Historic England

Control of Microorganisms in Historic Buildings

UVC Irradiation Treatment

Summary

UVC irradiation is a proven technology to control viruses and bacteria in various industries and building environments. It is also a viable method to manage microorganisms growing on damp surfaces in historic buildings and to treat mould growth that may appear following a flood or other water damage (for example, after a fire).

There is no previous guidance on the use of UVC irradiation in cultural heritage. This document is the first to describe the potential benefits, limitations and risks of UVC irradiation, as well as the necessary tools and methodologies to implement a treatment programme for inorganic materials (such as stone, brick and ceramics). The appendices list examples of previous uses of UVC irradiation on historic buildings, and two case studies illustrate its benefits.

This guidance describes two different approaches, or methodologies, to implement a UVC irradiation treatment programme on inorganic materials: one is empirical, based on graduated trials, and the other is scientific, based on identification of the microorganism(s) present.

As the use of UVC irradiation technology in building conservation presents known dangers to the user, and to flora and fauna, risks are addressed and methods to manage them are described.

This document has been prepared by John Stewart, Andrew More, Eric May and Rob Inkpen. This edition published by Historic England July 2026. All images © Historic England unless otherwise stated.

Please refer to this document as:
Historic England 2026 *Control of Microorganisms in Historic Buildings: UVC Irradiation Treatment*. Swindon. Historic England.

HEAG334

historicengland.org.uk/advice/technical-advice/buildings/maintenance-and-repair-of-older-buildings/UVC-irradiation

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Front cover: Roman mosaic at Newport Roman Villa, Isle of Wight, showing treated and untreated areas, five years after initial UVC irradiation.

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1. Introduction

There is often a need to control persistent microbiological growths in historic buildings, usually because they are unsightly, harmful to building materials or constitute a health risk.

The most common method of control is to use biocides, but the benefits of biocides are of limited duration and the treatment needs to be reapplied in response to local conditions. In contrast, treating surfaces with UVC irradiation (the short wavelength of the ultraviolet [UV] spectrum) can be highly effective over time. It is a low-cost, non-contact treatment, which uses simple technology.

UVC irradiation does not damage the surfaces of inorganic materials, but it is harmful to organic materials without special control (see Chapter 7). Furthermore, the technology has inherent dangers for the user (skin cancer and eye damage). It should, therefore, only be used by conservation professionals under strictly controlled conditions and only after rigorous threat and risk assessments have been carried out.

The method is not suitable for inorganic materials in every context. Various steps are required to determine if UVC irradiation is a viable treatment for a specific setting. These include assessing the condition of the historic surface and managing health and safety risks. Management of risk means UVC irradiation treatment is usually limited to internal environments that can be secured to prevent people entering and exposure to radiation.

The most effective treatments of microbiological growths in historic buildings require the microbial species to be identified. The growths can then be targeted with a calculated dose of radiation. If identification cannot be funded, graduated trials will be needed to determine the effective dosage.

2. The nature of the problem

2.1 The context

The growth of microorganisms is common on the stone, brick and other ceramic materials of historic buildings, including ruins, in damp and shaded conditions. Some microorganisms may contribute to the natural aged patina that gives historic masonry its appealing aesthetic. However, large areas of growth can be disfiguring and are usually indicative of damp conditions. Such conditions are often endemic and constitute long-term problems for the building fabric, such as timber decay.

More seriously, pioneer microorganisms (such as algae) encourage the colonisation and succession of higher and more damaging plant species, such as moss. Therefore, controlling microorganisms, preferably at an early stage, is usually essential to maintain the building's fabric and appearance.

Historic buildings can be subject to flooding and also water damage following a fire. These events generate mould growth, some of which can be dangerous or lethal to inhabitants.

2.2 Relevant types of microorganisms

The three groups of microorganisms that affect internal environments are as follows:

1. **Bacteria** are mostly single-celled organisms (usually 1µm to 5µm long); a few types are multi-cellular. They may adhere to surfaces by producing extracellular layers of slime. Their nutrient sources can be organic or inorganic. Bacteria can penetrate rock a few millimetres in depth and excrete acids that cause damage: attacking carbonate rocks, producing pigments and affecting material porosity, for example. Cyanobacteria are light-dependent bacteria that can form coloured biofilms, from green to black, and can live on low levels of light. They are also tolerant of desiccation and water stress. When humidity is low, cyanobacteria become dormant but they revive quickly with direct rain or higher relative humidity.

2. **Fungi** refers to a broad range of microorganisms that includes mushrooms, moulds and mildews (which are multi-cellular) and yeasts (which are single-celled). Each individual fungal cell is about 5µm to 10µm in size, but the multi-cellular types grow to form long branched filaments, called hyphae. These filaments can spread easily in search of nutrients and form an extensive mycelium (network) on surfaces or within porous materials.

Fungi are dependent on organic nutrients and they are essential agents of decomposition in natural environments. They produce enzymes and/or acids that degrade materials, notably timber and even rock, helped by penetrating hyphae that exert high mechanical pressures. The other significant feature of many fungi is their ability to produce large numbers of spores, often pigmented black, red, yellow, green or brown. These spores are small and light. They are typically produced in structures – sometimes in highly complex fruiting structures (for example, mushrooms) – that extend just above the substrate surface, allowing the spores to be dispersed in the air to colonise new surfaces.

Fungi that produce spores are commonly called moulds, or sometimes mildews. These terms are often used interchangeably. However, according to the US Environmental Protection Agency, mildew is a type of living fungus that usually has a flat growth habit. Mould growths quite often form more raised fuzzy coatings. As a rule of thumb, mildews are a restricted group of fungi, tending to grow on the surfaces of walls or objects. Moulds are a much broader range of fungi that may also be found growing into the underlying substrate. Both types of fungi are commonly encountered in historic buildings, and they are usually a sign of dampness and poor indoor air quality.

When a mould spore germinates, a mesh of hyphae (the mycelium) forms. This takes up nutrients and water from the surface on which the spore has germinated. Moulds grow rapidly in suitable temperatures and humidity (above 70 per cent), given a source of nutrients. A source of liquid water to solubilise nutrients for absorption is also essential for growth, whether this comes from a leak, condensation or both. Some mould species need a stimulant, such as thermal shock or a chemical activator, to break dormancy. A number of spore-producing fungi are dangerous to human health, causing allergies and respiratory diseases such as aspergillosis.

3. **Algae** are single-celled or multi-cellular organisms, a few micrometres in size. They require light and also large amounts of moisture. Deterioration mechanisms are unclear, but algae are aesthetically disfiguring and they are often embedded in slimy surface mats that may cause damage by chemical or mechanical means. Algae are early colonisers and provide nutrients for other biological growths. They may, therefore, coexist with other microorganisms to form complex patinas.

Generally, five factors are known to be associated with the growth of microorganisms, although the extent of their needs varies:

- all require a source of moisture
- all require a source of nutrients
- all require a suitable temperature range
- some may need light
- most will colonise readily in still air.

The specific environmental conditions – temperature, humidity, light and nutrients – define the type of organism that can colonise a particular surface. (Sometimes, the surface itself may provide the source of nutrients.) Some organisms only colonise specific substrates, such as carbonate rocks. The process is selective, and the final community of organisms is also dependent on the combination of environmental conditions.

Microorganisms are distinguished according to their nutrient requirements. In order to grow, they must have a carbon source and an energy source: the former to build their cells, the latter to make the cells work. For most bacteria and all fungi, organic compounds provide both the carbon source and the energy source (a few specialised types of bacteria can use inorganic minerals for energy and fix carbon dioxide for carbon). For cyanobacteria and green algae, carbon dioxide is the carbon source and light is the energy source.

Dust and spores are readily deposited in still air, and when temperature fluctuations favour surface condensation, microbial growth will occur. Growth of fungi is often triggered by surface condensation of water despite low relative humidity. However, some highly specialised fungi, known as xerophilic fungi, are well adapted to survive in dry environments. They are capable of growth at lower available moisture levels (60 per cent relative humidity) – below that of typical fungi (70 per cent relative humidity).

A layer of microbial growth often creates a biofilm that comprises one or more species. Biofilms are microorganisms embedded in slime that can vary in thickness and complexity. They may include other mineral and organic components. The microorganisms may have complex interactions with the underlying masonry, its treatment and each other. Their presence can provide nutrients for other organisms, which, in turn, may influence the porosity of specific material surfaces.

Changes in climate (increases in frequency and intensity of rainfall and temperature) can cause surface growth. This is particularly obvious for green algae, when a visual increase in ‘greening’ indicates more active algal colonisation.

Table 1 presents the general parameters that are associated with growth for each microbial type. Since microorganisms are an extremely diverse group of living organisms, especially with respect to temperature and water requirements, the information focuses on moderate, rather than extreme, types that may be present in a historic building. If suitable conditions for growth do not exist, many microorganisms produce stress-resistant structures, such as fungal spores or bacterial endospores, to allow them to survive and even disperse until growth is possible.

Table 1: General growth requirements of key microbial groups in a historic building.

Organism	Temperature	Minimum relative humidity	Nutrients required	Need for light	Presence in air	Comments
Bacteria, including cyanobacteria	Minimum 10°C Maximum 40°C Optimum 20–30°C	>90%	Most organic	Some	Some form endospores[1]	Photosynthetic cyanobacteria need oxygen
			Some inorganic and need carbon dioxide		Common in dust deposits	Readily form biofilms
Fungi, including moulds	Minimum 5°C Maximum 40°C Optimum 25–30°C	70–90%[2]	Organic	Never	Moulds form many spores[3]	Very hardy and tolerant of dryness
					Very common in dust deposits	
Green algae	Minimum 7°C Maximum 35°C Optimum 23–26°C	>85%	Light and carbon dioxide	Always	Occur in soil and dust	Grow in slimy mats of biofilm

Notes:
1 Extremely heat resistant.
2 Xerophilic fungi are tolerant down to 60 per cent relative humidity.
3 Most are heat sensitive.

3. Current methods of control

3.1 Preventive methods

The control of microorganisms should always be based on an understanding of the building and its environment. In this way, passive preventive methods can be used as much as possible. Moisture, light and nutrients sustain microorganisms in varying degrees, so controlling these parameters may inhibit propagation. Potential preventive measures include decreasing moisture content in masonry, increasing ventilation and managing light levels, at least where photosynthetic organisms are present (see Chapter 7). Where flooding is a risk, preventive measures should be in place to mitigate damage (see Historic England guidance).

Even if preventive measures are achievable, they may not be sufficient to manage propagation. For example, removing light may stop growth, but many photosynthetic microorganisms are able to regenerate when light is restored. Some algae can alter their activity and survive for a while without light. In any case, there will always be sufficient living cells present to grow when light is restored. Permanent absence of light may, eventually, exhaust the algae, but this is an unrealistic measure in a historic building.

3.2 Remedial methods

For historic buildings and sites, remedial methods are used as the standard approach to mitigating or killing microbial growths. This is either because such methods are expedient or because it is impossible to manage the catalyst(s) of propagation.

