Lead roofs on historic buildings

An advisory note on underside corrosion

ENGLISH HERITAGE

LEAD SHEET ASSOCIATION

Lead has been used for centuries to cover roofs and as a result of its excellent performance record, it continues to be widely used – particularly on historic buildings. These photographs show lead roofs at (1) Kingston Lacy, (2) Wittington House, (3 and 4) Hampton Court, (5) the White Tower, Tower of London, and (6) St Cross, Winchester

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Background

Lead is widely used in historic buildings and has an excellent performance record. Like several other metals, it can be susceptible to underside corrosion, and this occasionally contributes to premature failure.

Underside lead corrosion (ULC) has been known about for centuries. However, this did not affect lead's reputation for durability. Instead ULC was regarded as something which was sometimes found when this durable material needed recasting, when the corrosion product was collected and used in paint.

In the 1970s, incidences of severe ULC were thought to be increasing. In 1986 a study by the Ecclesiastical Architects' and Surveyors' Association (EASA) concluded that because fresh lead is attacked by pure water, the most likely cause was increased condensation, the result of changes to heating, ventilation, insulation and occupancy. EASA recommended reducing condensation risk by ventilation or design.

Shortly after this, the Lead Development Association and the Building Research Establishment found problems with 'warm' sandwich roofs, which since the 1960s had been regarded as good practice for new insulated construction and reroofing. Since then the Ventilated Warm Roof (VWR) has been recommended for new construction.

English Heritage (EH) commits large sums of money annually to grant-aiding lead roof repairs, some ULC-related. In such cases, EASA's recommendations often proved difficult to apply whilst the VWR conflicted with the principle of minimum intervention to the structure of an historic building. Even where great care had been taken, repairs were not always completely free from ULC, which was sometimes also found where there had been little or none before.

In 1993, English Heritage therefore started a programme of research to improve understanding of ULC: its occurrence, its causes, and whether it could be controlled whilst retaining historic details as far as practicable. Some technical and laboratory studies were jointly supported by the Lead Sheet Association (LSA) and the Historic Royal Palaces Agency.

Outline of the research

The laboratory research has included desk studies, computer modelling, and indoor and outdoor test rigs. Thirty buildings have also been subject to inspection, monitoring and testing. A web of complex processes, both adverse and beneficial, has been revealed. As a result, and owing to each building's individual circumstances, it has not yet been possible to develop universal guidance.

The purpose of this advisory note

In response to many requests from those working on historic buildings, English Heritage and the Lead Sheet Association have produced this summary of preliminary findings in order to make available the information from the research to date. It is intended to help professionals

- to appreciate some of the issues
- in their assessment of lead roofs in historic buildings
- in developing proposals for renewal or repair which can reduce the likelihood of ULC whilst minimising the amount of alteration to the building fabric

Summary of findings

Lead's natural durability arises because most of its salts are insoluble and form protective surface coatings during weathering. Unprotected lead is vulnerable to attack by pure condensed or distilled water and its underside cannot weather in the same way.

ULC can be particularly bad when organic acids accumulate, and these also break down passive layers. The corrosive effect of fresh oak is well known. It is less widely realised that old oak can also be corrosive, and that all timbers contain organic acids. Some timbers are very corrosive, as are some manufactured boards such as plywoods, particularly when damp. Timber preservatives can also cause problems: apart from any chemical effects, treated timbers often come to site damp. Some preservatives also attract moisture.

ULC is significantly influenced by the conditions to which the lead is exposed during laying and for some months afterwards. Clean lead can start to corrode as soon as it encounters moisture: a shower of rain, a damp building, dewy weather, or damp decking. In side-by-side tests, sand-cast and milled lead, and historic and modern lead show little difference in initial ULC rates. Once initiated, ULC can continue when conditions are adverse. Inappropriate heating and ventilation may exacerbate the situation.

In new buildings it is now recommended that the space under the lead is ventilated by outside air, as in the Ventilated Warm Roof (VWR). For these to work well, the study has found that it is essential that the whole of the underside is ventilated and that the vapour control layer is specified, detailed and installed to be both air and vapour tight.

In existing roofspaces, improvements to ventilation may not always be helpful unless there is a highly effective air and vapour control layer at ceiling level (something almost impossible to achieve in a historic building). It is therefore important to understand the situation before intervening.

Figure 1 The corrosion behaviour of lead is markedly affected by small changes in environmental conditions. This test specimen, near actual size, was placed on a sheet of polythene-backed building paper on softwood and subjected to evaporation / condensation cycles for two weeks. The paper had nine pinholes in it: above these, dots of corrosion product vary in colour from white through yellow to brown. In the square around them, a dark 'passive' layer has developed which has some resistance to ULC. At the outer perimeter, the lead is bright and virtually unaffected. This mechanism of spontaneous passivation in conditions verging upon the corrosive has helped lead roofs in some historic buildings to perform well, even in damp situations.

Many lead roofs in historic buildings often become damp but show little ULC owing to the development of passive protective films in vulnerable areas. Sometimes these form spontaneously in warm, moist (but not wet) conditions - as in the darkened area around the nine corroded dots in the photograph above. Paradoxically, additional ventilation can sometimes suppress this mechanism.

Since starting conditions greatly affect what initially happens, a replacement may not necessarily develop similar protection. Underside treatment may therefore be desirable, particularly if a dry start cannot be ensured. The research has tested protective coatings of linseed and patination oil and factory- and site-applied paint coatings. All these helped to reduce ULC, though with some drawbacks: pre-coatings are easily damaged, and oils and paints applied on site after the lead has been formed must have adequate time to cure. An alternative, and promising, process is the site application of slurries of chalk in water, which provides a chemical environment which encourages spontaneous passivation and allows the lead to be re-laid quickly after coating. Further trials of coatings are in progress.

Warning

Any applied pretreatment must not cause adhesion between the substrate and the lead sheet, or thermal fatigue failure may occur.

1 Introduction

Underside lead corrosion (ULC)

When plumbers strip the roofs of churches, or other buildings covered with lead, which has lain undisturbed for many years, they usually find that side of the lead which is contiguous to the boards, covered with a white pellicle, as thick sometimes as a half-crown: this pellicle is corroded lead, and is as useful for painting, and other purposes, as the best white lead......this calcined lead not being washed off by the rain, may, in the course of a great many years form the crust here spoken of.

From volume 3 of *Chemical essays* by R Watson, 1787

Lead roofs sometimes develop a certain amount of corrosion product underneath. It can be compact, powdery or flaky. It is usually white, sometimes pink or yellowish. Its chemical composition varies, but basic lead carbonate usually predominates, often with patches of red or brown lead oxide. Underside corrosion can also affect continuously-supported roofs of other metals, particularly aluminium and zinc.

Figure 2 This 1850s roof has eventually failed owing to fatigue cracks caused by thermal stresses in large sheets subject to constant thermal movement. A small amount of ULC was also visible under the sheets: this is perfectly normal, and has not contributed significantly to the failure.

Failures by ULC alone are rare

Most lead roofs which fail prematurely have cracked or slipped owing to thermal movement and the related stresses when sheets are too large, or fixed too rigidly, or not securely. *The lead sheet manual* (LSA 1990, 1992, 1993) gives recommended sizes and fixing details. Occasionally ULC itself can be severe and failure rapid, ie within 15-30 years and sometimes faster still. ULC, even if localised, can also accelerate thermal fatigue failure by creating weakened, thinned spots in which stresses become concentrated.

Underside corrosion is not new

ULC has been well known to plumbers for centuries, but did not harm lead's traditional reputation for longevity, being regarded as one of the products of the eventual decay of a long-lived material. In the 1970s, however, ULC was thought to be increasing. In 1986 two studies reported (see EASA 1986, LDA January 1988). They identified two principal causes, outlined as follows.

- ***Condensation corrosion problems***
  Fresh lead is attacked by pure water, as formed by distillation and condensation. Over the past decades, changes to heating, ventilation, occupancy and insulation have tended to increase condensation in many roofs. To reduce the risk, better construction and ventilation were advocated, on the principle 'no moisture - no corrosion'.

- ***Warm deck roof failures***
  Insulated 'warm deck' roofs - which had the lead directly over insulation above an air-and-vapour control layer (AVCL) - had been increasingly used in new and repair work. If the AVCL was poor, moisture from within the building could condense in the insulation. However, in roofs with a good AVCL, an unexpected new problem occurred. Rainwater or moist air could sometimes be drawn in by the partial vacuum which developed as the trapped air under the lead contracted when the temperature fell, particularly during a shower on a sunny day. The research has found that this 'thermal pumping' effect is most likely in low-pitched roofs with splash-laps, where rainwater which is drawn into splashlaps by capillary action can form an airtight seal.

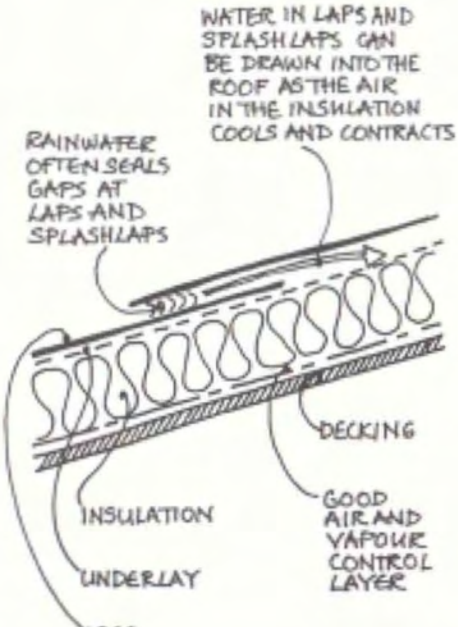

Figure 4 ***Warm roof construction should not be used*** *because water or moist air can be drawn in as the roof cools down.*

