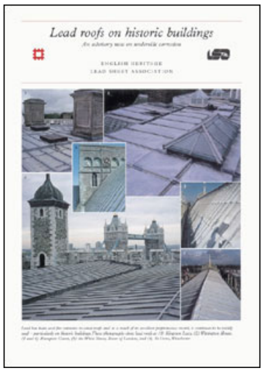
Lead roofs on historic buildings



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Although this document refers to English Heritage, it is still the Commission's current advice and guidance and will in due course be re-branded as Historic England.

Please see our website for up to date contact information, and further advice.

We welcome feedback to help improve this document, which will be periodically revised. Please email comments to guidance@HistoricEngland.org.uk

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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

Contents

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

Disclaimer

The information in this leaflet is necessarily preliminary. It has not yet been subject to the rigorous development and testing which will be needed before it could be considered for inclusion in possible good practice standards. Although the information is given in good faith, English Heritage and the Lead Sheet Association can take no responsibility for any consequences arising from its use. In the construction of lead roofs to new extensions on historic buildings, any relevant Building Regulations, British Standards and guidance from the Lead Sheet Association should be taken into account.

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.

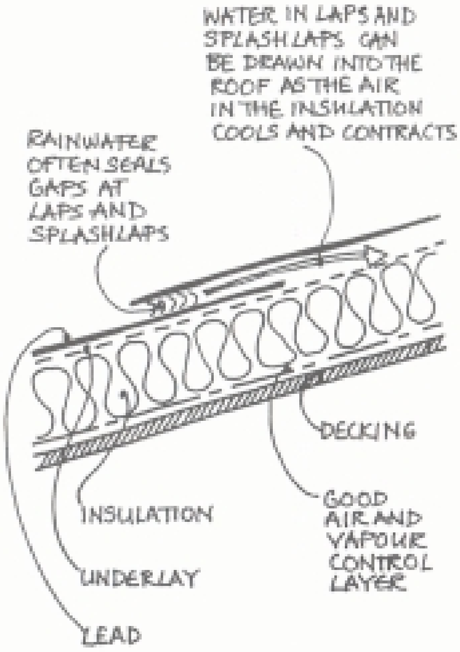

Figure 4 ***Warm roof construction should not be used*** *because water or moist air can be drawn in as the roof cools down.*

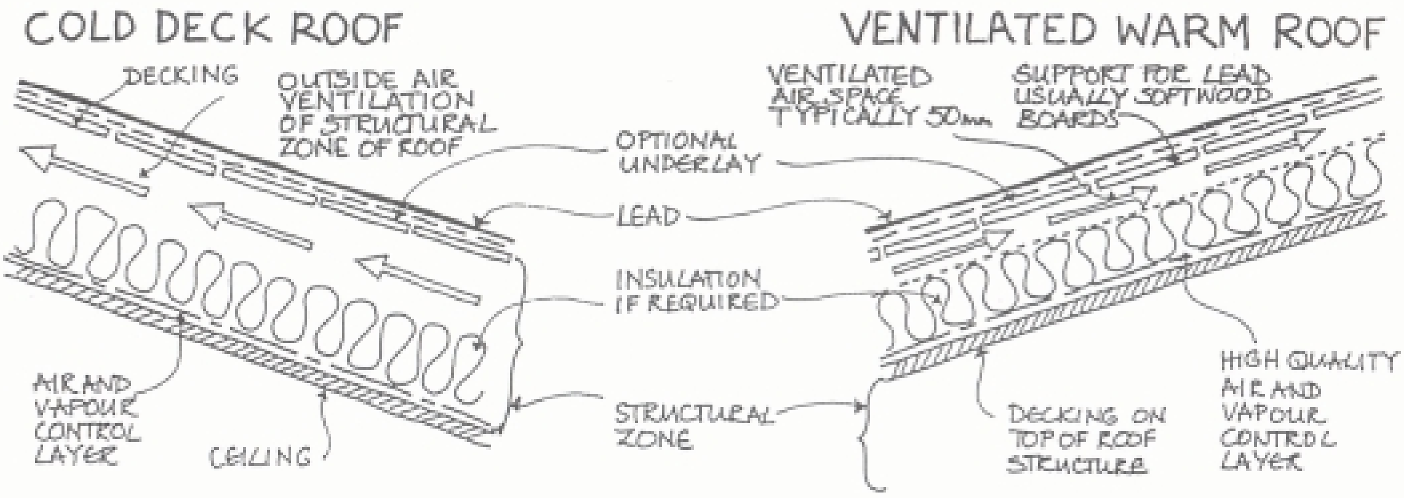

Figure 3 The cold deck roof (left) and ventilated warm roof (right) are similar in principle. Ventilation should be by outside air only, and run from bottom to top with no dead spaces. For good performance, the air and vapour control layer (AVCL) must be both air and vapour tight. This is much more easily 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.

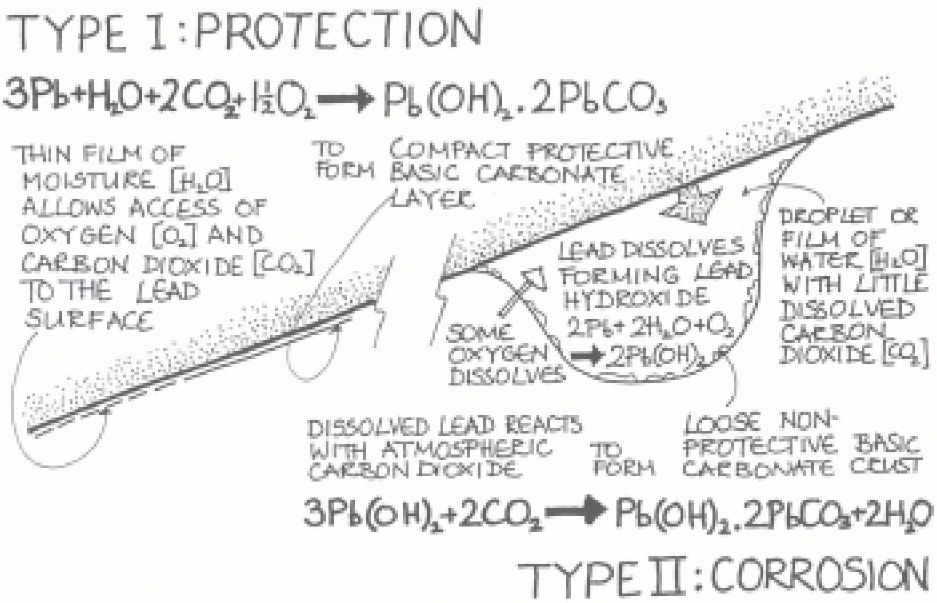

Figure 6 Where reaction with a thin film of water, oxygen and carbon dioxide occurs at the surface of the lead (left), a compact film of basic lead carbonate (often also containing lead oxide) can build up. This can help to protect the lead from further corrosion. On the right, however, carbonation occurs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

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

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)

- 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