Wet cleaning

A conservative way to remove microbial growth is wet cleaning with water, without using biocides. Hot or warm water is almost always more effective than cold water. However, wet cleaning delivers only a short-term aesthetic gain, so it is not cost-efficient. It can also damage friable surfaces, and overzealous cleaning (for example, with high-pressure jets or superheated water systems) can roughen the surface and therefore create an open pore structure that may encourage further colonisation. Even on more robust substrates, frequent cleaning can be damaging over time and may scour weak pointing mortar. In addition, wet cleaning can push biological contaminants deeper into the material being conserved, which risks spreading contaminants into the surrounding environment.

On a sound surface with a low abundance of microorganisms, a 70 per cent solution of alcohol in water is a potentially effective sterilant. However, many academic sources state the solution will not affect spores, in which case the benefit is minimal.

Biocides

Applying low concentrations of approved biocides is the most common remedial treatment of microbial growth. It is of limited benefit, though, because biocides are non-residual, and their long-term efficacy is brief. Even if the treatment is successful and kills algae, it may stimulate the growth of bacteria and fungi. Frequent applications of biocides over time contribute new chemicals or salts into the masonry. Extensive use may also promote the growth of a biocide-resistant microbial population – possibly more harmful than the original – and may cause staining and erosion of the substrate.

The types of biocides available are changing, and many are prohibited by health and safety legislation (approved chemicals and their manufacturers are identified on the Health and Safety Executive website). Therefore, biocides are not an effective long-term control measure. Some conservators choose not to use them at all.

Bioinhibitors

Alternatives to chemical biocides have been sought for environmental reasons or because of stricter national legislation. Research has often focused on using natural products (commonly derived from plants), employed as crude extracts or essential oils for paper, wood and inorganic surfaces. The outcomes from such research have shown that further work needs to be done to establish dose uniformity for chemicals of natural origin. Commercially available phytochemicals, such as essential oils, can be a costly option. Nevertheless, academic sources have reported some success in using essential oils, such as thyme and clove, to remove biofilm and inhibit fungi, respectively. Several cleaning procedures to control biofilm or filamentous fungi are based on enzymes (oxidase, lipase, chitinase). Other techniques investigated have used suspensions of bacteria or their spores to remove biofilm or salts on brick and stone, and viruses to destroy algal biofilms on stone. Some of the methods based on biological inhibitors show promise with respect to the environment and human safety. However, there is much to be done, especially with standardisation and specific substrate interactions, to translate them into practical options. This means the use of bioinhibitors is in the realm of wealthy clients who are able to commission specialist expertise.

Chemical barriers

Injecting chemical damp-proof courses into the walls of a historic building to control damp is, unfortunately, common. These treatments are unlikely to rectify the problem and will only mask the damp or redirect moisture elsewhere in the masonry. Chemical barriers can potentially cause significant harm to building fabric and are best avoided on multiple counts.

4. UVC potential in historic buildings

4.1 Principles

UV radiation is invisible to the human eye and is beyond the shorter end of the visible electro-magnetic spectrum. It is split into three wavebands: UVA, UVB and UVC. UVA (long wave) is from 315nm to 400nm, UVB (medium wave) is from 280nm to 315nm, and UVC (short wave) is from 100nm to 280nm.

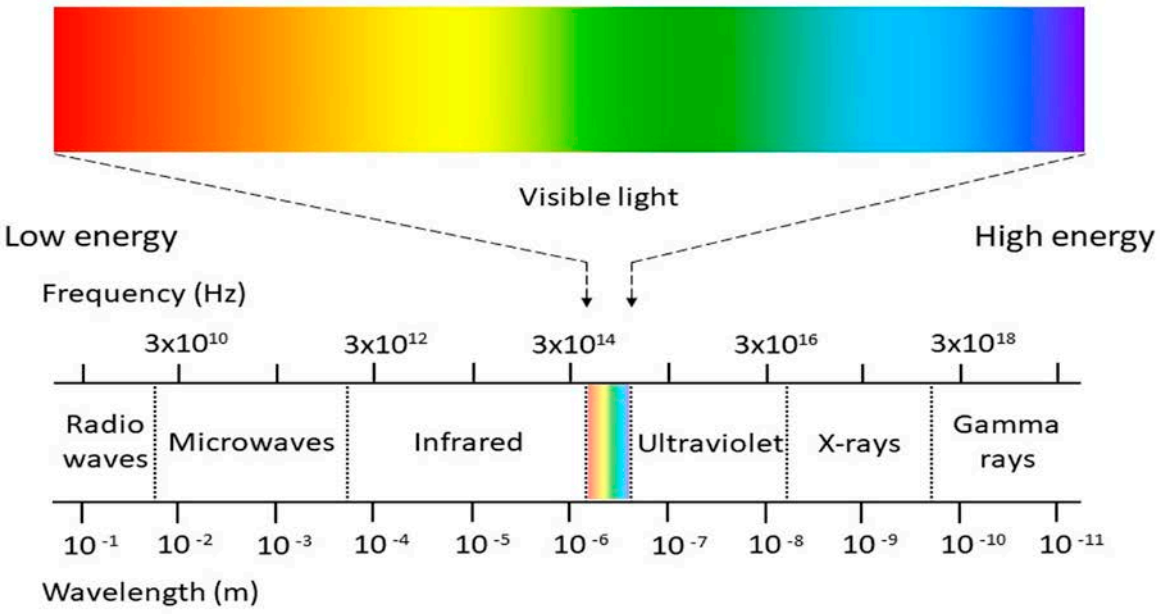


Figure 1: The electro-magnetic spectrum, showing the disposition of UV radiation, from UVA, through UVB to UVC.

UVC irradiation is a very effective method of sterilisation, known in industry as UV germicidal irradiation (UVGI). It uses short wave radiation to destroy cells or prevent their reproduction. A cell that cannot reproduce is considered dead because it is unable to multiply. Bacteria, including cyanobacteria, green algae and fungi, all contain DNA that is vulnerable to UVC radiation. Fungal spores and bacterial endospores are also susceptible to UV radiation. The most effective wavelength is 265nm. A wavelength of 254nm is often cited in research on the effects of UVC irradiation on microorganisms. This happens to be the peak emission of mercury discharge UVC lamps, but their emission spectrum is wide enough to eradicate microorganisms at 265nm.

4.2 Applications

UVC radiation has been routinely used for disinfection since the mid-20th century to control microorganisms such as bacteria, viruses, moulds or algae, some of which can flourish within buildings (an example is the notoriously dangerous aquatic organism *Legionella pneumophila,* which causes Legionnaires' disease). Applications of UVC radiation include those used for or within:

- air disinfection
- aquaria and ponds
- drinking water and other beverages
- fruit and vegetables
- HVAC air filtration and cooling coils
- laboratory and hospital sterilisation including operating theatres
- pools and spas
- semiconductor and integrated circuit manufacture
- wastewater.

The COVID-19 pandemic brought the use of UVC radiation to public attention, as a method to disinfect surfaces from viruses. UVC lamps mounted on mobile robots were used and small UVC devices became readily available for domestic or office use (see Chapter 6). To avoid people being exposed to UVC radiation, the system must be 'closed' (radiation contained within a secure space) or only operated after a full and strict health and safety risk assessment has been carried out.

4.3 Delivery

The UV radiation emitted by a source is expressed in watts (W), and the irradiation density is expressed in watts per square metre (W/m^2). For germicidal action, dose is important. This is the radiation density multiplied by the time in seconds and expressed in joules (1 joule is 1 watt-second) per square metre (J/m^2). If the dosage is sufficient, a surface will be disinfected – as long as the path of radiation is not blocked.

The running cost of a UVC system is very low. Devices are powered by regular mains socket outlets or specially arranged lighting circuits. The process is environmentally friendly, in that there are no dangerous or toxic chemicals. UVC lamps are made of special glass and so require no more special handling than any other lamp made of glass. UVC light emitting diodes (LEDs) require no more special handling than any other sort of LED (see Chapter 6). Precautions are required, however, when the lamps are in operation (see Chapter 7).

4.4 Potential in historic buildings

There has been little application of UVC irradiation in the conservation of cultural heritage. However, the technology offers numerous advantages over other treatments. UVC irradiation requires no physical contact with the surface to be treated and it does not leave any residual chemicals. Inorganic materials such as stone, ceramic and mortar are not affected by it.

UVC irradiation can be used to manage microorganisms and disinfect surfaces in problematic sites where environmental parameters cannot be sufficiently modified, such as those with endemic dampness. Examples include fully enclosed damp archaeological or historical spaces, such as a crypt or basement provided it is not supporting protected species, such as bats, or important habitats (see Chapter 7). This potential is especially useful for surfaces that would normally be cleaned manually with chemicals that may not be particularly effective or that may damage fragile surfaces.

Another application of UVC irradiation is in the treatment of mould growth after a flood (waters are often contaminated with sewage), after a fire (water damage from firefighting) or due to poor environmental conditions (see Appendix D). Mould growth in an occupied space can cause serious illness and even death. Conventional responses to problematic conditions include drying the fabric using dehumidifiers, fans and ventilation, and treating surfaces with fungicides. UVC irradiation has the potential to complement these methods.

Literature searches on academic databases and the Internet reveal a number of case studies of UVC irradiation treatment on cultural heritage sites, but the documents are usually brief (see Appendix B). Other cases that have not been published are known from professional contacts. These vary from highly scientific programmes to those developed through empirical trials.

Figure 2: A medieval vaulted chamber with an expansive cover of microbial growth. The enclosed nature of the space and the fact that access can be restricted make it an ideal environment for the safe application of UVC technology.

Figure 3: Microorganisms on areas of endemic dampness that cannot be easily remedied, such as this subterranean brick vault, can be managed with periodic UVC treatment, followed by wet cleaning (if the condition of the stone surface is not friable).

5. Risks and limitations

5.1 UVC characteristics

UVC radiation is dangerous. It is harmful to human skin and eyes, potentially causing conjunctivitis (inflammation of the mucous membranes of the eye) and erythema (reddening of the skin), and there is also a risk of cancer. Skin and eyes must, therefore, be protected from direct exposure. People exposed to radiation need to wear suitable clothing to cover the skin and specialist UVC glasses to protect the eyes. All UVC delivery systems need to be designed to prevent radiation leakage.

UVC is a non-visible radiation source. It is dangerous and, according to some sources, impossible to verify that the device is in use by sight. Operational verification, therefore, needs to be carried out by means of a UVC sensor.

In the UK, a health and safety risk assessment is legally required when using UVC irradiation in premises accessible to the public and others that may be affected, even if the premises are not classified as a workplace.

UVC radiation is harmful to organic materials if used in high dosages or for a prolonged period of time. Its impact has been studied in various aquatic and terrestrial environments, in planktonic situations and on surface biofilms. In certain natural environments, UVC radiation can potentially modify ecosystems in unpredictable ways. In heritage situations, this could be detrimental. For example, new colonisers may appear that require a different treatment regime.

5.2 Treatment efficacy

The antimicrobial effect of UVC exposure depends on the formation of extra chemical cross-links in the DNA of the colonising organism (called pyrimidine dimers). These extra cross-links distort the molecule and block its functionality, notably replication and cellular reading of the genes. While DNA is the main target for UVC, proteins and other biological molecules may also be affected, especially in more complex cells like those of fungi and algae, where most DNA has some protection within a nucleus. The actual germicidal effect of UVC depends on the extent of microbial exposure.