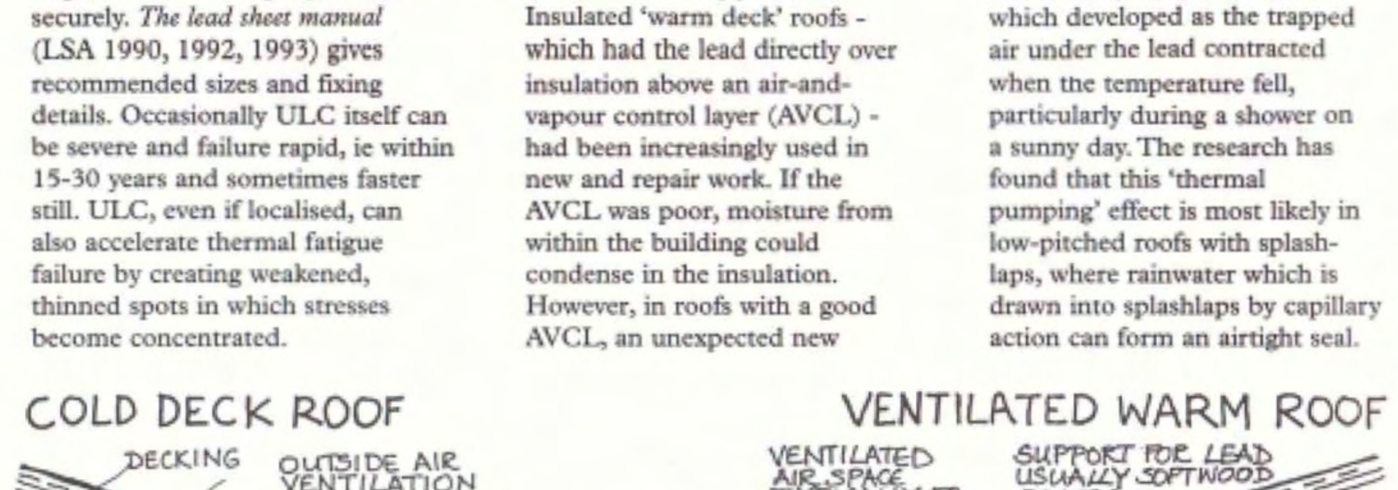

Figure 3 The cold deck roof (left) and ventilated warm roof (right) are similar in principle. Ventilation should be by outside air only, and run from bottom to top with no dead spaces. For good performance, the air and vapour control layer (AVCL) must be both air and vapour tight. This is much more easily done in the VWR, where the AVCL can be applied on top of the structure. In an existing building it is very difficult to instal an effective AVCL at ceiling level.

In 1986 warm deck roofs ceased to be recommended. This has removed one of the principal causes of rapid ULC-related failure. For new roofs, Ventilated Warm Roof (VWR) principles are now recommended, as illustrated in Figure 3. The alternative 'cold' roof is less desirable, being difficult to construct and maintain to the standards required. Flat sandwich cold deck roofs have a particularly poor performance record and also do not comply with Scottish Building Regulations. Pitched versions with accessible roof voids are more tolerant, and they also permit the structure to be inspected.

Roofs in historic buildings

Roofs in historic buildings seldom comply with the current recommendations outlined above. Many buildings (particularly village churches) have no ventilated roof spaces at all.

Conversion to a VWR is often historically or aesthetically unacceptable; there are added technical problems of geometry, space, appearance, weight, or cost. Preliminary studies for English Heritage have also indicated that

- 'no moisture, no corrosion' was difficult to apply in practice. In addition, the relationship between the amount of ULC and the amount of moisture did not seem to be direct: some relatively dry roofs were more severely corroded than other very wet ones.
- changes to ventilation, heating and vapour control were not always as helpful as expected, and sometimes even counter-productive. Monitoring showed that the dynamics of evaporation and condensation were significant, with the most rapid corrosion taking place not when the lead was at its wettest, but while it was drying out.
- the condition of the lead, the building, the decking and the weather at the time of laying and for a few months afterwards could greatly affect initial corrosion behaviour, and so influence long-term performance.

Results of the current research

Preliminary findings of the research have been published in Bordass, 1996: also Bordass, in *EH Res Trans* 1997. These confirm the importance of

- the initial condition of the building, the weather, the decking and the lead
- the physical and chemical properties of the decking timbers
- the nature of the underlays
- the dynamics of moisture movement

Simple all-purpose answers have been elusive, short of a meticulously-detailed and well-built VWR, a solution best suited to new construction.

Apart from some belfries, lead roofs in historic buildings seldom approach the modern ideal, but most have given excellent service over long periods. To preserve as much as possible of the existing construction, a careful assessment of risks is needed. It may not always be necessary or desirable to add roofspace ventilation - at least as far as the lead is concerned.

In any renewal, it is important to avoid early corrosion by protecting the lead from moisture and organic acids. Protective surface treatments are discussed in Section 6.

2 Why does lead corrode?

Pure water attacks fresh lead

Lead's natural durability in many circumstances arises because many of its salts are insoluble and form protective surface layers. Fresh, clean lead lacks this protection and can begin to corrode as soon as it gets wet. For example, white deposits can often be seen on a new lead roof after the first rain or dew. Eventually, however, this loose material is washed off in the rain while carbon dioxide and air pollutants (particularly sulphur compounds) react with the lead and the residues to form protective coatings. The white run-off can be unsightly, and can also stain surrounding building materials. LSA-approved patination oil should be used to minimise this effect.

The underside cannot benefit in the same way. If fresh lead is laid in damp conditions, ULC may start to appear in places after a few hours. This does not mean that the life of the roof is threatened, but ULC, once initiated, is more likely to continue to build up when

Figure 5 A quinquennial inspection found a compact layer of white corrosion product under this roof on a historic house in Dorset. Over most of the roof, lead which was wire-brushed clean did not corrode again. It was concluded that most of the corrosion had occurred during or shortly after re-roofing, when the lead was vulnerable and the substrate timbers were damp. Coatings of various kinds can help to protect fresh lead from this initial corrosion: see Section 6. At the bottom right, note also the mild corrosion originating from the distillation of rainwater trapped in the splashlap by capillary action. This is discussed further in Section 3.

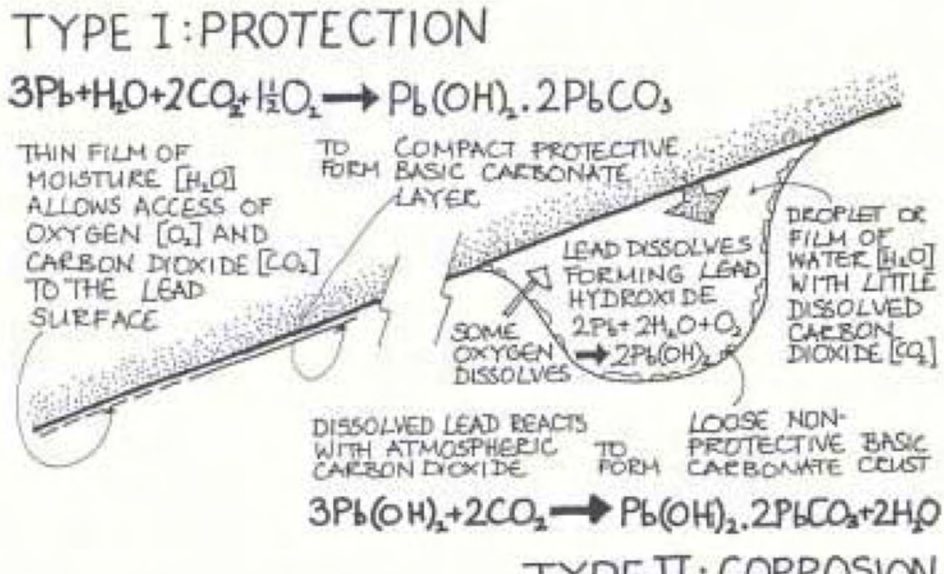

Figure 6 Where reaction with a thin film of water, oxygen and carbon dioxide occurs at the surface of the lead (left), a compact film of basic lead carbonate (often also containing lead oxide) can build up. This can help to protect the lead from further corrosion. On the right, however, carbonation occurs at the surface of a water droplet, and this forms an unprotective powdery or flaky crust.

Figure 7 This scanning electron micrograph (Scale: x 130) shows platelets of Type II corrosion product formed around the base of a water droplet. (Photograph courtesy of Interface Analysis Centre, University of Bristol)

conditions are adverse. Occasionally this may cause the sheet to corrode through in places. More often, local thinning by ULC can increase lead's vulnerability to failure by fatigue under thermal stresses, or even under its own weight.

Carbon dioxide affects the outcome

Lead can react with water, oxygen, and carbon dioxide in the air to form basic lead carbonate, which is relatively insoluble. Depending on the conditions under which this happens, and the physical form of the product, it may either help to protect the lead or make it susceptible to further corrosion, Hoffmann (1970) defines two distinct types, as outlined below.

Type I: Protective carbonate formation

The carbon dioxide dissolves in the water. This then reacts at the surface of the lead, forming a compact, protective layer of basic carbonate.

Type II: Corrosion

The water contains dissolved oxygen but little carbon dioxide - for example in freshly-formed condensate droplets or in damp places with poor access of air. The lead now dissolves in the water as lead hydroxide and diffuses as ions to the outer surface, where it reacts with carbon dioxide at the outer surface of the droplet, again forming basic carbonate. This in turn removes lead ions from solution, allowing more lead to dissolve and more basic carbonate to form towards the outer surface. This corrosion product, although chemically identical, is loose, non-protective and tends to trap moisture.

Condensation and trapped moisture

Moisture is a critical contributor to ULC. Water may

- attack the lead directly
- influence the reaction with carbon dioxide, as outlined above
- mobilise chemicals, which may be aggressive or passivating
- transport soluble materials from the lead surface - this may expose fresh surface for reaction; but copious wetting may also wash organic acids and salts away
- partially cover the lead and control oxygen diffusion: corrosion is often worst near the wet/dry interface

Condensation and corrosion

The temperature of a lead roof varies constantly in relation to outdoor and indoor conditions, modified by the thermal performance of the roof. Owing to radiation, it varies by more than the outside air temperature. In strong sunshine, it can reach 70°C or more depending on orientation, shelter and surface finish.

In still weather, radiation losses to a clear sky can make the surface of a roof colder than the outside air itself (at night by 5°C or more). This is when dew or frost tend to form. Flat roofs become coldest under these conditions because they have the greatest sky 'view'. Above gaps in the decking boards, moist air in the roofspace can easily reach the underside of the lead. When the lead's temperature drops below the dew point, condensation will occur and on fresh lead rapid corrosion may follow. However, lead which has been able to develop a passive coating may be unaffected.

