Hill found to be slightly less corrosive than Swedish whitewood and redwood, and (just) the least corrosive of all the samples tested (Hill 1982).
12 Museums have also found that manufactured boards tend to be highly variable in their corrosive effects, not only by product type, manufacturer and source, but also from batch to batch (Tennent, Tate & Cannon 1993).
13 To avoid interstitial condensation, this inner layer of insulation must not be too thick in relation to the outer one.
14 Ventilated warm roofs have a buildability advantage in that the AVCL can be placed rapidly and, if suitably detailed, act as temporary weatherproofing. However, to avoid initial moisture and corrosion the insulation and the supporting structure for the lead should nevertheless be protected from rain during construction.
15 *Architecture with Rheinzink Roofing and Wall Cladding* also recommends preservative-treated softwood decking with a continuous layer of bituminous roofing felt or other non-porous lining on top in order to protect the metal from alkali, condensation and wood preservatives (Rheinzik GMBH 1988). However, for lead we have found that bituminous linings can melt and adhere to the lead. In addition, as a consequence of lead's chemistry, even small amounts of moisture trapped between lead and impervious underlays can cause large amounts of underside lead corrosion from refluxing water in the absence of air, particularly if there are also any acid contaminants, which have sometimes been claimed to be present in bitumen itself, though Hoffman & Maatsch (1970, 293) do not agree.
16 the reason for a smaller outlet than inlet in the UK is probably to reduce the negative pressure in the air gap, which could otherwise draw additional moist air through. Though BRE could not confirm this (C Sanders, BRE Scottish Laboratory, pers comm), recent North American studies support this practice.
17 Another referenced document (DTO 40.21) suggests that humid Channel and North Sea coastal regions of France require similar care.
18 A Canadian paper recommends four-way CDR ventilation with a counter-battened arrangement (Shaw and Brown 1982).
19 In 1737 it was ascertained that the roof of Salisbury Cathedral contained 2641 tons of timber (Gwilt 1982)
20 In a ventilated warm roof it is good practice to put a breather layer which is impermeable to liquid on top of the insulation, detailed to allow any condensation or water ingress from above to run out into the gutter.
21 Exceptions are constant distillation, as in accelerated testing and in some failed warm roofs, situations where the lead is thin or highly stressed and a small amount of corrosion has a disproportionate effect, and sometimes in nosings surrounded by splashlaps which are often rainwater-filled.
22 One contractor told us that in this inflationary age, he finds 'pound gaps', slightly wider gaps, about the thickness of today's pound coin (just over 3 mm) to be more suitable.
23 Computer modelling by BRE Scottish Laboratory suggests that if lead is laid over dry softwood in September, this will help to protect the underside from condensation for the entire first winter. However, the model does not allow for short-circuiting of moisture through gaps.
24 In general, and owing to natural buoyancy effects, air will tend to enter the church at low level and leave at high level. Water vapour, being lighter than air, also tends to rise to high level though the effect is often small because the air is mixed by convection currents. The consequence is that, on average, the dewpoint will tend to be higher at high level. However, when the church is heated either artificially or by sunshine, it will tend to be warmer there too. Differences in the dynamics of heat, air and moisture transfer will affect the corrosion patterns observed.
25 The running-out of condensate into the laps is also a characteristic pattern where Type II corrosion is involved. While one might expect condensate to accumulate more around the line of the lap between the two sheets, for the porous arched structures observed with Type II corrosion, water can move around under the outer surface of the corrosion product. Indeed, on the day this photograph was taken, the outer surface of the corrosion product above the gap appeared to be dry, but when scraped it exuded moisture and turned into more of a paste.
26 We have not actually found any sites with bituminous felt layers alone, but in RTL's tests they did not perform very well even in the absence of acetic acid because of the corrosive effects of any ingressed and trapped moisture. They also tended to stick themselves to the lead.
27 This is where oak boarding is most often found because it also serves as the ceiling.
28 Some recent evidence suggests that, as it ages, timber becomes more permeable to moisture and increases in equilibrium moisture content (Ridout 1995).
29 A pressure of 1 Pascal is approximately equal to 0.1 mm WG (Water Gauge) on a manometer.
30 A study of the statistics of lead roof failures is beginning and will examine some parish records more systematically.
31 It is also possible that the age of coal, which brought with it high ventilation rates, dry atmospheres in buildings (at least if they did not have too much gas lighting), depressurization of roofspaces and a high-sulphur local environment might have been a golden age as far as lead survival was concerned.
32 In real life, however, the situation is dynamic, changing with season, time of day and activity within the building. This applies particularly to the timber immediately in contact with

the lead, whose temperature swings greatly exceed those of the outside air owing to warming by the sun and radiant cooling to the clear night sky. At the same time moisture will come and go to the lead wood interface both through the wood itself, around the edges of the planks, and via joints in the lead.

33 With the possible exception of very old lead with a high content (> 1%) of other metals, which is usually very difficult to work.

34 The louvres have fans behind them which are intended (and used) for exhaust ventilation of the roof void in hot sunny weather only, in order to reduce radiant heat gains into the rooms underneath. However, since the fans do not have shutters, the louvres are always available for natural ventilation too, and the dominant air movement path is of warm air rising from within the building under natural buoyancy.

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