The effectiveness of UVC treatment relies on the ability of radiation to reach the organism and deliver a sufficient dose to kill it. Microorganisms within ‘holes’ of very porous materials, such as some bricks or tiles, may not be reached and effectively irradiated. Fungi do not have roots, so killing the surface parts of their multi-cellular hyphae may not necessarily destroy parts below the surface. Some fungi are prone to fragmentation, and such fragments may survive to recolonise. When UVC irradiation is used on biofilms with an inherent depth and/or irregular surface, its effect on the component microbes may be less destructive due to limited UVC penetration. A UVC source only irradiates surfaces within its sightlines. If something is in the way, the architectural feature or object will block radiation and create ‘shadow areas’. The diversity of natural populations and the shielding effect of a 3D structure will induce selective killing, so that the balance of the biofilm cover will change. Light-dependent organisms (which will be at or near the surface) will be most vulnerable to the applied UVC radiation.

UVC is absorbed by most materials, including standard flat glass (which absorbs all UVC). An exception is quartz. Therefore, quartz can be used to protect UVC lamps where they are liable to be broken by accident or damaged by damp conditions. UVC radiation is reflected by shiny surfaces, which is more dangerous, as this increases its radiation range. These complexities mean that it is best to err on the side of caution and rely on secondary protective kit for skin and eyes.

Electrical apparatus can generate heat. If UVC lamps are enclosed in a box, heat can build up and cause any soluble salts present within masonry to dehydrate, thus damaging porous building materials. The extent of damage depends on the type of salts and the pore structure of the masonry (see Appendix C). Cooling or limiting the operation time of the UVC radiation treatment may be required to maintain low temperatures, preventing the mobilisation of salts.

In addition, there may be risks from the microorganisms themselves, such as from mould. Appropriate health and safety measures need to be in place to protect those administering the treatment.

6. Irradiation sources and devices

6.1 Criteria for selecting irradiation devices

UVC irradiation sources need to be selected according to:

- practicality of installation and operation
- effectiveness – with regard to intensity relative to distance away from the surface to be treated
- usable life – may need to be monitored by an 'hours run' meter used in conjunction with information from manufacturers regarding lifespan and decline in output
- ability (of the source and its associated housings and other equipment) to operate in damp settings if required.

6.2 Types of irradiation devices

The six UVC irradiation sources currently available are:

- upper air disinfection luminaires
- LEDs as lamps
- linear or compact low-pressure mercury lamps
- LEDs as components
- cold cathode linear lamps
- pulsed xenon UVC flash lamps.

Upper air disinfection luminaires

These units are commercially produced by leading manufacturers such as Philips. They are mounted at high level in rooms to disinfect the air circulating within. These devices are the modern version of the original UVC systems first used in the late 1930s.

Advantages

- They work in both naturally and mechanically ventilated spaces.
- Operation is continuous.
- Sources used do not generate ozone.

Disadvantages

- Floor to ceiling height must be at least 2.4m to allow the air to circulate by natural convection.
- Not suitable where there is not a complete ceiling (for example, a ceiling system that is partially open and where some services are exposed at ceiling level).
- The devices do not treat surfaces directly, but only reduce the spread of organisms in the air. This may restrict their usefulness to maintaining a lesser level of organisms generally present. Surfaces should be treated using the sources detailed below.

LEDs as lamps

UVC lamps in 'corn on the cob' format (so named after their distinctive tubular shape covered with LEDs) are now available.

Advantages

- Have the control gear built in and can be simply plugged into an E27 lamp holder.
- Costs are low or modest.
- Lamps are easily sourced.
- Emission is at 265nm (thus avoiding the risk of producing ozone). This wavelength is better suited to killing organisms than the peak 254nm emission of linear or compact low-pressure mercury lamps.

Disadvantages

- Quality and efficacy are variable and lamp specifications need to be carefully assessed before use.
- Information about the lamps' outputs may be lacking, such that accurate calculations cannot be made regarding the exposure times required to kill various types of organism.
- Lamp size may impede the uniform distribution of UVC irradiation.
- Emission at 265nm only is invisible and an operation sensor may be required.

Linear or compact low-pressure mercury lamps

The most widely available UVC irradiation source is linear or compact low-pressure mercury lamps. They take the form of fluorescent lamps made of a special glass that filters out very short UV wavelengths that would produce ozone. They do not have an internal fluorescent coating and are thus clear in appearance.

Advantages

- Readily available from various suppliers in a range of lamp types and wattages, made by a number of leading and specialist manufacturers.
- Costs are modest.
- Some compact types have control gear built in and can be simply plugged into an E27 lamp holder.

- Lamp holders and control gear for linear lamps are readily available.
- The controls technology will be familiar to electricians and easily understood by anyone capable of simple household electrical works.
- Information is available detailing the lamps' outputs and lifespan. This enables accurate calculations to be made regarding the exposure times required to kill various types of organism.

Disadvantages

- Glass tubes are fragile and may incur high delivery costs.
- Some tube lengths can be unwieldy.
- Lamps contain mercury, which requires specialist disposal.
- Lamps need the appropriate lamp holder(s) and control gear. For some types of compact lamp, these are becoming difficult to source as the lamp technology fades into obsolescence.
- Devices are not as energy efficient as LED technology and thus generate more heat.
- Peak emission of this type of lamp is 253.7nm (sometimes cited as 254nm). The most effective wavelength for UVC irradiation is 265nm, so some energy is wasted.

LEDs as components

Component LEDs for bespoke applications are now available.

Advantages

- LEDs have a very small point light source that makes for easier lighting calculations.
- They are low energy and thus operate at low temperatures.
- Emission is generally at 265nm (thus avoiding the risk of producing ozone). This wavelength is better suited to killing organisms than the peak 254nm emission of linear or compact low-pressure mercury lamps.

Disadvantages

- Costs can be high, especially when LED components are bought in small quantities for bespoke systems.
- LED components need to be sourced from specialist suppliers.
- Surface mount technology requires specialist soldering equipment and techniques (rather than the more familiar 'two-pin through-hole package' form of LED, which requires only simple soldering).
- Specialist driver technology is probably needed, which may have to be made to suit.
- Information about LED outputs and lifespan may be lacking, such that accurate calculations cannot be made regarding the exposure times required to kill various types of organism.
- Outputs may be quite low, thus limiting the device's usefulness.
- Emission at 265nm only is invisible and an operation sensor may be required.

Cold cathode linear lamps

A small range of cold cathode linear lamps is available. They are of linear tubular construction, with wiring connections at one end.

Advantages

- Smaller in diameter than the more common linear or compact low-pressure mercury lamps.
- Their small diameter reduces the size of the housing and makes the light source nearer to that of the line source (i.e. a longitudinal source of minimal diameter) which eases lighting calculations.

Disadvantages

- Costs are higher than for linear or compact low-pressure mercury lamps.
- Information about the lamps' outputs may be lacking, such that accurate calculations cannot be made regarding the exposure times required to kill various types of organism.
- Specialist control gear is needed, which may have to be made to suit.
- Checks are necessary to establish whether the lamps emit ozone, which would preclude their use.

Pulsed xenon UVC flash lamps

Commercially produced flash units are available. They can be incorporated into bespoke installations or fully complete systems. The units operate by producing a continuous series of short duration flashes from a specialist dedicated variant of photographic electronic flash tubes. They operate for such short periods of time that heat build-up is not a problem.

Advantages

- Units provide powerful high-intensity emissions relative to size.
- Highly efficient source of energy.

Disadvantages

- Lamps use broad spectrum emission, which may mean energy is wasted.
- Costs are higher compared with other systems.
- Bespoke installations require specialist professional design.
- Information about the lamps' outputs may be lacking, such that accurate calculations cannot be made regarding the exposure times required to kill various types of organism.
- Checks are necessary to establish whether the lamps emit ozone, which would preclude their use.

6.3 Future developments

UVC lasers are being developed. If successful, they may add greatly to the resources available. Other types of lasers are already being used for stone cleaning, and it is envisaged that methods of use for UVC lasers would be similar to those for stone cleaning. The advantages and disadvantages will be much as for LEDs as components.

7. Designing a UVC treatment programme

7.1 Considering safer preventive options

UVC irradiation is a dangerous technology and other safer options, such as preventive methods (see Chapter 3), should always be considered before its use. The success of preventive options will depend on the building's context, its materials, design and environmental conditions. (See Historic England guidance on Understanding the Environmental Performance of Historic Buildings for Conservation). These factors need to be fully surveyed by a conservation professional, who will be able to recommend trials to reduce moisture content and improve ventilation. A specialist in environmental performance may also be required to fully understand the exterior and internal environments to inform these works.

Measures to reduce moisture content in the building fabric include:

- **Improving peripheral drainage by:**
  - ensuring that existing land drains are functioning properly and clearing them if necessary
  - installing French drains or improving existing ones
  - installing new drains uphill, where slopes are present
  - removing excessive levels of soil adjacent to the building (subject to archaeological assessment, as needed).

- **Ensuring good management of roof rainwater by:**
  - maintaining and repairing roof gutters and drainage grates
  - replacing downpipes to increase their capacity
  - and enlarging drainage grates, in response to climate change (according to predictions of increased rainfall)
  - consulting Historic England guidance on resilient rainwater goods.

- **Promoting drying of building fabric by:**
  - removing impermeable cement pointing mortars and renders, and replacing them with permeable ones of lime mortar (if appropriate for the building)

- amending ambient environmental conditions, to increase ventilation or prevent condensation events
- strategically placing ventilation fans
- installing conservation heating, controlled by humidistat (a method mastered by the National Trust).

- **Where flooding is a risk, protective measures comprise:**
  - undertaking a flood protection survey, including a risk assessment and proposals for appropriate forms of protection
  - consulting Historic England guidance on flood resistance and flood-proofing measures.

7.2 Assessing the land and space

Threats and risks to the land and space proposed for UVC irradiation need to be identified and assessed to determine the treatment's feasibility. The work should look at the following factors, in this order:

1. Ecological issues
2. Site configuration and security
3. Historic materials present and those to be treated
4. Health and safety

Ecological considerations

UVC radiation is harmful to all flora and fauna. Potential ecological impacts should be considered early in any treatment proposal, and any requirements related to protected species or sites should be identified.

Protected species

In the UK all bats and their roosts are protected by law. Always start with the assumption that bats are present in a building or the surrounding site, unless a bat survey within the last 2 years shows that no bats or signs of bats are present. Further advice can be found in Historic England's guidance on Building Works and Bats.