Moisture absorption in decking boards

Above decking, moist air and water vapour has to diffuse through the

Figure 8 A historic house by the Thames, now used as offices. One October fresh lead was laid over new geotextile felt on the original softwood boarding. This photograph taken three weeks later shows how the autumn dews initiated ULC above the gaps between the boards. Note the characteristic 'fish-tailing' of white Type II corrosion product on the underside of the lead to the inside of the rolls. This is where moist air from within the building rises into the rolls and sometimes condenses. Above the decking, the lead is not corroded because moisture cannot reach it so easily and some has been absorbed by the boarding.

boards or pass through the gaps between them. As conditions become damper, moisture is also absorbed by the boards, potentially delaying the onset of condensation and possible corrosion. Suitable decking boards (eg pine, not the more permeable and less absorbent oak), which have been dried over a hot summer are sometimes even able to protect the lead from condensation throughout the following winter (paradoxically, solar shading by temporary roofing can reduce this effect, though rain protection is naturally more important). Conversely, decking which has become wet may retain moisture for long periods before it eventually disperses.

Moisture and corrosion risk

The research indicates that the amount of ULC is not solely or directly related to the amount of moisture under the lead.

- The initial state of the lead greatly affects its susceptibility to corrosion when condensation occurs.

Figure 9 After forty years, ULC has consumed, on average, about one-quarter of the thickness of the lead here,and the roof is beginning to fail. Here, and frequently when ULC is severe, the prime cause is trapped moisture plus organic acids from the substrate: in this case hardboard over oak, which are both aggressive to lead. The rather less corroded stripes running up the sheets show where the rafters come.

- Chemicals can have major effects on the amount of corrosion.
- Condensation corrosion tends to be fastest not when the lead is cold and wet, but when it is warmer and in the process of drying out.

Condensation is not always corrosive

Moist but not quite condensing conditions can create compact, passive layers which afford some protection from ULC. Although this mechanism cannot be relied upon, the research suggests that it has helped to protect lead on many historic roofs. The outcome will vary with the state of the building, the lead, and the weather at the time of laying, which helps to account for some of the observed variability in performance. Protective coatings have therefore been investigated, as discussed in Section 6.

Distillation effects

Often greater in its corrosive effect than fresh condensation is the distillation of trapped moisture from any source (condensation, construction, rainwater or thermal pumping). This may occur, for example, in rapidly alternating sunshine and cloud. The mechanism helps to explain why corrosion is often worse on south and west slopes than on the - often damper - north-facing ones. ULC can be much worse (and not so orientation dependent) when organic acids are present, as they frequently can be - see below.

The effects of acids

Lead resists many strong acids because their salts are insoluble. Unfortunately, weak organic acids such as formic and acetic form lead salts which are very soluble, and so can cause severe ULC. The effect is also catalytic: once formed, the salts then react slowly with carbon dioxide in the atmosphere to form basic lead carbonate, releasing free acid which is then ready to attack the lead yet again.

Where do the acids come from?

> *It is believed .....that lead which lies on deal boards is not so apt to be covered with this white encrustation, as that which lies upon oak: if there be any truth in this observation, it may, perhaps, be explained from hence, that oak contains a much stronger acid than deal, and this strong acid being distilled, as it were, by the heat of the sun in Summer, attaches itself to the lead, and corrodes it: or this corrosion may be the effect of the sun and air, which, by their constant action, calcine or corrode the lead.....*
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> From volume 3 of *Chemical essays* by R Watson, 1787

While fresh oak is notorious, all timber and timber products contain acetic acid, a spontaneous breakdown product of 'dead' cellulose which can be broken down by water to form more acid. Timber products such as plywood, chipboard, hardboard and oriented strand board (OSB) often contain formic and other acids in adhesives and binders, which can make them very aggressive when

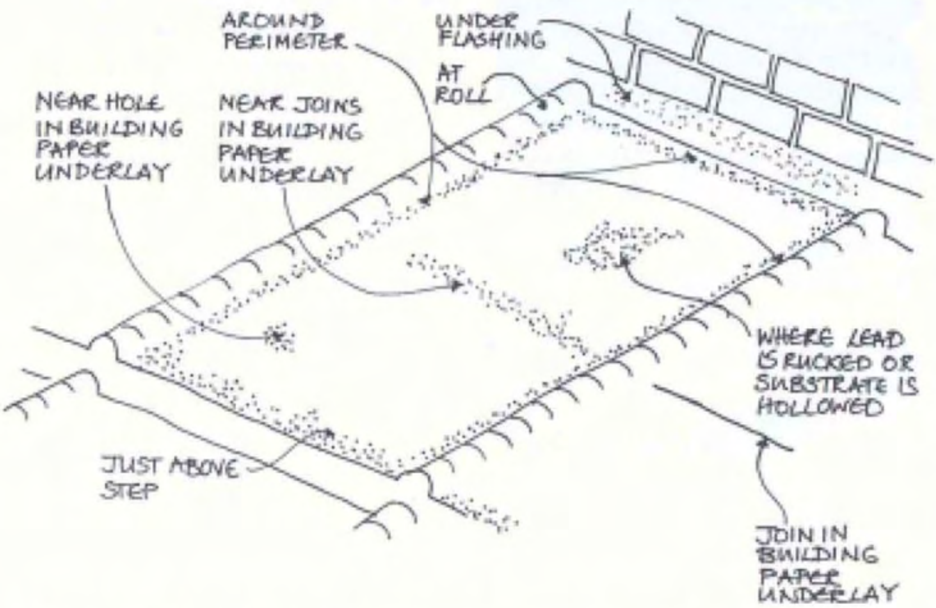

Figure 10 Typical locations of acid-related corrosion. If acids are present, corrosion is often found around the edges of the lead sheet: inside rolls, above laps, and above areas where the lead has become blistered or folded, or the substrate dips away. This appears to be a consequence of distillation of water across the air gap, easier access of carbon dioxide to regenerate acid from the lead salts, and electrochemical effects.

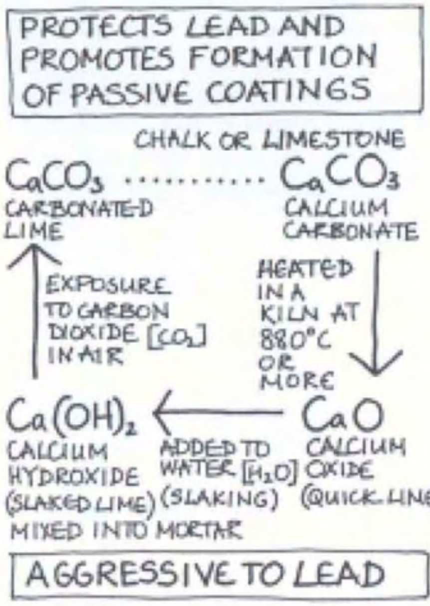

Figure 11 The lime cycle. Calcium carbonate – $CaCO_3$ – the start and end point of the cycle, is nearly neutral, does not attack lead and can help to protect it. Slaked lime – $Ca(OH)_2$ – is alkaline and aggressive to lead.

damp. If acid vapours cannot disperse readily, this action continues until harmful quantities accumulate. Even old timbers are not necessarily safe, and they can generate more acid if they become damper or are in a state of decay. Heat accelerates the reaction, making trapped moisture particularly aggressive in moist and distilling situations. Acid can also accumulate in new timber during kiln drying. Acid corrosion is often worst where the lead does not quite touch the substrate: here distillation can occur and more carbon dioxide is available to regenerate the acid.

How to reduce the risk and extent of ULC

- Do not roof in damp conditions or using damp materials. Timber moisture content should not be more than 16% at the time of laying, unless some form of lead pretreatment is used.
- Take care when considering additional ventilation. (See Section 3.)
- Do not use substrate species and materials known to be aggressive. Check that initial acidity is also low. (See Section 4.)
- Choose appropriate underlays. (See Section 5.)
- Consider pretreating the lead. (See Section 6.)
- Avoid trapped situations, particularly if acids are likely.
- Try to lay between April and July. Avoid the autumn. Where temporary roofs are used, seasonal effects are less important but spring or summer completions are still preferable.
- Operate the building's heating and ventilation to help minimise accumulation of moisture in the substrate.

Alkaline environments

It is also well known that embedded lead is attacked by alkalis, in particular fresh lime in mortar and concrete. Hence built-in lead (beyond the first 15-20mm where mortar carbonation occurs rapidly) is routinely protected with a coating of bitumastic paint. Where lead roofing and guttering is placed over concrete or mortar, barrier layers have often been used (but see Section 5). As a general rule, the environment under a lead sheet should be close to neutral (pH 7). Lead oxide and hydroxide are also less soluble near the neutral point, furnishing a certain amount of additional protection.

Do some types of lead resist ULC better?

Laboratory and site tests to date have revealed little difference in the nature and amount of ULC for similarly-prepared milled and sand-cast lead, and between historic lead and modern lead. Continuously machine-cast (DM) lead has only recently been included in the research and test results are not yet available. Most differences found so far in the performance of different lead specimens are related not to composition or production method but to its initial surface state. While alloys with a tin content of over 1% are more resistant to corrosion from acid vapours, they are too hard to be used for roofing.

3 Roof construction and ventilation

Introduction

ULC problems are often blamed on 'an absence of ventilation'. However, in historic buildings, extra roofspace ventilation does not always reduce ULC unless the true principles of a 'cold' roof are achieved. These include

- an air and vapour control layer (AVCL) to stop any significant amounts of moist air or water vapour entering the ventilated airspace under the lead
- ventilation of this space by 100% outside air

Roofspaces in historic buildings

Roofs in historic buildings seldom comply with the above principles and the guidelines outlined in Section 1. People are often tempted to make do as best they can, for example by adding a certain amount of ventilation and an incomplete vapour control layer. However, the research suggests that such half measures can sometimes be worse than useless.

It is important to assess the performance of the roof as it stands. Many historic roofs have worked well, or reasonably well, even though the substrate decking sometimes forms the ceiling of the space, with no roofspace, no outside air ventilation at all, and frequent condensation near gaps between the boards, and sometimes more generally.

The research has been seeking to find out why so many lead roofs perform better than an analysis of condensation risks would lead one to expect. The results have been mixed: whilst many roofs show little ULC, there are some which are problematic today and also seem to have required more frequent attention in the past, though maintenance lifetimes of less than 30-50 years are rare. Owing to the influence of starting conditions (see Section 2) even in risky situations corrosion rates can vary significantly, and even roofs at high risk may enjoy some long intervals of trouble-free service.

