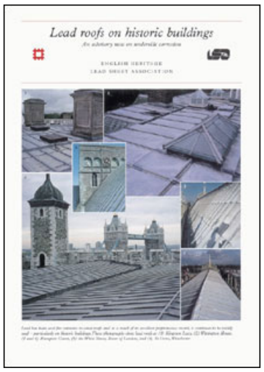
Lead roofs on historic buildings



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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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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.

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.

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.
- 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.....*
>
> 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

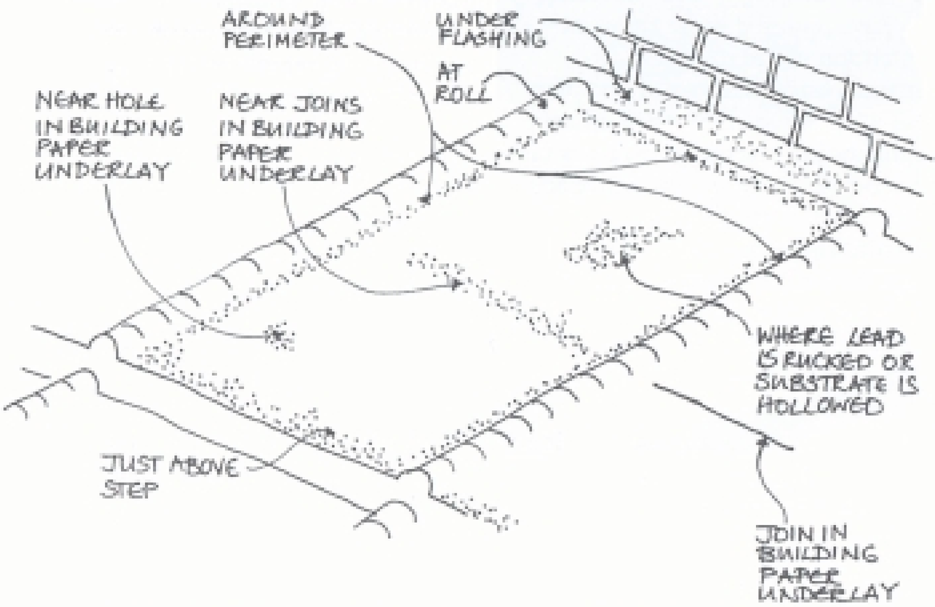

Figure 10 Typical locations of acid-related corrosion. If acids are present, corrosion is often found around the edges of the lead sheet: inside rolls, above laps, and above areas where the lead has become blistered or folded, or the substrate dips away. This appears to be a consequence of distillation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

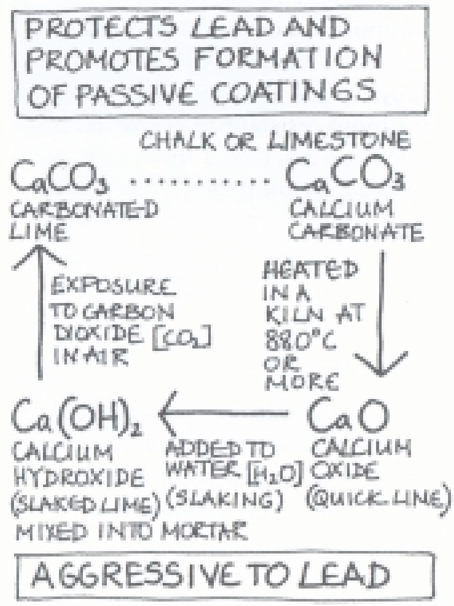

Figure 11 The lime cycle. Calcium carbonate – $CaCO_3$ – the start and end point of the cycle, is nearly neutral, does not attack lead and can help to protect it. Slaked lime – $Ca(OH)_2$ – is alkaline and aggressive to lead.

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.

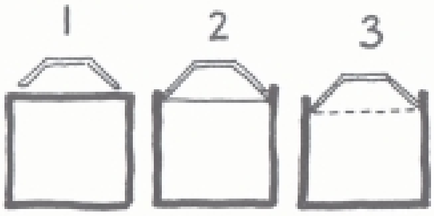

Figure 12 Three typical roofspace situations

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.