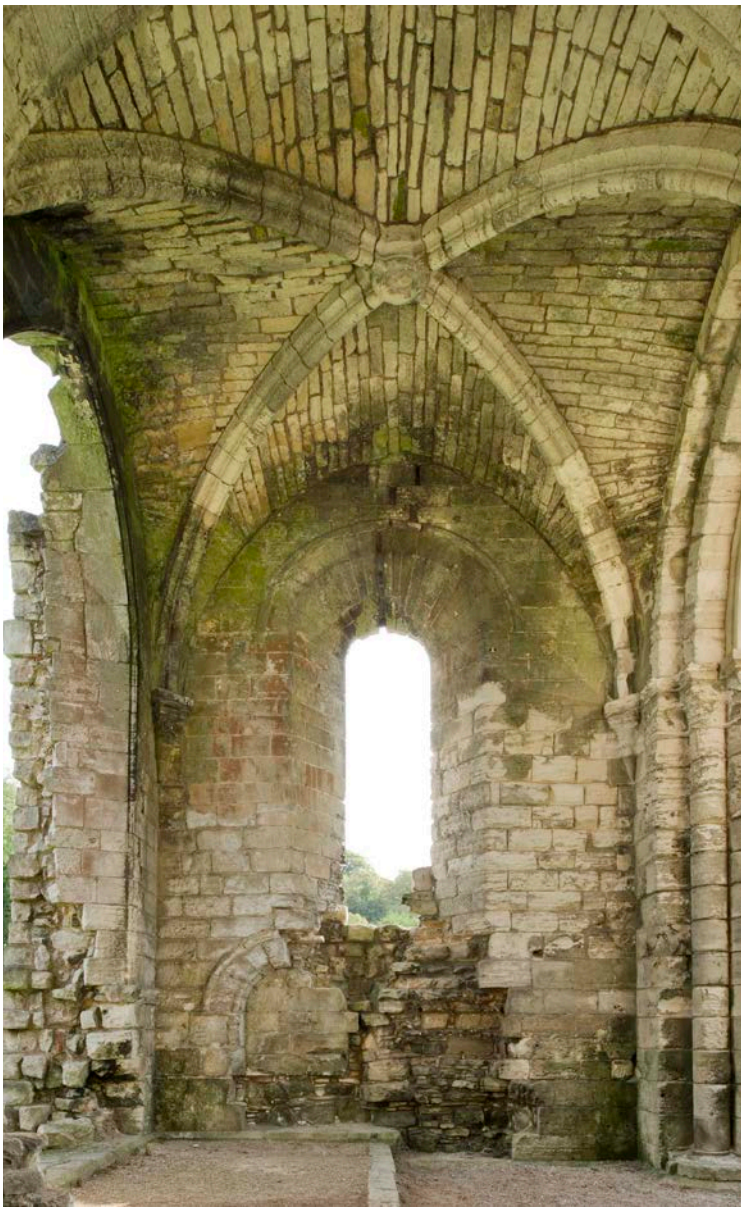
Some lichens are also protected by legislation. However, these are most likely to be found in exterior locations, so would not be affected by internal UVC treatment. However, if identified in treatment areas (e.g. ruins), they can be protected with a blackout material.

Protected sites

Natural England designates SSSIs (Sites of Special Scientific Interest) based on special interest related to wildlife, geology or landform. Some activities within SSSIs require a licence from Natural England. It is important, therefore, to clarify at an early stage if a site where UVC treatment is proposed is within a SSSI, and whether the proposal would require a licence. The status of a site can be checked on the Land Charges register or the MAGIC map system. Further information on SSSIs and the consent process is available on the Natural England website.

Site configuration and security

Most importantly, this part of the assessment must include determining site and/or building security measures and the location and type of all doors, windows and other apertures. All current and potential access should be identified, including for authorised staff, members of the public and potential intruders. Such assessment will inform the specification of any security measures needed during irradiation treatments.



UVC irradiation treatment is not appropriate in environments in which unauthorised entry cannot be prevented. For example, it should not be used in an external or semi-enclosed context, unless the perimeter can be secured and all radiation sources are out of sight. Similarly, interior spaces with complex access arrangements and large unglazed apertures may not be suitable for UVC irradiation treatment, unless controls can be put in place. As stated previously, UVC is blocked by glass (but not quartz) and most clear plastics. It is, therefore, possible to safely observe a UVC system through a window. However, if the windows are insecure and may be opened accidentally or breached by intruders, this constitutes a potential risk.

Figure 4: A ruinous medieval church with large open apertures. Unless these can be securely blocked, or radiation sources can be placed out of the line of sight, UVC irradiation cannot be safely administered here.

Historic materials present and those to be treated

In the area proposed for UVC irradiation treatment, the type of materials (inorganic and organic), their character (immovable or movable), and their significance, condition, extent and access need to be identified.

This guidance addresses UVC irradiation on inorganic materials, but the advice is subject to several caveats. Inorganic materials may have coatings and/or paint layers of sensitive organic pigments (see below). If surfaces are particularly vulnerable and significant, an experienced conservator should be engaged to assess their condition, recommend appropriate cleaning and stabilisation methods, and carry out the work.

Historic organic materials may be present in the area to be treated. These can include immovable heritage such as timber, wall paintings and wallpapers, and the last two may have photosensitive pigments, such as vermillion, lake pigments or indigo. Technical analysis may be needed to establish this beforehand, but it is more economical to assume that photosensitive pigments are present and protect them accordingly. Movable objects that may be damaged by UVC include timber, textiles, leather, plastics and rubber, some of which may also have sensitive coatings.

Health and safety

A rigorous health and safety risk assessment needs to be undertaken before using a UVC irradiation treatment. If the work is to be carried out by a contractor, their risk assessment must be obtained and reviewed by the client to ensure a safe working environment. Managing UVC systems should never be entrusted to untrained personnel or volunteers.

A health and safety assessment needs to identify:

- all reasonably foreseeable hazards
- who might be harmed and how
- risks with no controls (severity, likelihood, risk ratings)
- existing control measures
- risks with controls (severity, likelihood, risk ratings)
- actions required

This enables appropriate control measures to be specified and implemented. A sample Historic England risk assessment is provided in Appendix A.

7.3 Methodology

Planning

Once the assessments have been completed, the UVC treatment programme can be planned and formalised in detail. This entails identifying:

- all of the sequential tasks necessary for a successful and safe treatment programme; this should include the two possible treatment methodologies (empirical or scientific, see below)
- key personnel and consultants; these may include some or all of the following: building manager, architectural conservator, microbiologist, imaging specialist, electrician, health and safety advisor
- areas to be treated in preliminary trials (see Chapter 8)
- the most appropriate UVC delivery device for the context (see Chapter 6), and either purchasing it or commissioning its manufacture
- health and safety measures necessary to secure the treatment areas
- the programming of trials (for example, in buildings with public access, treatment during periods of closure)
- the budget available; this will determine if an empirical or scientific methodology is to be followed.

Finding professional consultants

The lead professional for UVC treatment on an archaeological site or in a historic building should be an architectural conservator who has an understanding of the inorganic materials to be treated. Very few conservators have experience in this domain, so the appointed professional should follow the advice in this guidance.

When funding is available to identify microorganisms, a microbiologist will be needed to help design and steer this part of the project. University academics may have interest in this field, as part of their research. Otherwise, a microbiologist from an accredited laboratory needs to be commissioned.

Historic England has published guidance on finding accredited professionals who manage the conservation of historic buildings.

Securing the space

The assessment of the land, configuration and space will have identified threats and risks to both humans, flora and fauna. The following are examples of means to secure the space and control access:

- blocking points of open access and apertures through which UVC radiation could be viewed
- providing door interlock systems
- involving named keyholders in the treatment programme
- posting exterior warning signs and keyholders' contact details, in the event that emergency services need to access the space.

Protecting vulnerable historic features

The assessment of historic materials present and those to be treated will have identified the materials at risk and the measures needed to protect them. Measures can include placing screens or blackout fabric over immovable organic materials, and relocating movable features such as furniture during treatment.

In sensitive contexts (such as unstable ruinous masonry), access arrangements can pose risks to the building fabric when moving and installing treatment equipment (see Figure C3). These risks can be reduced by issuing guidelines for access. See Historic England's guidance on Temporary Protection of Historic Features During Building Works.

Implementing health and safety control measures

General considerations include but are not limited to:

- issuing instructions to all operatives involved in the treatment programme
- briefing cleaning and security staff, as well as other building users, about the risks and operation of UVC irradiation equipment and systems, especially if the treatment may take place outside normal working hours
- providing appropriate protective gear to operatives as needed (including protection from mould, where it is present)
- locating the UVC power source outside the irradiation treatment space so that it can be turned off before entry, or connecting a power cut-off device to the door
- ensuring that equipment is designed with an IP (ingress protection) electrical rating appropriate to the conditions in which it is being used. This may mean that the irradiation sources need to be protected by quartz sheets or sleeves and appropriate gasket material. Commercially available quartz sleeving is suitable for use with linear low-pressure mercury lamps. Quartz sheeting may have to be sourced on a bespoke basis. Specialist advice will be needed regarding the choice of gasket materials.
- confirming that electrical equipment is connected to the appropriate protective device, for example a residual current device where equipment is being used in damp conditions
- using UVC sensors to verify that a UVC device is operational.

Choosing the appropriate treatment methodology

There are essentially two different technical methodologies available for UVC application, depending on funding.

The empirical approach involves graduated trials of different dosages of radiation, followed by visual appraisal of the results using conventional photography. Specialist analyses of microorganisms described in this document would not be implemented.

The scientific approach entails some level of identification of microorganisms and accurate means to record them, before and after treatment. A range of analyses, described below, may be carried out.

These two approaches are appraised in Table 2. Examples of both are described in Appendix C.

Table 2: Characteristics of empirical vs scientific treatments.

Consultant(s) required	Advantages	Disadvantages
Methodology: Empirical		
Conservator	No additional cost for microbiologist or imaging specialist.	Assessment of efficacy is imprecise, beyond visual comparison with untreated areas.
	Irradiation does not have to wait for results of laboratory analysis of microorganisms.	The rate of regrowth cannot be accurately measured.
	Once the method/technique is established (specifications), the treatment can be carried out by a non-specialist.	Visual monitoring of regrowth may be particularly difficult unless there is a consistent form of illumination.
		The lack of precise identification of the type of microorganism(s) may render treatment less effective and efficient.
Methodology: Scientific		
Conservator **Microbiologist** **Imaging specialist**	Assessment of efficacy can be accurately measured in relation to dosage administered.	Initial cost of specialist analysis is high.
	Cost of specialist may initially be high, but will reduce greatly with monitoring (image analysis).	
	Once the method/technique is established (specifications), the treatment can be carried out by a non-specialist.	
	Accurate measurement of regrowth can be factored into an efficient maintenance retreatment programme.	
	Academics from universities may be interested and may provide services *pro bono*.	
	Level of identification of microorganisms may be reduced on advice of microbiologist.	

Sampling and identifying microorganisms

Considerations include:

- types of microorganisms
- presence of a biofilm
- presence of photosynthetic organisms
- sampling possibilities: non-destructive or destructive
- choice of sampling sites
- location of laboratories relative to sampling location (if analysis is to be done)
- transport of samples
- choice of analysis: culture-dependent or culture-independent.

Identifying the microorganisms present is not essential for using UVC irradiation in a historic building context. Obtaining this information is expensive and requires specialist expertise, so the complexity of the microbial populations present on heritage surfaces puts detailed scientific analysis beyond the means of some conservation budgets. Nevertheless, there are small steps that can be taken to provide useful understanding of the effects of UVC on target microorganisms and to inform choices about the irradiation dosage. Even the most basic microbiological investigations will increase an operator's understanding of the treatment. A microbiologist could make a single visit to the site and extract samples. This could be followed by basic microphotography and macrophotography of designated control areas before, during and after treatment, especially if photosynthetic microorganisms are involved. This information could then be related to a record of irradiation parameters – frequency and density of irradiation – to allow an appropriate dosage to be calculated.