Three typical situations

When a roof in a historic building is to be repaired or replaced, ideally its construction and detailing should be changed as little as possible. Three situations are common, as outlined below.

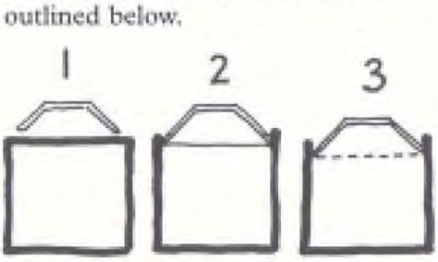

Figure 12 Three typical roofspace situations

Situation 1 Very well ventilated

This occurs, for example, in belfries, barns, porches, and sometimes over vaults, etc. The roofspace environment can sometimes be virtually independent of the occupied space below, and often approach 'cold' roof principles. If they are not subject to water ingress, such roofs may exhibit little or no ULC, provided that the substrate materials are not chemically aggressive. However, ULC performance is borderline, even for an ideal 'cold' roof, as illustrated in the photograph shown in Figure 13. Inspections, tests and precautionary measures are therefore advisable before re-roofing (see Appendix A). In other circumstances, air and water vapour from inside the building may enter the roof void - for example through stairs and access doors - creating Situation 2 or 3.

Figure 13 This outdoor test rig near Manchester has 100% outside air ventilation. Little ULC has been found here, apart from an area of the flat central section above which a shallow puddle of rainwater collects. Evaporation from this cools the lead in windy conditions (increasing the risk of condensation) and lengthens the drying-out period when it is warm. In an enclosed roof or a VWR, a small amount of moist air or water vapour entering the ventilated airspace can have a similar effect.

Situation 2 Separate roofspaces above sound and reasonably imperforate ceilings or vaults

Such roofs are often thought to need more ventilation, but the research indicates that this is not universally helpful. 'Buffering' by moisture stored in the timbers and other materials in the roof can sometimes help to protect the lead. When strong sunlight falls on the lead, it causes moisture to evaporate from the decking and structure. The resultant warm, moist (but not condensing) conditions can sometimes promote self-passivation as outlined in Section 2. Conversely, when the roof cools, moisture re-absorbed into the fabric helps to stabilise the environment and can even have a dehumidifying effect. With added ventilation, moisture and heat disperse more rapidly and these passivating and stabilising mechanisms may be lost. In addition, where the ceilings are not reasonably airtight, extra ventilation may sometimes encourage more - usually moister - air to rise into the roof from the rooms underneath.

Where the lead exhibits little or no ULC, and the timbers are in good condition and not excessively damp, subject to tests (see Appendix A) one may find that ***additional ventilation is not always necessary or desirable.***

Figure 14 Gratuitous ventilation may sometimes increase corrosion. When this roof of a historic house in the Midlands was repaired, insulation faced with a vapour control membrane was fitted between the ceiling joists and outside air ventilation was introduced. Since the membrane was not continuous under the joists, it did not stop water vapour and moist air rising from the building into the roof (which was also now colder in winter owing to the additional insulation and ventilation). There is active ULC over the board joints where transient condensation occurs, and over the boards themselves which are now damper than before. A later phase of work did not add ventilation and is uncorroded. In both phases an initial underside coating would have been a useful precaution.

Figure 15 Village churches with oak ceilings which have lead laid directly above them are particularly susceptible to ULC. The reddish-brown coloration of lead oxide here is quite common, as are the passivated areas near the gaps where the acid vapours can disperse. In situations like this, where it is important to retain an oak ceiling, a Ventilated Warm Roof above may be the only answer.

Situation 3 No roofspaces, or roofspaces above relatively permeable ceilings

These tend to be at the greatest risk of condensation, corrosion and sometimes timber decay. The buildings, churches in many cases, are frequently damp. This can be exacerbated by insufficient maintenance to gutters, pointing and rainwater systems, which should be attended to. Heating and ventilation may also be inadequate: gentle continuous background heating and ventilation will help to keep the building slightly warm and to remove excess moisture. However, heating without ventilation can create a humid environment which can make the roof very wet; and ventilation without heating is effective only in relatively warm, dry weather. Occasional heating - often used in churches - can be unhelpful because moisture starts to evaporate from fabric and furnishings when the building begins to warm up, is added to by occupants and their activities, and is then redistributed - often into the roof - as the building cools afterwards. Flueless heaters make matters worse by injecting water vapour as a product of combustion.

In marginal situations, especially where it is important to preserve the original structure and design of the roof, calculated risks may be possible using suitable coatings and underlays, but detailed investigations may well be required. Do not use copper nails for fixing in these situations as cold-bridging owing to their high thermal conductivity can cause pattern staining and even drips of condensation from the ceiling: stainless steel nails are preferable. In more severe conditions, in order to retain historic ceiling/decking boards (particularly of oak) while minimising the corrosion risk to the lead, upgrading to a carefully-designed and constructed VWR may be necessary. Even vapours from oak rafters and purlins can sometimes be troublesome.

Ventilated warm roofs

The research has also examined roofs which have been upgraded to VWRs in line with current recommended design principles for new buildings. The outcomes have been reasonably effective, but areas of misunderstanding and poor execution have been revealed. ULC has sometimes been present, and ways of reducing it have been tested.

The purpose of a VWR is to have a clear ventilated zone typically 50mm deep (and more if possible in low-pitched roofs) under the lead and its supporting decking. It should be ventilated by outside air to help equalise pressures and to avoid thermal pumping. Under it should be an effective air and vapour control layer (AVCL) to stop any ingress of water vapour and moist air from inside the building. These principles are not understood by all: designs have sometimes shown this airspace ventilated by inside air, or a mixture of inside and outside air.

Figure 16 This early example of a VWR was ventilated from side to side, rather than from bottom to top. ULC has occurred in the less well-ventilated area near the eaves between the two bottom vents.

Figure 17 Most of the VWR above was completely free from ULC, as in the foreground. The stripes of heavy ULC further back occurred in a bay in which the AVCL was poorly terminated around a roof window (not visible to the right). This let moist air and water vapour from the interior into the ventilated layer. The lighter corrosion just visible at the top right occurred near a valley where there was no through ventilation. Some eaves ventilators had also become blocked where the free edge of the AVCL at a joint in this position had become unbonded and had curled up.

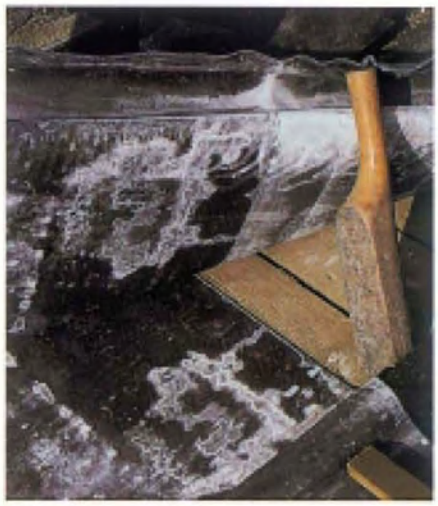

Figure 18 In this VWR, the AVCL terminates some distance short of the abutment. The lead nearby has corroded underneath, which is to be expected in the circumstances. Some condensate has also entered the lap and caused local corrosion.

Ventilation paths

It is important for the ventilation to run through all parts of the roof from bottom to top. (*The lead sheet manual*, vol 3, pages 62-63, shows some ventilator details.) In roofs which do not have through-ventilation, corrosion is often found in the dead spots. Occasionally the ventilation has become restricted owing to

- the expansion of glass and mineral fibre insulation into the gap. A durable breather layer above non-rigid insulation is often desirable both to retain the insulation and designed to drain any water that may happen to enter the airspace away to the gutters.
- the edge of the AVCL springing up at the eaves, blocking air inlets (the AVCL should be firmly sealed here in any event to stop leakage around the edge)
- excessively fine bird/insect mesh becoming blocked

Ventilation quality

The airspace must be ventilated by 100% outside air. However, this air cannot be relied upon to sweep away harmlessly any moist air or water vapour which has found its way there from inside the building. Any holes, or unsealed gaps or joints in the AVCL can lead to corrosion.

It is therefore essential that the AVCL is well specified, well detailed and correctly installed. Joints must be air- and vapour-tight and junctions, penetrations, abutments and free edges must be well detailed and properly sealed. High-performance AVCLs, adhesive bonded or bedded in hot bitumen, are preferable to loose-laid membranes which can be difficult to terminate effectively and are easily dislodged or torn.

Additional protective measures

Since even with the best-detailed and constructed roofs, starting conditions may still initiate ULC, further protective measures are desirable. In initial tests, a layer of plain reinforced building paper has been successful in controlling the corrosion that can otherwise occur on a dewy night. Coatings may also be a helpful precautionary measure (see Sections 5 and 6).

Joints between sheets

ULC is often particularly severe at the edges of a bay, just beside and rising into the rolls and just above laps or steps. These environments tend to be the most variable, and most susceptible to cyclic wetting

Ventilated warm roofs: other cautionary points

Specifiers may wish to consider the points below, which although not directly related to ULC, were encountered in the course of the research.

- In severe gusts, the ventilated layer may not be able to equalise pressure quickly enough, and wind uplift is theoretically possible, particularly where ventilators are exposed in a positive pressure zone, for example under projecting eaves.
- Care in detailing may be required at the perimeter. An AVCL could trap moisture in this potential 'cold bridge' position, possibly increasing the risk of decay to joist ends etc. *Thermal insulation: avoiding risks* (BRE 1994) gives more information on avoiding risks associated with insulation, ventilation and vapour control.
- The ventilated air gap might encourage the spread of fire, particularly where the openings are in projecting eaves.