When more detailed scientific microbiological evaluations can be funded, a multi-pronged approach to sampling, examination and analysis will provide most information. Microbiological investigations commonly employ one of two types of sampling: non-destructive or destructive. In general, the method chosen will be dictated by the nature of the contamination and the heritage surface beneath. If removing material is not an option, such investigations will necessarily be non-destructive.

If microbial contamination has caused a biofilm to form, biological material can be removed using adhesive tape (this technique is widely used in cultural heritage). The simplicity of this minimally invasive approach has much to recommend it, especially for coloured photosynthetic microorganisms in which colour changes after UVC treatment may be evident to the naked eye.

Examining tape samples with a light microscope makes it possible to observe the presence of algae and fungi, but many bacteria pose more of a challenge because of their small size. For such situations, it is possible to sample surfaces using a sterile cotton wool swab, to obtain direct surface impressions using agar contact plates or, perhaps, to remove small samples with a sterile scalpel. However, these methods are classified as culture-dependent

(where microorganisms are grown on nutrient media and isolated into pure cultures) because they require further analysis. If resources, expertise and sampling protocol allow, more information can be obtained using scanning electron microscopy (SEM) and confocal laser scanning microscopy (CLSM), which provide a 3D assessment of the surface, any biofilm present and microbial interactions.

Identifying the species of microorganisms provides the genus of organisms involved, and can also indicate how UVC affects the balance of populations and highlight any resistant types. Light microscopy is rarely enough to identify types with any certainty. For most purposes, this detail is not required, but if further analysis is needed it will usually involve culture-dependent methods or culture-independent methods (where population DNA is extracted from the sample, DNA genes are amplified by the polymerase chain reaction technique, commonly called PCR – a standard in molecular biology and hospital laboratories – and then the individual types present are identified). In practice, isolated organisms can be used to create molecular probes that can be employed to locate and assess the distribution of particular types of microorganisms using the fluorescence in-situ hybridization (FISH) technique.

Sampling case study: Newport Roman Villa, Isle of Wight

The biological sampling methodology used at Newport Roman Villa for a photosynthetic biofilm on a heritage surface illustrates a possible approach if resources and expertise are available. This approach is summarised in Figure 5. A more detailed description of UVC treatment methodology is explained in Appendix C.

Since the targets of investigation were living organisms, sample collection and laboratory analysis had to be done on the same working day, to ensure that the data obtained were representative of the populations sampled. Samples were stored in a cool box during transport to the laboratory.

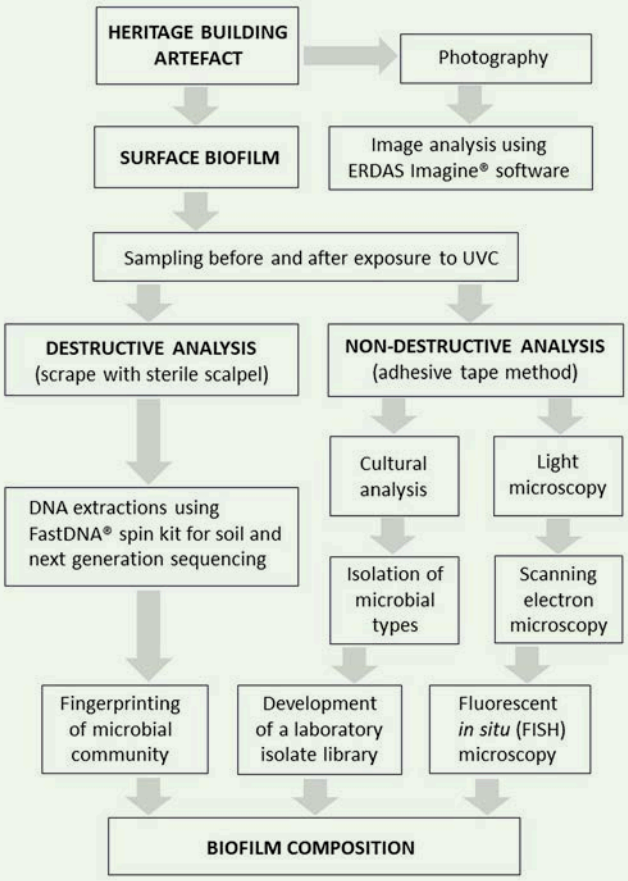


Figure 5: Biological strategy for sampling at Newport Roman Villa, Isle of Wight.

Non-destructive removal of biofilm using adhesive tape
Surface samples were removed using a 40mm length of clear adhesive tape. The tape (with its microbial loading) was then attached to a glass microscope slide and taken to the laboratory for examination. Figure 6 shows the tape samples obtained from nine sites before and after UVC treatment; green-pigmented photosynthetic organisms were clearly visible. Even without further investigation, it was possible to see with the naked eye that the colour intensity was reduced after UVC treatment. The samples were viewed by light microscopy within four hours of removal to assess the morphology and arrangement of the microorganisms. This approach gave useful information on the range of cellular shapes (spherical, rods and filaments), relative abundance and distribution (see Figure 7).

Destructive removal of small amounts of biological material by scalpel
Scrape samples were removed using a clean sharp scalpel into 2ml plastic tubes. At the laboratory, these were crushed using a small agate pestle and mortar. They were suspended in phosphate-buffered saline (a solution that protects and maintains the integrity of the microbial cells), shaken and allowed to settle for five minutes. The cleared liquid suspension over the sediment was used to further identify the microorganisms present by DNA analysis and fingerprint analysis of the biofilm community.

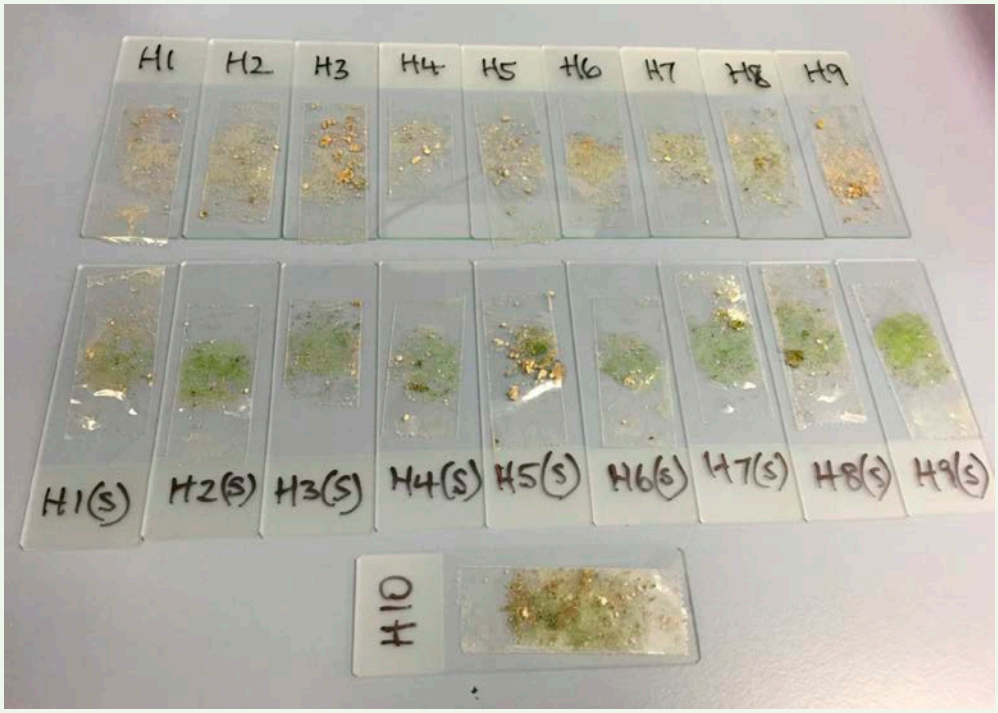


Figure 6: Samples of microorganisms removed with adhesive tape and applied to glass slides for microscopic examination. The top row for sites H1 to H9 were UVC irradiated and the second row were covered; H10 is an unirradiated control.

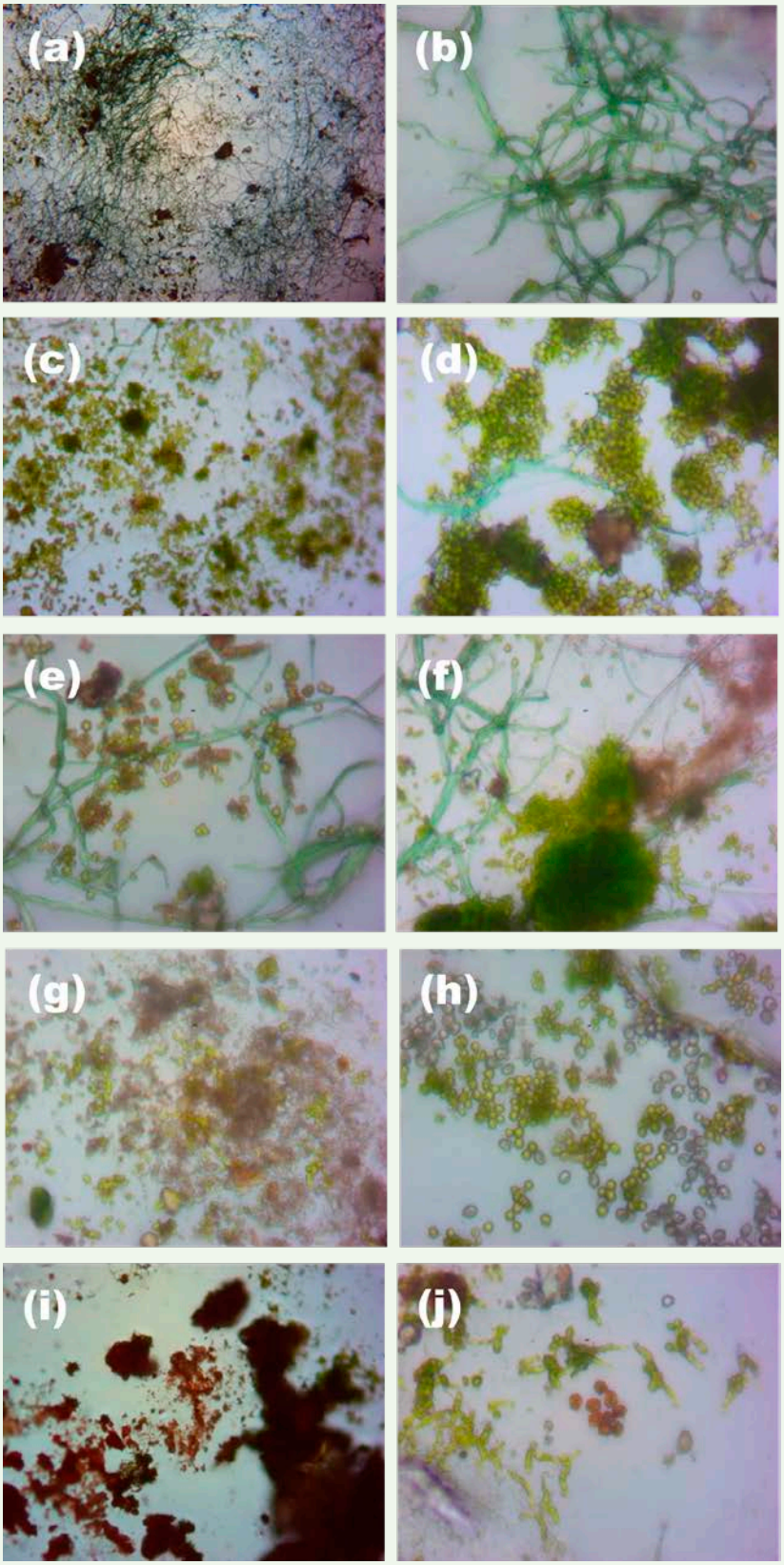


Figure 7: Light microscopy images of algae at Newport Roman Villa, Isle of Wight. Filamentous green pigment algae (a and b) are very common, as are other single-celled types (e and f). Coccoid spherical single-celled algae with yellow-green pigment were also found at many sites (c, d and f). A range of other single cells, often with red or pinkish pigments, were observed less commonly (e to j).