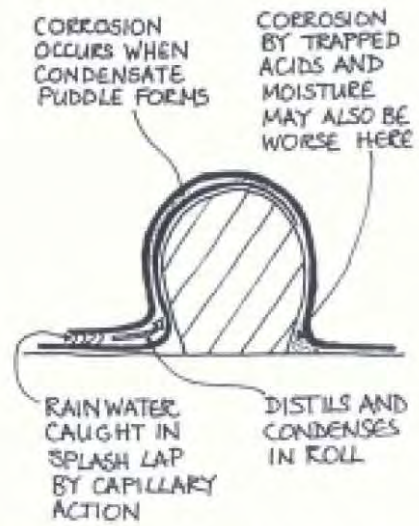

Figure 19 Corrosion in splashlaps. This diagram illustrates two types of ULC which tend to be exacerbated by splashlap detailing. The left hand side shows where rainwater can cause small amounts of ULC, particularly where the undercloak and overcloak come sufficiently close together to trap their own capillary 'puddles' of distillate. On the right, trapped moisture from within the construction finds it more difficult to emerge and can be destructive if acids are present. Occasionally the acids find their way over the top and both sides become badly corroded.

and drying, distillation of trapped moisture (particularly in oblique sunlight), differential aeration and carbonation, and accumulation and regeneration of organic acids, particularly where the lead is laid on sheet deckings or impervious membranes.

As a general rule - and provided they can keep the weather out - loosely-made joints are preferable to tight joints because they let moisture and other vapours escape more easily. Where there is risk of ULC, roofs with splashlaps tend to show more because

- the overlap area increases the egress distance for moisture and acid vapours
- the overlap can also become completely sealed at times by rainwater drawn and held in by capillary action - particularly on low-pitched roofs.

Sometimes distillation of trapped rainwater may also cause some ULC in laps and splashlaps, as sketched left: this occurs independently of conditions inside the building, and is seldom serious except where organic acids also accumulate. Preliminary tests suggest that coatings can also help to reduce it.

In roll positions, splashlaps can sometimes be avoided by using hollow rolls or retention clips. At steps, an increase in height will sometimes suffice. However, it is appreciated that in some circumstances splashlaps will be needed for weather protection, or to mask rows of nails. Hollow rolls also tend to be less subject to ULC than batten rolls.

4 Decking materials and their performance

Lead roofs are often laid on softwood boarding, with 'penny' gaps (some 2–4mm wide) between them to permit moisture movement and to provide 'ventilation' to the underside of the lead. One also finds

- 'gap' boarding, often with narrower timbers, 50–100mm wide separated by gaps of 10–20mm. This is most common on older, more steeply-pitched roofs and with thicker codes of lead (Codes 7, 8 or more). With shallower pitches or thinner codes the lead may sag or be trodden into the gaps.
- 'close' boarding, where the timbers are butted more tightly, and sometimes tongued and grooved
- hardwood, particularly where the decking serves also as the ceiling for the space underneath
- timber sheet panel products such as plywood, chipboard and OSB

The boards usually run horizontally, sometimes vertically or diagonally (this can make fatigue cracking less likely above joints). Insulating material was sometimes used, but these 'warm deck' roofs proved vulnerable to waterlogging and corrosion and ceased to be recommended (see Section 1).

Continuous or gapped deckings?

Both types have strengths and weaknesses.

- Gapped deckings provide a direct path from the air in the roofspace to the lead: a disadvantage in allowing water vapour and moist air to get there rapidly under condensing conditions; but providing an exit route for moisture and acid vapours which might otherwise be trapped and cause severe corrosion. Site studies suggest that the passivation tends to be better the wider the gap: though to date

Figure 20 A gap-boarded roof. Softwood gap boarding is common in the steeply-pitched roofspaces of medieval cathedrals. It is normally unsuitable mechanically for flat or shallow-pitched roofs. For a variety of reasons, these roofs tend to be relatively resistant to ULC and the construction can often be maintained without any modification. A pretreatment on the underside can help to avoid initial corrosion. See Section 6.

it has not been possible to verify this in laboratory tests.

- Deckings of sheet materials isolate the underside of the lead from the roofspace environment, so condensation does not immediately occur. However, if condensate builds up or water ingress occurs, the trapped moisture frequently causes damage, particularly because the organic acids which are often present in timber panel products also accumulate. Plywood can also trap water in its inner layers even when its surfaces are apparently dry.

As a general rule, in dry conditions both continuous and gapped substrates can perform satisfactorily (but avoid risky timbers - see below and refer to Section 5 on underlays). In damper conditions, both are susceptible to corrosion but trapped moisture and acids tend to create more severe problems above continuous substrates than condensation does with gapped substrates. However, the detailed performance in gapped situations is complex and corrosion varies.

Acidity in timbers

As discussed in Section 2, all timbers contain acids which can build up to harmful concentrations and attack lead. Even when dry, vapours from some species - notoriously but by no means exclusively oak - can attack metals, as noted below [source: *Corrosion of metals by wood* (separate publications by DoI 1979 and BRE 1985)]. This list is not exhaustive.

Severe risk Oak, Sweet chestnut

High risk Beech, Birch, Douglas fir, Gaboon, Teak, Western red cedar

Moderate risk Parana pine, Spruce, Elm, African mahogany, Walnut, Iroko, Ramin, Obeche

While no timber product is completely free of risk, in practice standard white softwood (usually Baltic whitewood) appears to be as satisfactory as any. Wood-based panel products are usually more corrosive than their constituent species: processing often causes hydrolysis and introduces formic acid. Whilst details vary with type, manufacturer and batch, in the absence of other evidence they should all be regarded as *severe*. They should never be used in potentially damp situations.

Assessing existing deckings

Reviewing suitability

Deckings seldom decay unless they have been subject to gross condensation or water accumulation. Insects and fungi cannot easily flourish in the wide range of temperatures and moisture levels that changing weather imposes on deckings. One can therefore often retain existing deckings, particularly if they are sound softwood, low in acid content.

However, aggressive species - particularly oak (even if old) and manufactured boards - may still be a hazard. If there is already ULC, the corrosion product and the timber should be tested for the presence of acetate and formate, and great care should be taken if levels are above 50ppm and 20ppm (parts per million) respectively. Even if not, these timbers may still attack fresh lead: tests and precautionary measures are desirable (see Section 6 and Appendices A and B).

What if the decking is aggressive?

Replacement or protection may be necessary. In any replacement, consider the guidelines in the box below and if possible test the proposed solution in small areas (see Appendix A). For protection, impervious separating underlays have often been used. However in practice their performance sometimes causes problems, as discussed in Section 5.

If it is essential to retain certain timbers in spite of their aggressiveness to lead, then chalk and other coatings may provide useful protection from initial corrosion (see Section 6 and Appendix B). However, given the

Checking timbers for acidity

Even if decking timbers are chosen from species not known for high corrosion risk, initial acidity will vary with provenance and processing. In cases of uncertainty, initial pH (acidity) tests can be helpful. Most laboratories will be able to do this easily. (The Lead Sheet Association can provide a list of contacts.) The procedure is as follows

Select a clean, sharp drill bit (typically 10mm in diameter)

Drill out samples of wood from several positions in each batch

Wipe clean the drill on a dry paper towel after each drilling

Place each set of drillings in a sample bag and label it

In the laboratory, weigh out 0.5 grams of drillings

Place in a test tube with 50ml of pure deionised water

Cap, shake, leave overnight and shake again

Measure pH with an electronic meter or a chemical indicator

Compare samples of each batch for consistency

Take additional samples if the spread is large

Reject timbers with an average pH consistently less than 5.5. (The lower the pH, the higher the acidity.)

cumulative effect, this protection may not last indefinitely. For complete isolation, it would be necessary to form a VWR (see Sections 1 and 3) by placing a long-lived AVCL over the aggressive boarding, insulation above that as required and an externally-ventilated airspace over that. While this might seem radical, maintenance records suggest that some roofs now subject to severe ULC may also have required frequent attention in the past: over seasoned oak lifetimes of some 40 years are typical. More detailed historical research on lifecycles is now in progress.

Concrete and mortar substrates

Fresh concrete, mortar and lime are aggressive to lead, and contact should be avoided, particularly where there is any likelihood of dampness and condensation. In marginal situations, a bitumen-cored building paper underlay is often used to provide some protection. Conversely, carbonated mortars and concrete can themselves have a protective effect.

Selection and use of new deckings

Where new decking timbers are used in replacements or repairs, the research indicates

- Choose a wood known to have a low corrosion risk, typically whitewood. Avoid all species listed in *Acidity in timbers* (p13). Use manufactured boards with great care, and only where moisture cannot be a problem.

- Protect the work from the elements and keep the substrate timbers dry. Where timbers have an initial moisture content above 16%, lead pretreatment is desirable. See Section 6.

- Seek to avoid timber preservatives in deckings and roll battens: the wood often arrives damp; preservative salts absorb moisture from the air and are electrolytes which can increase corrosion. The solvents in solvent-borne preservatives (now increasingly rarely used) may also inhibit passivation: they should be allowed to evaporate for several weeks with the boards stacked so that each is well-ventilated.

- Ideally, check the acidity of samples: the lower the pH, the more acid. (See box *Checking timbers for acidity*.) NB: this is an additional test for benign species: even high risk species do not always have a low initial pH - their acidity can develop over time.

5 Underlays and their performance

Purpose and function

Underlays are often put under the lead, in order to

- promote free movement, reducing thermal stresses and fatigue

- hold back moisture or condensation

- provide an even base for the lead

- isolate the lead from acid deckings, such as oak and plywood

- isolate the lead from fresh concrete or mortar, which are alkaline.

Underlays can also be useful carriers for protective chemicals (see Section 6).

Is an underlay necessary?

In many historic buildings the lead rests directly on planed or rough-sawn boarding. On sawn, non-resinous timbers of non-aggressive softwoods, this can work well, particularly on relatively dry, steeply-pitched gap-boarded roofs. On lower-pitched roofs, it is normal to find at least some corrosion. There can also be problems where the wood is resinous (when it may stick the lead down in places), acid (where it may attack the lead), or on low-pitched roofs (where the lead is not free to move, it is more likely to buckle as it expands or stretch as it contracts).

Comparative performance of underlays

Impermeable underlays

Impermeable materials such as roofing felt and polymers can potentially shield lead from moisture and chemicals originating inside the building. However, if moisture from any source (condensation, ingress, or construction) becomes trapped between the underlay and the lead, it can do substantial damage by standing or distilling in a poorly-ventilated environment, particularly in the presence of organic acids. Condensation occurring beneath the underlay is also more likely to be

Figure 21 A typical corrosion pattern where lead has been laid directly over softwood boards in this historic house by the Thames, now used as offices. After 90 years, the underside of the lead is still in relatively good condition, but moisture and acids have caused some corrosion over the boards, while areas above the gaps are passivated. Note the heavier corrosion under the nosing, where trapped moisture is less readily able to disperse.

trapped because it has no route for outward escape; this can increase the risk of decay in the underlying timbers.

Warning

Bitumen-containing underlays can soften in the sun and stick the lead down, possibly causing failure by thermal stresses. Resin binders in inodorous felts have also sometimes had the same effect.

Building paper

In relatively dry conditions, the absorptive effect of a building paper surface in contact with the lead appears to be helpful. Modern synthetic breather materials do not have the same effect and in tests undertaken up to the time this leaflet went to press more corrosion has usually been found. The paper should be lapped by at least 200mm, and run across rather than down the slope. It must be taken under the rolls, with battens - if used - fixed down through it.
If the paper is dropped-in between the roll battens, water vapour, moist air and acids tend to emerge in a concentrated stream along the edges, causing local corrosion. In more aggressive conditions, moisture and acids finding their way through laps and even small holes can cause severe local corrosion, particularly at the perimeter of the bay or near gaps in the underlying decking, where fluctuations in conditions tend to be greatest and air and carbon dioxide have better access. Fungal attack and spread on building paper has been reported occasionally.
Bitumen-cored building paper can occasionally exude bitumen, and adhere to the lead, particularly where the bitumen is leached out by resins from knots or by organic solvent carriers used in some preservatives and insecticides.

Permeable felts

Blanket-like materials of organic fibres (eg inodorous felt) or synthetic geotextiles can ventilate the underside of the lead, helping to bring in carbon dioxide and let out moisture. Conversely, however, when the air is moist, condensation will start more rapidly, leading to more initial corrosion on unprotected lead. More frequent condensation/evaporation cycles can also increase corrosion of unprotected lead, although passivated surfaces may withstand them.

Geotextiles tend not to absorb moisture while permitting relatively free passage of air and water vapour. Sometimes this can reduce the potentially beneficial buffering effects of contact with low-acid timber. In moist conditions the timber is also less able to protect the lead by absorbing moisture: and in sunny weather the chance of a self-passivating effect is also reduced. Hence more condensation corrosion is often found over fleeces than over softwood alone. The corrosion tends to be most marked above the gaps between the boards through which moist air emerges (as shown in Figure 8). Some geotextiles have strong capillarity, causing moisture to be retained and to travel long distances from a damp patch. Others encourage water to run off.

In relatively dry conditions, ULC tends to be less over organic fibres (which are less permeable to air and can also absorb some moisture) than over geotextiles. In damper or more aggressive conditions, however, the situation may reverse, since acids in particular can disperse more easily through the geotextiles, while the organic fibres can retain moisture and acid and may also decay.

Breather membranes

These can provide controlled access of air by diffusion through the membrane and controlled egress of trapped moisture if necessary, while restricting the bulk air movement which can cause rapid condensation over permeable felts. They are helpful in reducing the amount of transient overnight condensation but not for more prolonged dampness. New developments tend to be making these products increasingly permeable and hence less good at protecting the lead in this way.

Double-layer underlays

Condensation risk analysis suggests that a relatively permeable fleece over a relatively impermeable membrane could allow trapped moisture to escape relatively easily via the fleece and the joints in the lead. In practice, however, corrosion by ingressed moisture can be a problem, and small-scale tests have been disappointing. In addition, although the volume of air trapped in the fleece between the impermeable membrane and the lead is small, it could draw in moisture by thermal pumping as in the 'warm roof' (see Section 1).

Figure 22 At this church in Yorkshire, roofing felt was used to protect the lead from acid vapours from the oak ceiling/decking. Although much of the lead has been protected, local membrane failure together with some water ingress has led to localised corrosion which in places has perforated the lead sheet.

Conclusions on underlays

Most underlays have both good and bad effects, and the research to date has not been able to recommend any one approach unequivocally. Meanwhile

- in steeply-pitched roofs with roofspaces, where gap boarding is already used, an underlay may not be necessary. However, it is recommended that tests are carried out first (see Appendix A). Pretreatments may be desirable (see Section 6).
- in well-ventilated situations, such as VWRs, a plain building paper underlay can provide some protection from transient condensation, and assist passivation. Pretreatment may also be a useful precaution against minor shortcomings in design or execution.
- in reasonably dry conditions, and where pre-existing sheet materials such as plywood are present but are dry and do not appear to have caused problems, bitumen-cored building paper may be helpful, but it must be carefully laid, well-lapped and undamaged. It is particularly important that the butt joints between plywood sheets are well covered: it is here that water vapour and acids tend to emerge in the greatest quantities as the plywood is heated, particularly in the sun, sometimes causing severe local corrosion.
- with fleeces, severe long term corrosion may be reduced, but initial corrosion can sometimes be rapid. Where aggressive substrates such as oak are present, the fleece can provide some separation and absorb large amounts of chalk slurry as a protective layer.
- tests are currently being undertaken with coatings applied to the lead (see Section 6). Application of chalk paste to building papers, geotextiles and - directly - to suitable substrate boarding is also being studied.

6 Protective coatings

The nature of initial corrosion

Initial effects on lead can vary dramatically according to circumstances.

A If lead encounters water early in life - for example if it is laid on wet decking, a damp building, or in weather which subjects it to condensation - it can start to corrode rapidly. Once initiated, this corrosion tends to continue.

B In dry initial conditions, the lead may remain completely bright and unaffected. However, if conditions subsequently become damp, corrosion may start.

C In warm and slightly moist circumstances, passive layers may form spontaneously: they provide some initial protection from ULC when condensation does occur. The mechanism, described in Section 2, appears to have been an important contributor to the long life of some damp historic roofs.

Figure 23 Tests at BRE Scottish Laboratory, which show the protective effect of chalk treatments. TOP: corroded after 2 and 4 weeks. BOTTOM: protected by chalk. MIDDLE: here the chalk has been brushed off to show a grey passivated surface beneath. Left of centre, a wisp of corrosion is appearing over the gap between the decking boards, which here were preservative-treated.

Lead laid in the early summer is more likely to follow routes B or C and may be less susceptible to ULC. Conversely, lead laid in winter, and particularly in the dewy autumn months, will usually suffer some Type A initial corrosion, making it susceptible to further corrosion in adverse conditions. To avoid such largely uncontrollable variations and uncertainties, some initial protection to the lead is desirable.

Factory-applied coatings

Earlier research (EASA 1986) found that most suggested candidates could not survive handling and working on site. Recently, however, acrylic colour-coated lead flashings have come on the market which can survive a limited amount of bossing into shape: if necessary, these can be touched-in on site (important, because corrosion tends often to be worst at the edge of a damaged area). At present the products are not appropriate for most historic buildings, being available in narrow widths and thicknesses only, and usually coated on both sides. However, the future is promising.

Site treatments

The research has investigated treatments involving relatively simple, safe, readily-available materials suitable for use on site.

Water-repellent materials such as silicone oils, greases and sprays. These were disappointing on test rigs and in one-year site tests, though in the longer term a degree of protection was afforded.

Protective coatings such as linseed oil, patination oil and paint. These were relatively good, provided that they were applied after the lead had been shaped and given time to dry before the sheets were finally laid: this was usually difficult and slowed down the process. If not cured first, they were less effective and could also stick down the lead. Curing times vary with temperature and humidity, but are typically

- 24 hours for patination oil and paint (less in warm weather)
- several days for linseed oil

Fast-drying 2-part coatings would merit further investigation. In the past, linseed oil was used as a lubricant in some rolling mills, and some plumbers also routinely wiped lead with linseed oil, particularly after leadburning. On some sites this might incidentally have provided a certain amount of protection from ULC.

Pre-passivation Chemical methods were sought to create passive patinas similar to those obtained when the upper surface of a lead roof weathers for several months in the atmosphere. The chalk treatment described below was found to be most effective.

Treatments using chalk (calcium carbonate)

The simplest and most successful treatment studied in the laboratory was to apply a slurry of chalk powder in water to the lead. Limestone powder was also tried but soft chalk was better. The chalk assists initial passivation of the lead by controlling the pH of the water and providing a source of carbonate ions. The process is described in Appendix B. Further laboratory and site testing is in progress, with encouraging results to date.

Steps in the chalk coating process

A range of chalk treatment was tested on site and on a full-scale test rig. They included various combinations of an initial slurry coating when the lead first arrived on site, thicker paste coatings once the lead had been formed into shape and chalk-impregnated underlays. Preliminary findings were as follows.

- The initial slurry coating was the most important, as it provided some protection during sitework. The lead was visibly patinated after a few minutes at room temperature and had some resistance to initial corrosion.
- A second paste coating was desirable: this repaired any damaged areas and provided a reservoir of chalk to assist longer-term protection.
- Coated underlays were not sufficient in themselves: moisture could reach the lead and initiate ULC without activating the chalk. However, coated underlays prevented the chalk from falling away over gaps, etc. Extra chalk also gave some useful initial protection over acid substrates. However, in the long term it is likely that acids will ultimately accumulate to aggressive levels, but the lead's life might be usefully extended.

Site test results

In site tests up to the time of writing, the observed protection by chalk coatings and underlays was always good. The damper the roof, the better the protection tended to be: a useful property in protecting the lead from adverse starting conditions, for example over wet buildings and timbers, and from dewy nights. There is also the prospect of retaining some inappropriate decking materials of historic interest. However, application methods need to be improved, long-term tests have yet to be undertaken, and the general rule still applies that substrates should where possible be of low acidity and aggressiveness.

Suitable underlays for chalk

To date the best results have been obtained where chalk has been applied to the underside of the lead and the upper side of a plain reinforced building paper. Geotextile felts allow a thicker chalk layer to be used and are better at retaining it. However, in tests they have been less effective except in very damp or acid conditions. Here there is another possible problem: in very damp conditions, the chalk can stick to itself and to the lead. The bond is not strong, but the added reinforcement of geotextile could increase the risk of thermal fatigue cracking.

Contractors' experience with chalk coatings

Contractors vary in their acceptance of chalk coating: some have taken it in their stride, others find it a nuisance. The main problem is on steeply-pitched roofs where the chalk can fall off or blow off underlays such as building paper, particularly in windy conditions. Here a synthetic fibre scrim has helped to provide a 'key' but rucks in the scrim have been a problem on one site. Lifting the lead to apply the second coating before final fixing, always a nuisance, is also more difficult on steeply-pitched roofs, where temporary fixings may also have to be inserted and removed. A tough, quick-drying or factory-applied and easily retouched paint-like coating would clearly be more convenient.