Recording and monitoring

The abundance (or intensity) of microorganisms should be recorded before, during and after irradiation. The various techniques and levels of recording and their precision are described in Table 3, with respect to UVC irradiation.

Table 3: Indirect UVC irradiation monitoring methods.

Technique	Description	Accuracy
Earth Resources Data Analysis System (ERDAS) image analysis	A remote sensing software that uses spectral analysis of photographic images so that each pixel can be classified for its content. For microorganisms, particular attention is given to green growth. Before and after UVC treatment, sample sites are photographed, and the resulting images are selectively subjected to ERDAS analysis.	Provided the imagery used is associated with a measured control area, the size of each pixel can be determined within the software. Measurements are then made, accurate to the calculated size of an individual pixel. This level of accuracy also applies to areal measurements.
Infra-red (IR) probe or photography	An IR probe that measures wavelengths of light from visible through to infra-red. Organic growth has spectral signatures that reach into the infra-red. Using these wavelengths will enable the identification of organic growth not visible to the naked eye.	IR probes come in a range of sizes. The probe size determines the spatial area across which a spectral signature is integrated. The smaller the probe, the smaller the area, so more samples are likely to be required to provide a representative indicator of the spectral signature of an area. An IR camera produces an array of pixels with values for each wavelength. Pixel size is a function of the distance of the camera from the surface and the pixel resolution. Pixel size can be calculated within a software package such as ERDAS, as noted above.
Spectrophotometer	Colorimetric measurements: wavelength or in terms of L x a x b colour measurement. This is a way to represent colour space by L – lightness, a – red/green value and b – blue/yellow value. For any point measured on a surface, this means that its colour can be represented by a set of co-ordinates (L, a, b) in this colour space.	The spectrum measured depends on the range of the instrument used. At least the spectrum of visible light (380–700nm) will be needed to identify organic growth. The size of point measured depends on the measuring aperture of the instrument, which provides a measurement area in degrees.

Adobe Photoshop (or similar processing software)	Photographic imagery of areas using normal cameras, with flash to standardise lighting conditions. A Kodak colour card can be used within an image to ensure colours are consistent between images. If a Kodak colour card is not available, there are colour card phone apps that will provide the same function: that is, ensuring comparability between images.	The size of pixel depends on the size of the area being imaged, and it can be calculated using the dimensions of the control area and the number of pixels within that control area. Areas of organic growth can be identified via their colour signature and used with the magic wand application to identify areas with similar colour signatures. The extent of these areas can be compared in before and after images.
Adenosine triphosphate (ATP) bioluminescence assay	ATP is present in all microorganisms, plant and animal cells. It is the molecule that provides energy for cellular metabolism. The ATP bioluminescence assay is used to measure the sterility of a surface after cleaning, particularly in medical and food contexts. The ATP assay could be used to count how many cells are present and whether they survive UVC treatment, and also to demonstrate the necessity of repeat treatments for thick biofilms on a historic surface to achieve higher killing rates.	An ATP luminometer provides quantitative measurements by bioluminescence. Precision and accuracy depend on the quality of the luminometer.

Documenting the nature and extent of the damage associated with microorganisms is a key starting point for assessing the effectiveness of a treatment regime. Although the procedures set out below can be used for detailed academic analyses, their primary purpose is to provide information to conservators on the effectiveness, or otherwise, of UVC irradiation treatments. It is up to the individual conservator to decide how accurately or extensively they wish to undertake the suggested stages, based on the requirements of their monitoring brief.

Initially, it is important to identify the area and the characteristics of the damage to be monitored. Defining the area helps to establish the amount of photography and recording required. It also helps to identify which resources will be needed for the monitoring. Identifying the characteristics of the damage enables the person carrying out the treatment to establish a baseline from which change can be identified and quantified. It is important that the observer is clear at the start of the process what type of damage they are looking for and what level of damage is viewed as unacceptable. It is advisable to create a set of photographs that identify different types and intensities of damage, for reference purposes.

This will help the observer to identify and map damage, using graphic survey standards, as monitoring progresses. It will also enable them to compare the damage at one site to damage at others.

Having established which resources are required for monitoring, the next stage is to ensure that the damaged area can be easily identified throughout the treatment programme, by means of labels (see Figure 9). This will require the permanent installation of at least three, preferably four, control points. These points should be located at the edges of the area to be monitored. Labels need to be attached to the surface, and their relative distances from each other accurately measured (+/-0.50mm). This provides a reference plane within which any point on the surface can be located, enabling repeated monitoring of any changes in the surface characteristics of a specific point or area.

The next step is to photograph the area(s) to be monitored. It is important to include a colour card, such as a Kodak colour card, at the edge of the monitored area, as a reference point for colour consistency. Colours recorded should not change between photographs because using flash should ensure that light conditions are the same. Each photograph should be taken as perpendicular to the surface as possible. This will limit any areal distortions from variations in camera angles and ensure that the same areas are compared between treatments. When taking the photograph, the observer should ensure that all the control points (labels) and the colour card are clearly visible within the frame.

It is recommended that a common recording system is used for the areas photographed and the photographs themselves. For example, each location has a letter (A, B, C and so on), and each individual monitoring area within the location has a number (1, 2, 3 and so on). Any photographs (P) are then affixed to each area, for example A1-P1, A1-P2, A1-P3. Additional coding for before and after treatment or for the date of photography can also be included, for example A1-P1-25-08-22, A1-P2-25-08-25. Documentation summarising what each code refers to should be kept. The coding system will then provide the observer with the precise location of the monitoring area and the date of the photograph associated with it.

As a minimum, there should be a set of before and after treatment photographs for each area. Photographs should be cropped to show only the area within the control points. This will ensure that the same areas are compared before and after treatment.

There are a number of ways to analyse any changes in these images, the choice of which will depend on the observer's expertise and the software available. At the simplest level, the two cropped photographs can be compared visually. The observer will need to decide if the UVC treatment has altered the surface characteristics and if it has affected the microbial damage. Either way, a record of this assessment should be recorded and the photographs retained for future reference or further analysis.

Specialist image analysis software, such as ERDAS IMAGINE©, or readily available photographic processing software can be used for further analysis. Whichever software is used, the basic idea is the same. An area is selected as being typical of a location covered by organic growth. This area then provides the spectral signature – the red, green and blue values of pixels – for the presence of organic growth. With this information, the user can employ the software to pick out and highlight areas with the same or similar spectral signatures within the image. The extent of these areas can be mapped and measured in terms of the number of pixels. Carrying out this analysis for both the before and after treatment photographs of the same area will provide the operator with two processed images, each showing the extent of organic growth and each providing a measure of the number of pixels covered by this growth. Comparing the two images will permit both a qualitative and quantitative assessment of the effectiveness of the UVC treatment programme.

A fluorometer could also be used to assess the effectiveness of UVC treatment. This hand-held instrument uses a modulated ultra-bright blue LED to induce fluorescence in chlorophyll-a and in related pigments. When linked to computer software, it can produce a map of algae population on a solid surface in real time. A variety of commercial models are available.

Calculating UVC dosage

The most effective UVC treatment requires the correct dose for a particular species or mixed community, such as a biofilm. Otherwise, it is helpful to know the generic types present. Intensity of the source, exposure time and distance between UVC source and treatment area need to be considered. The higher the intensity of UVC radiation, the less time it will take to eradicate microorganisms. However, the potency of radiation decreases with distance from the source, following the inverse square law. This means that at twice the distance, UVC radiation will have a quarter of its power. This determines the distance within which a single source of UVC radiation is effective.

If a scientific methodology is being implemented, and the principal microorganisms have been identified, technical literature from manufacturers and others will give the times required for UVC to kill commonly found bacteria and viruses relative to the irradiation power and distance. For example, a dose of 3,000J/m2 will be required to eradicate blue-green algae. Further experimentation may be required for newer UVC sources, such as LED, or other types that are not yet extensively documented. Alternatively, if an empirical methodology is being used, a process of graduated trials will be required (see Chapter 8).

Sample UVC calculations

The following calculations are the basis for the works carried out at Fort Brockhurst, Gosport, detailed in Appendix D.

The calculations follow the methodology given in the 2001 publication titled 'Perfection preserved by the purest of light' (UV disinfection and application information) from Philips Lighting. This has now been updated and publication details can be found in the Further reading section of this guidance.

The use of 11W PL-S compact fluorescent lamps was suggested, located 300mm above the surface of the stone to be treated for mould.

Reference to Table 6 on page 35 of the Philips document shows that the chosen lamp has an irradiance value at 1m of 30µW/cm^2. 1µW = 1 micro-Watt = 0.000001W, and there are 100cm x 100cm per square metre. 30µW/cm^2 = 0.00003 x 100 x 100 = 0.3W/m^2.

As the lamps are tubular, the radiation will vary in proportion to the circumference of the circle a given distance away from the lamp (assumed to be a longitudinal source of minimal diameter):

- At 1m away from the lamp, the circumference is 2 x pi x 1 = 6.284m.
- At 300mm (0.3m) away from the lamp, the circumference is 2 x pi x 0.3 = 1.885m.
- The irradiance at 300mm away from the lamp will be (6.284/1.885) x 0.3 = 1W/m^2.

For each type of mould, there is an effective dose = irradiation density (W/m^2) x time (seconds). From this, the 'dwell time' (the time required to kill off the mould) was deduced.

Table 4: Irradiation required to eradicate specific moulds

Mould	Dose	Calculation	Seconds	Minutes
	Irradiation density in W/m^2 x time in seconds	Dose divided by irradiance in W/m^2 to give time in seconds	Result in terms of seconds	Result in terms of minutes for ease of setting a timer
Aspergillus flavus	600	600/1	600	10
Aspergillus glaucus	440	440/1	440	7.3
Aspergillus niger	1320	1320/1	1320	22

The stone was then exposed to meet the worst-case timing requirement, with the radiation controlled by a timer to minimise energy consumption.

Listed building or scheduled monument consent

If a building is listed or is a scheduled monument, you may need consent for temporary protective measures. Historic England guidance on heritage consents explains who you need to contact. You may need to provide a method statement for the protective works as part of the application or as a condition of its approval. If the need for temporary protection is identified after permission for building work has been approved, contact the authority that granted the permission to discuss whether further consent is needed.

As UVC is a non-contact treatment, consent for its use may not be required. However, consent may be needed depending on the level of listing status and precleaning requirements.