Appendix A

Initial inspection, diagnosis and testing

Introduction

Whenever a lead roof is carefully inspected, it will be worth determining if ULC is present, and if it merits attention. However, it is not unusual to find some; it is seldom serious, and chalk treatment (Appendix B) may at first sight resemble ULC. If significant ULC is found, one should review whether it is serious, how it might have originated, and how it might be controlled. Before re-roofing, some tests are desirable even if there is little or no ULC, as new lead will not necessarily perform similarly.

Inspection from above

In extreme situations, evidence of holes, cracks, or repairs can be seen from above (see Figure 24). Piles of corrosion products - typically white flaky or granular material - can sometimes be found in gutters, or can fall out of rolls and laps when they are tapped. A badly-corroded roof may also have an uneven appearance and feel 'crunchy' underfoot, as layers of corrosion product are compressed. Incipient perforation is most readily visible when the roof is drying out after rain or dew: the failing areas will absorb some water and retain it for longer, giving them a darker appearance.

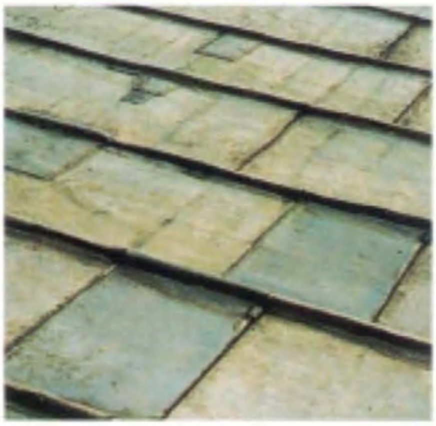

Figure 24 The large patches to the laps in the foreground suggest acid corrosion-related failures, which often first destroy the lead near the head of the lap. So do the smaller patches at the sides of the sheets, though similar damage can be caused by restrained thermal movement at tight fixing clips. The decking here is oak, probably 150–200 years old, but 35 years after re-leading, corrosion is severe.

Where is corrosion most commonly found?

This depends on the building, position and orientation. ULC commonly starts above gaps in the substrate boarding; at the perimeter of the sheet (on the inside of a roll; or in a lap or step, just above the top of the undercloak), or in a nosing. In general

- low-pitched roofs are more susceptible than steeply-pitched
- roofs with laps and splashlaps are more susceptible than roofs without
- very well-ventilated roofs (eg bell towers) are less afflicted
- roofs with roofspaces (ventilated or not) are less prone to corrosion than those without
- for those without roofspaces, high level roofs are more prone to corrosion than low level roofs

Checking elsewhere

If corrosion is found on one sheet, check similar parts of other sheets: there may be a regular, consistent pattern, at least over one area. However, patterns often change with location, pitch, and orientation, and are influenced by the underlying construction and environment.

Inspection under the lead

If ULC is suspected, try to look under the lead. This is most easily done in collaboration with a plumber, especially if there are hollow rolls or concealed clip fixings, which make opening-up and reinstatement a particularly skilled job. Where batten rolls are used, it is usually possible to lift at least the corner of a suitable sheet. Those who inspect lead roofs regularly may wish to take one of the short introductory courses in leadwork for specifiers that are run by the Lead Sheet Association (see Useful addresses, at end).

Equipment checklist

For those who wish to make their own inspections, useful equipment for lifting, recording and taking samples includes

- A steel prying bar, to help to lift the lead and remove nails
- A claw hammer, to help to lift, prop and to replace fixing nails
- A screwdriver, useful for prising apart and for testing timber soundness, as well as for removing screws
- Props to support the edge of the lead, once lifted. To avoid damaging the lead, avoid sharp points, edges or corners. A set of 25 x 50mm timber blocks between 150 and 300mm long with rounded arrises can be useful.
- A lead dresser, to replace the lead
- A mallet or rubber hammer for tapping the dresser
- A tape measure (This also helps to give a scale in photographs.)
- A torch
- A moisture meter, preferably with traditional resistance pins for local tests and non-intrusive electronic detection for scanning
- A camera with flash, preferably with zoom/macro lens
- A long-handled hooked paint scraper to collect samples
- Self-closing polythene sample bags
- Self-adhesive notes for identification in photographs
- A solvent-based permanent marker, for recording notes on the underside of the lead for later reminders, in photographs, and on sample bags. **CAUTION:** 'permanent' marking on the exposed side of the lead usually survives only a few months. It is best to locate positions in drawings and photographs.

Figure 25 Typical set of equipment

Lifting lead for inspection

The skill is to be gentle; if possible two people should work together. Select sheets which are easily lifted, not obstructed by adjacent sheets, lightning conductor cables etc, and unlikely to be torn or otherwise damaged during lifting. Start by opening out the overcloak near the foot of the roll using the prising bar. Then try to lift it by prising up gently near the corner. Often one can then begin to lift the lead off the batten roll: check carefully whether it can be eased. If not, it may be better to try another sheet.

If the lead begins to lift at the bottom, support it there and try higher, aiming to loosen the whole length over the roll. If so, work up from the corner but take great care not to kink the lead over the roll. If kinking starts, ease back immediately and try to lever the lead away from the batten under the kink. Once the lead has begun to lift, check what is happening at the bottom (avoid kinks here too) and at the far side where the lifted sheet forms the undercloak: this may also need easing to permit free movement, particularly if there is a splashlap. Normally the corner can be lifted safely by between 200 and 300mm and propped in this position, to permit inspection and photography (see Figure 26).

Figure 26 A sheet with its corner raised and propped

Replacing lead

Lead which has been lifted carefully can often be lowered gently back into position and worked down by firm hand and finally foot pressure. Be gentle: bossing too early can make it difficult to return the lead into place. When lowering, it is important that the upper sheet drops properly into the inside of the roll: sometimes the edge of the undercloak is bent upward when the sheet is lifted, and needs to be pushed back down first. Once the overcloak is nearly back into position, it will need final bossing-down to help the joints close reasonably.

DO NOT knock the outer edges back down first: instead work towards them from the inside of the roll and only tap them finally into place. Try to avoid bossing the lead into the base of the roll as this will make the sheet more difficult to remove on another occasion. It is often gentler not to hit the lead directly with the dresser, but to place the dresser in the required position and to tap it with a rubber hammer.

Safety precautions while working with lead

Lead and its corrosion products are hazardous to health and care must be taken not to ingest or inhale them. Wear a disposable dust mask and gloves which should be thrown away after each use, overalls which should be washed after each use. Always scrub your hands and wash your face thoroughly when work is finished and before handling or eating food. Sweep up any loose offcuts and corrosion products and dispose of them safely. To reduce fire risks, hot work is banned on many sites and subject to permits and agreed procedures on most others. Smoking is not allowable. For further safety information, see *Working with lead in construction: a guide to healthcare* LSA (1996).

Figure 27 Replacing the lead

Typical appearance of the lead

One may find the underside is

- ***Badly corroded*** (Figures 9 and 15) Major changes in detailing may be needed to isolate the lead from moisture and acids, including an additional layer of ventilated construction.
- ***Somewhat corroded*** (Figures 5, 14 and 21) Care must be taken to understand the situation and to check that alterations proposed are likely to make things better. The corrosion may be recent, or it may have occurred long ago. Tests are desirable to assess current conditions and to ensure that the proposals work in the manner intended.
- ***Showing little or no corrosion*** The lead may be either in bright, as-new condition (indicating that it has been very dry); or dulled (indicating that it has sometimes been damp, but that passivation has occurred). For roofs in good underside condition, past advice has been to renew as before, perhaps with some additional ventilation. However, if the old lead was passivated long in the past, or if the new lead was laid in adverse conditions (eg in the autumn, on wet or initially acid timbers, or on a damp building), ULC may occur. Small changes (eg in substrates, underlays, detailing or ventilation) may also be critical. Tests are therefore desirable.

Appearance of the corrosion product

ULC is usually white and predominantly the basic carbonate. Where organic acids are present ULC will also include acetate and/or formate. There may be some lead oxides: in reddish patches on their own, often in areas beneath the white corrosion product, sometimes giving the basic carbonate a yellow or pink tinge. Typically ULC is found in one of the following forms

- Thin powdery layers. These often indicate initial corrosion which is no longer active.
- Thin compact layers, which are difficult to scrape off. These tend to be protective but ultimately they may part company with the lead underneath, and corrosion will accelerate, forming additional layers.
- Thicker flaky or granular layers. These indicate more serious corrosion.

Distribution of ULC over a lead sheet

Occasionally a uniform layer of ULC covers the whole of the underside of a sheet. More often the distribution varies in relation to the location on the sheet, the pattern of the underlying deckings and underlays, local defects, and the history of moisture and acidity. Common patterns include

- Stripes of corrosion above the joints in the underlying boards, and opening out into the rolls in a 'fish-tail' pattern. This tends to occur in relatively dry situations where dew has formed before the lead has had a chance to build up its own passive coating.
- Stripes of corrosion as above, but spreading on to the boards from the gaps between them. This indicates a rather damper situation.
- Stripes of passivated (usually dark-coloured) lead above the gaps and in the fish-tails, and corrosion over the boards. This indicates a damp situation, with possible chemical activity over the boards.

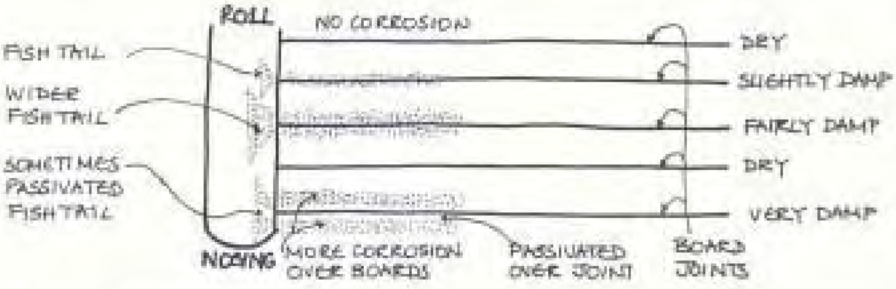

Figure 28 Characteristic variations in corrosion pattern over boards and gaps with changing moisture levels

Samples and tests

Samples of corrosion product

If significant amounts of ULC are found, it helps to have them analysed, particularly for formate and acetate content to indicate whether organic acids are involved: concentrations of over 50 parts per million (ppm) of acetate and 20ppm of formate in the substrate or the corrosion product are considered liable to put the lead at significant risk. These levels will be detectable only in professional analytical laboratories. (The Lead Sheet Association can provide a list of contacts.)