8. Preliminary treatment and assessment

8.1 Implementing protective measures

After considering the issues described in Chapter 7, a formal treatment plan can be made. This plan includes designing health and safety procedures and also actions to protect any sensitive historic surfaces. Once in place, the measures should be fully assessed for their efficacy before treatment begins.

8.2 Cleaning

In general, all surfaces will benefit from cleaning before UVC treatment, to remove surface dirt, spores and dead organisms. Dense biofilms can vary in thickness and complexity. As such, they will protect microorganisms from UVC to varying degrees, and so impede effective UVC treatment. Dense biofilms should, therefore, be removed before any treatment takes place. If historic surfaces or objects are at risk of damage from cleaning, seek the advice of an architectural conservator before work commences. It is best that they carry out the cleaning (see Chapter 7).

Cleaning should be subject to initial trials, beginning with the most benign materials and tools (for example, warm water and sponges or soft brushes). Cleaning methods and results should be recorded and archived for future reference. Initial methods may use wet sponges to minimise the amount of water applied into the building fabric and to prevent microorganisms migrating deeper into very porous materials. On robust substrates in good condition, the following options can be considered:

- water (distilled or deionised), possibly with a non-ionic detergent
- superheated water (high-pressure steam)
- dry cleaning with a HEPA filtered vacuum and a brush (particularly where soluble salts are present and wet cleaning needs to be avoided).

Where mould is present, appropriate PPE needs to be worn. Cleaning methods should not cause scattering of spores.

8.3 Preliminary UVC trials

Trials are required to define effective large-scale treatment programmes. They should be carried out to test the range of treatment parameters and to determine the most appropriate dosage. Where there is a clear difference in the abundance of microorganisms on the surfaces to be treated, areas with low, medium and high abundance should be chosen for trials.

If an empirical methodology is being applied, a spectrum of dosages is administered in graduated trials (low, medium, high), then visually compared. Further iterations can be applied based on preliminary results. Where there are funds for a scientific methodology, the dosage required to eradicate the specific microorganisms present provides a starting point for treatment.

Simple monitoring of environmental parameters (temperature, surface temperature and relative humidity) is a useful baseline to help understand their effect on UVC treatment (see Figure 8). Monitoring can then be continued to observe the rate of post-treatment regrowth.

Treatment areas should be numbered and photographed with a colour scale, before and after treatment (see Figure 9 and Appendix C), as described above (see Chapter 7).

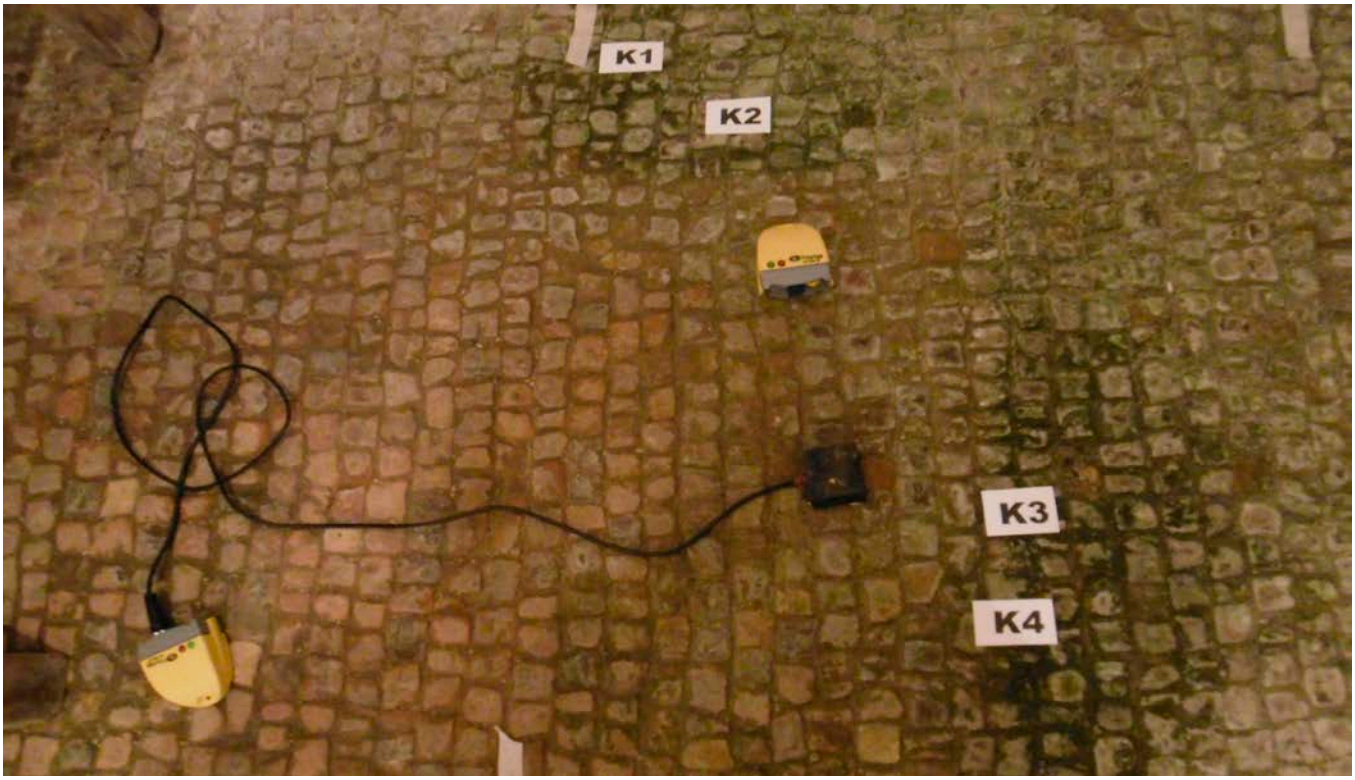


Figure 8: Environmental monitoring of a treatment site, with ambient temperature and relative humidity datalogger (centre) and surface temperature datalogger (lower left).

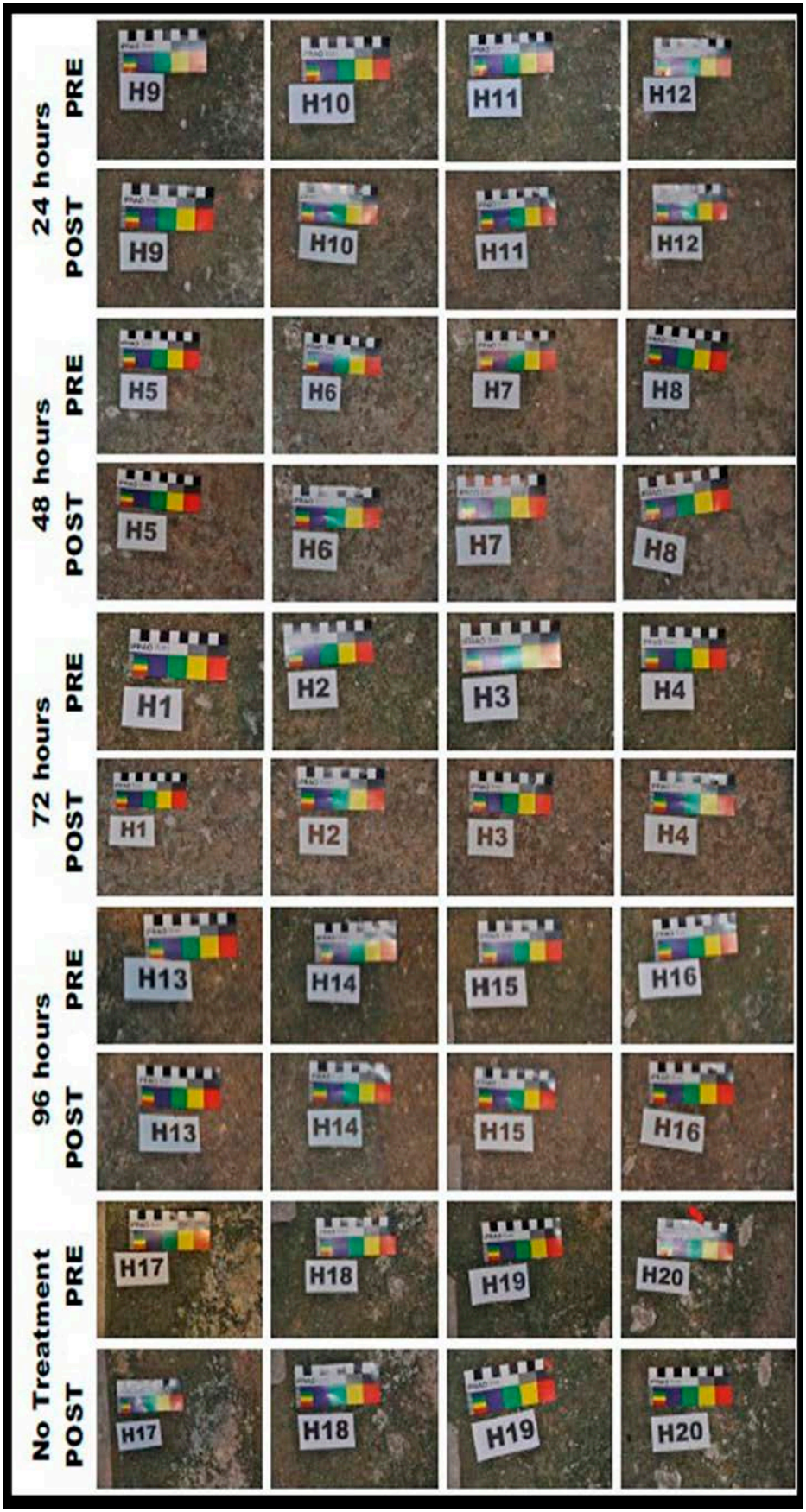


Figure 9: Comparison of images for different treatment times before and after UVC irradiation. This includes a control with no treatment.

There are several ways to measure how much UV energy a surface has received. Dedicated instruments can measure the cumulative intensity of UVC output so that adequate treatment times can be interpreted. UVC dosimeters are also available. These change colour based on the amount of UVC radiation received. They exist in a variety of formats, cards or stickers. Dosimeters communicate if the dose is strong enough to kill or inactivate specific microorganisms. They are designed for use with 254nm light sources, so will not provide accurate measurement for far-UVC (207–222nm), LED UVC or pulsed xenon light sources.

If there are soluble salts within the masonry, there is a risk that any heat generated by electrical equipment from irradiation sources may cause damage through cycles of salt crystallisation. This is a particular issue when the irradiation source is enclosed, such as in a box. In initial trials, small datalogger sensors – measuring ambient temperature, relative humidity and surface temperature – can be placed on the treated surface. The same sensors need to be placed outside the treatment area for comparative purposes (see Appendix C). Data can be downloaded onto a computer with its associated software.

This approach allows assessment of whether the temperature of the treatment area is excessive. Periodic inspection of the treatment area for any signs of surface salt efflorescence should also be carried out during pauses between treatments. If surface salt efflorescence occurs, the design of treatment should be re-evaluated to reduce the surface temperature of the area being treated.