Samples can be collected (taking appropriate precautions against contact, ingestion and inhalation) with a long-handled hooked scraper and put into a self-closing polythene sample bag. At least one gram of sample should be collected. Record carefully where it came from, both on the bag and in notes, using a unique sample code. To aid future identification, it helps to photograph the sample position. Samples of substrate are most easily taken by drilling a hole and collecting the drillings in a sample bag. Samples of the lead itself may also be required for investigations of composition and microstructures, but are not normally needed for ULC analysis.

Preparing for tests

Locations for specimen testing should include as wide as possible a range of conditions, and in particular

- any locations exhibiting evidence of some ULC in systematic patterns, eg above gaps, between boards
- uncorroded locations, to check that the environment is still inert
- in the centre of a bay and at the edge. Some samples (or cleaned areas) should be taken up into the area of the roll, particularly the inside where corrosion often occurs.
- over gaps and other weaknesses in the underlying decking

Testing specimens

Many tests can be made by wire-brushing patches of the existing lead to expose a clean surface, taking appropriate safety precautions. Alternatively, samples of new lead with pretreatments etc, as required, can be placed under the existing lead. Lift the lead, lay the samples (typically 150mm square, though they can be any size) where required (see above) and re-lay the existing lead as a weatherproof cap sheet, making sure it is in good mechanical and thermal contact with the samples underneath. Alternatively, the whole sheet can be replaced, with different parts of it treated as required.

Decking materials and underlays for in situ tests

Different substrates and underlays can be placed underneath the specimens - or specimen areas - as required. Remember that

- large specimen areas will normally be necessary to permit all conditions to be monitored.
- ideally, tests of impervious underlays require a complete bay, with the underlay sealed at all edges and extended under and beyond the roll battens. In the case of small samples, water vapour and acids can easily find their way around the edges.

Programming the tests

1 Ideally, samples should be first set up in May or June.

2 A further inspection in late September will then reveal if any corrosion or passivation has occurred during the summer. At this time, half the area of each sample (or one sample where pairs are being used) should be wire-brushed (and part re-coated, if coatings are being tested - see Section 6).

3 ULC is often most active in the autumn, and so the samples should be checked again in December.

4 Finally, in April, the two parts of each sample can be compared.

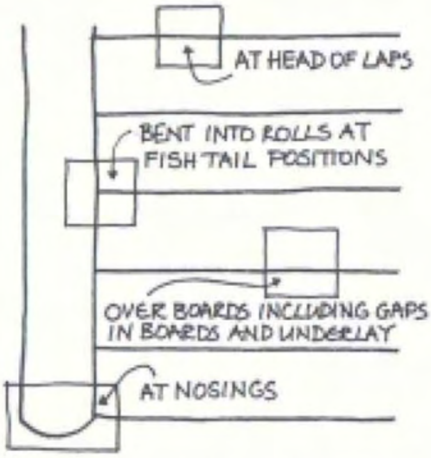

Figure 29 Typical corrosion sites and possible locations for test specimens or cleaned patches

If no specimens of a particular type are corroded then one can proceed with caution, though care will still need to be taken to keep the site dry during laying, and chalk coatings should be considered (see Appendix B). Otherwise, more thought will be required.

Caution

Anomalously good results may be obtained in years of exceptionally dry weather, as in 1995–97.

Appendix B

Chalk coating procedure

Ideally the lead should receive a pretreatment before or as soon as it arrives on site. This will help to stop it corroding if it gets wet when lying around. This should be followed by a final in situ treatment, after it has been formed into shape and just before it is finally laid. Stage 1 may be omitted in good, protected conditions where the lead can be kept dry until it is finally laid.

Stage 1: pretreatment

1.1 Remove any deposits from the lead sheets with a nylon scourer, to expose a bright and shiny surface.

1.2 Prepare a slurry of chalk powder in three times its volume of water. Stir regularly during application to ensure that the chalk remains in suspension.

1.3 Using a paintbrush or spray, apply a uniform coating of the slurry to the undersides of the lead sheets.

The slurry may also be applied to the top surface to help avoid initial corrosion.

1.4 Leave this for at least two hours, and preferably overnight. Then brush off any remaining chalk.

Stage 2: in situ treatment

2.1 Prepare a paste of chalk powder in twice its volume of water, to give a consistency similar to that of emulsion paint.

2.2 After bossing each lead sheet into shape, turn it over and paint on the paste to a sufficient thickness and uniformity that the surface of the lead can no longer be seen.

2.3 In order to avoid possible capillary attraction of rainwater, do not apply chalk to the bottom 50mm of a lap, the flat part of a splashlap, or the bottom 15mm of the adjacent step or roll (see Figure 31). Wipe off any chalk inadvertently applied to these areas.

2.4 If required, the chalk may also be applied to the substrate or underlay.

2.5 After a few minutes, when the chalk is touch-dry, lower the sheet carefully and fix in place.

Use of chalk-coated underlays

A chalk-coated underlay may also be beneficial (see Section 5). This can take various forms, including

- a thin coating of paste applied directly to the substrate boarding or to a building paper or similar underlay
- a chalk-impregnated geotextile underlay
- a 3mm skim coat of chalk paste applied to an underlay using plasterer's tools

Tests of alternative methods are currently in progress and their success is being evaluated. Chalk treatments and underlays are subject to a patent application. Alternative methods are currently being evaluated.

Some issues as yet unresolved

1 Chalk coating is subject to further development. Short-term tests are promising. Long-term performance is not yet known, both generally and in the event of damage to the protective layer. It appears that some 'healing' can occur if sufficient chalk is left in place.

2 Chalk left in place and on an underlay can provide initial protection against acetic acid. Since concentrations of organic acids often build up over time, it is not known how much long-term protection is afforded. In extended tests representing several years of adverse conditions, corrosion has sometimes been found (see also Section 4).

3 Precise details on application techniques have yet to be resolved. On windy days and on more steeply-pitched roofs, it can be difficult to get the chalk to

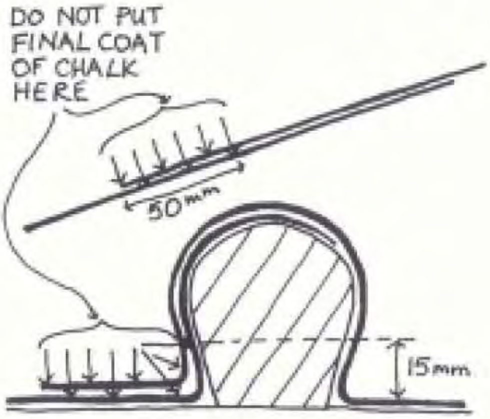

Figure 31 Do not put chalk at the very edges of the sheets. It could draw in moisture.

Figure 30 Applying the chalk slurry to the fresh lead. The coating thickness is sufficient when the surface of the lead can no longer be seen.

stay in place. Improved techniques would be desirable.

4 If water ingress or heavy condensation occurs, thick coatings of chalk may stick the lead to the base. This could be a particular problem when using a geotextile felt, where the fibre strands may reinforce the weak chalk and increase its tensile strength, and the risk of thermal fatigue failure.

5 Chalk paste which is left in place could draw in rainwater by capillary action. Residues should therefore not be left on the matching lead-to-lead surfaces in splashlaps, to the bottom 50mm of laps, or to the bottom 15mm vertical distance of rolls and steps.

6 A chalked environment might conceivably be more conducive to growth of moulds and fungi.

Safety precautions while working with lead

Lead and its corrosion products are hazardous to health and care must be taken not to ingest or inhale them. Wear a disposable dust mask and gloves which should be thrown away after each use, overalls which should be washed after each use. Always scrub your hands and wash your face thoroughly when work is finished and before handling or eating food. Sweep up any loose offcuts and corrosion products and dispose of them safely. To reduce fire risks, hot work is banned on many sites and subject to permits and agreed procedures on most others. Smoking is not allowable. For further safety information, see *Working with lead in construction: a guide to healthcare* LSA (1996).

Glossary

Aggressive Chemicals or environments likely to cause lead to corrode

Batten roll A roll formed over a timber batten

Bossing Beating the lead into shape using a dresser

Breather layer A membrane of paper or synthetic material which is permeable to air and water vapour but not to liquid water

Capillary action The process by which water rises into a thin gap owing to its surface tension

Code A reference for the thickness of lead sheet *Code 5:* 2.24mm *Code 6:* 2.65mm. *Code 7:* 3.15mm. *Code 8:* 3.55mm. Roofs in historic buildings usually use *Codes 7, 8* or thicker. Thinner Codes are used for flashings.

Dew point The temperature at which dew first begins to form on a cooled surface. A useful measure of the moisture content of a body of moist air and the likelihood of condensation.

Dresser A wooden or hard plastic tool used to boss lead into shape

Direct machine-cast (DM) lead Lead sheet prepared by pouring molten lead over a water-cooled drum

Geotextile A fleece of synthetic fibres typically 3mm thick developed for soil stabilisation, filtration etc, but also used as an underlay for lead

Hollow roll A roll formed around a hollow core

Inodorous felt A roofing felt based on flax fibres with resin binders used as an underlay to roofs covered with flexible metal sheet

Milled lead Lead sheet prepared by passing a billet between steel rollers

Overcloak / undercloak The upper / lower sheet of lead at a roll or lap

Passivation The development on a metal surface of a protective patina which provides some resistance to corrosion.

Patination oil A site-applied coating which protects new lead while it develops a protective patina. This avoids the initial corrosion and white run-off which may sometimes be caused by early rain or dew.

Roll A raised semicircular joint between two lead sheets

Sand-cast lead Lead sheet prepared by flowing molten lead out over a sand bed

Splashlap An extension of the free edge of the overcloak for typically 40-50mm beyond a roll or step in order to provide additional strength and weather resistance

Thermal pumping A process by which moisture can be drawn into (or expelled from) a cavity by the cyclic expansion and contraction of the air trapped within it as the temperature changes

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Useful addresses
(current at time of going to press)

Lead Sheet Association
St John's Road, Tunbridge Wells
Kent TN4 9XA Tel 07000 656463

Lead Contractors Association
(Address as for Lead Sheet Association)
Tel 01892 513737

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