8.4 Documentation

The minimum documentation for trials and larger treatments should include:

- objectives of the treatment programme
- protective measures employed (health and safety and protection of historic surfaces)
- names of all team members and building management staff
- operating and maintenance instructions for equipment and systems
- periodic test and inspection certification for bespoke fixed installations built into the building services
- portable appliance testing (PAT) certification for portable appliances and equipment connected to fused connection units
- readings from a UVC meter to measure dosage and ensure lamps are operating properly; this can also identify when lamps have failed
- surface and ambient temperatures recorded using simple dataloggers (if an enclosed box is used, which could generate heat)
- a diary or log of events that details the following so that accurate treatment calculations can be made:

- dates and times or duration of operation
- equipment used
- extent of surface(s) or object(s) being treated.

8.5 Post-treatment cleaning

As stated above, dead organic matter generated from UVC exposure may provide nourishment for other microorganisms, so it needs to be removed. If the treated surface is fragile, seek guidance from the conservator advising on the project, or commission them to clean it.

Sound surfaces can be cleaned using a brush and dustpan or low suction vacuum cleaner, perhaps followed by a modest wet clean with a sponge and deionised water.

8.6 Assessment

After the preliminary trials, the results should be reviewed. This means equating image analysis (see Chapter 7), or other form of recording, with the UVC dosage administered in each trial area (see Figure 9). Ideal treatment parameters can then be determined: distance of the UVC device from the treated surface and duration of irradiation. This information forms the basis for the design of a regular maintenance programme.

9. Monitoring and maintenance

Surfaces treated with UVC radiation should be monitored as part of the routine maintenance of a historic building. This may entail taking photographs annually (including a colour scale), and adding them to the maintenance records.

(a)

(b)

(c)

(d)

Figure 10: The hypocaust at Newport Roman Villa, Isle of Wight, before and after treatment in 2016 and 2018: **(a)** 2 March 2016, **(b)** 10 March 2016, **(c)** 15 February 2018, **(d)** 22 February 2018. There was a marked decrease in visible microorganisms after initial treatment in 2016. Some regrowth had occurred two years later. In this damp location, regular treatment is required.

Even if a single UVC treatment is successful, microorganisms will reappear if environmental conditions are favourable. These microorganisms may differ from those previously present. An environmental monitoring programme (ambient temperature, surface temperature, relative humidity) can inform an understanding of the rate of regrowth of microorganisms.

Repeat treatments are normally required when the concentration of microorganisms becomes aesthetically disturbing. Over repeated applications, the ideal interval between treatments will become apparent.

The parameters for repeat treatments should follow those that were most effective in the initial programme, in terms of intensity, time and distance between the device and the surface. These parameters should be duly recorded, as in the preliminary treatment phase (see Chapter 7).

Appendix A: Sample risk assessment form

The following sample form shows the type of information that needs to be included in a thorough risk assessment of UVC irradiation treatment.

Assessment date		Assessor name		Group/ department	
Office/location					
Assessment title	UVC irradiation treatment of medieval stone masonry				
Description of activity*	Use of UVC germicidal irradiation lamps to eradicate microorganisms on internal stone surfaces of medieval walls, within a small site museum managed by the local authority. Treatment will be carried out during the winter closure period.				
Assessor's signature					
Line manager/project manager's signature					

***Note:** Try to describe as much as possible about usage, surrounding environment, weather and so on.

Persons affected: enter the approximate number of people who may be affected against each category below.

Museum manager	1				
Skilled contractors	3				

Hazards: rate existing controls, additional controls and their ratings (see severity ratings in table below).

Hazard type	Who may be harmed and how	Existing controls	Current risk rating			Additional controls	Revised rating See Note 1		
			S	L	S × L		S	L	S × L
Exposure to UVC germicidal radiation lamps: erythema (skin) and conjunctivitis (eyes). With chronic (lengthy) exposure: skin cancer, cataracts and retinal damage.	Any person who enters the irradiation area (staff, emergency services, intruders) with unprotected skin and eyes may be exposed to UVC irradiation.	The museum is closed to the public during the winter period and is secure against unauthorized entry. There is no need for staff to regularly access the building during the irradiation period. The irradiation area is completely enclosed, with no external windows. There is glazing (internal door and window) at the entry to the irradiation area. This is a natural block for UVC irradiation. There are three external doors: two are bolted inside so do not allow entry from the exterior; the only door that does allow entry from the exterior is the front door. Two of the external doors have glazing of reinforced glass. The only other window is in the WC. It does not have reinforced glass but the WC door can be locked.	5	2	10	The conservation contractors will be made fully aware of the Historic England guidance: Control of Microorganisms in Historic Buildings: UVC Irradiation Treatment. The electrical power source for the UVC unit will be located outside the irradiation area (connected to UVC bulbs with an extension lead), allowing for UVC bulbs to be extinguished before entry into the irradiation area. All staff with access will be informed of this requirement. The glazing (internal door and window) at the entry to the irradiation area will be enhanced with a blackout curtain. The front door (the only one that permits entry from the exterior) will be fitted with an additional lock. There will be only one keyholder (the person monitoring the trials). This member of staff will be briefed on the contents of this risk assessment and will be instructed not to enter the room containing the radiation source. Warning (irradiation) signs will be placed on all three external doors and the one window. These will include the name and telephone number of the keyholder in the event that emergency access is needed.	1	1	1
Electrical See Note 2			3	2	6	All portable electrical equipment will be tested and visually inspected by the local authority electrical engineer prior to use.	1	1	1

State any risk assessment actions required in the table below.

Description	Responsible person	Due date	Date completed
Engage an electrical engineer to inspect all relevant equipment.			
Place a blackout curtain onto glazing			
Brief the keyholder member of staff on the contents of this risk assessment and instruct them not to enter the room containing the radiation source.			
Place warning (irradiation) signs on all three external doors and the one window, including the name and telephone number of the keyholder.			

Scoring guidance

Severity (S) - Identify the worst reasonably foreseeable consequence		
Score	Description	Example
1	Insignificant	Injuries or illnesses requiring no treatment or first aid only, e.g. superficial cut, bruise or abrasion, temporary discomfort or pain
2	Minor	Injuries or illnesses requiring medical treatment beyond first aid only, e.g. deep wounds, moderate eye, skin or respiratory irritation, drowsiness or dizziness, minor sprain/strain, mild burn
3	Moderate	Temporary impairment, causing lost time or job restriction, e.g. minor fracture (finger, toe etc.), severe irritation, moderate burn, serious strain or sprain, mild to moderate depression/ anxiety/stress
4	Major	Permanent/prolonged impairment, e.g. complete/ partial loss of hearing/vision, amputation, major fracture or multiple injuries, severe burn or tissue damage, major irreversible disease
5	Catastrophic	Fatalities or severe illness e.g. fatal injuries, cancer, birth defects, heritable genetic damage, impaired fertility

Likelihood (L)		
Score	Description	Example
1	Rare	Incident unlikely ever to happen. Probability of incident close to zero
2	Unlikely	Incident foreseeable but probability very low. Incident might be seen once during working life (40-year period).
3	Possible	Incident may have occurred in the past. Expect to see several incidents during working life (40-year period).
4	Likely	Incident has occurred in the past. Expect at least one incident per year. Personnel would not be surprised by incident.
5	Almost certain	Incidents occurred frequently. Expect significant number of incidents each year.

Prioritisation Risk Matrix

		Severity (5)				
		1 - Insignificant	2 - Minor	3 - Moderate	4 - Major	5 - Catastrophic
Likelihood (L)	1 - Rare	1	2	3	4	5
	2 - Unlikely	2	4	6	8	10
	3 - Possible	3	6	9	12	15
	4 - Likely	4	8	12	16	20
	5 - Almost certain	5	10	15	20	25

For example: Risk = Likelihood x Severity (3 Possible x 3 Moderate = 9)

Green – No further action is required

Yellow – Actions should be identified to reduce the risk

Red – Consult with the Safety Team as soon as possible and consider suspending the task until actions have been completed that reduce the risk to 9 or less

Black – Suspend the task immediately and consult with the Safety Team

Note 1 : With revised risk rating, the severity rating in a risk assessment typically does not change. It is the likelihood rating that lowers the risk .

Severity is typically assessed based on the potential consequences of a hazard, and while control measures can reduce the likelihood of an event, they do not always change the inherent severity of the hazard itself, regardless of how careful someone is. Severity can change if the hazard itself is eliminated or significantly reduced: for example, substituting the hazard for something less hazardous. However, in some cases, effective control measures can reduce the severity of potential consequences. A review of the risk assessment may be warranted if significant changes are made to the hazard or control measures.

Note 2: The current risk rating refers to unsafe conditions involving electricity that can cause injury (shocks or burns), death or property damage including fires, and explosions from faulty wiring, damaged equipment or improper use of electrical devices.

As electricity has the potential to cause death, fires and explosions, the severity must convey the worst outcome if this were to occur, as it is the likelihood of it happening that lowers risk.

Revised risk rating: Unless the electricity is going to be completely isolated, the severity would be 5.

Appendix B: Cultural heritage sites with UVC irradiation treatment

The following table provides an overview of historic sites treated with UVC irradiation. The treatments vary greatly, from single experimental phases of treatment to thorough scientific programmes. The latter are more likely to have produced publications. It is by no means an exhaustive list.

Table B1: Historic sites treated with UVC irradiation.

Dates	Site or other details	Nature of treatment
Pre-1980	Church of St Stephanus, Pilsum, Germany	A mobile ultraviolet unit (MUVU) was developed that successfully eradicated microorganisms on the unpainted plaster of damp church walls. A 40W lamp with aluminium reflector was placed 80mm to 200mm from the wall, and applied continuously for one week. After treatment, the selected area was practically clear. Results were confirmed by infra-red photography, quantitative chlorophyll determination, light microscopy and scanning electron microscopy.
		Reference: Van der Molen, JM et al 1980 'Growth control of algae and cyanobacteria on historical monuments by a mobile UVC unit (MUVU)'. *Studies in Conservation*, **25** (2), 71–7
1988	Work of Claude Bassier, France	Claude Bassier reported on his use of UVC irradiation on a mosaic pavement and some polychrome stone statuary in France, beginning in 1976. This was not described in detail.
		Reference: Bassier, C 1989 'Le rayonnement ultra-violet dans la désinfection des matériaux de nature ou d'origine minérale: Exemples d'application'. *Patrimoine Culturel et Altérations Biologiques: Actes des Journées d'Étude de la SFIIC, Poitiers, 17 et 18 Novembre 1988*. Champs-sur-Marne: Section Française de l'Institut International de Conservation, 201–6

1996 to 1998	Lacock Abbey, National Trust, UK	This medieval structure is on a very damp site. A programme of emergency plaster conservation took place between 1996 and 1998. It included trials of UVC irradiation to eradicate fungi and algae at the base of the walls, carried out over a period of five days. All visible microorganisms were eradicated, as confirmed by an experimental fluorometer developed by a team from Robert Gordon University. The instrument recorded concentrations of chlorophyll (type a) in algae and cyanobacteria cells. The surface was surveyed by the fluorometer 18 months later, and no surface recolonisation was detected.
		Reference: Lithgow, K and Stewart, J 2001 'Conservation strategies for damp buildings and plaster: Lacock Abbey in Wiltshire'. *Journal of Architectural Conservation*, **7** (2), 7–26
1989 **2015**	Abbeyknockmoy, County Galway, Éire Katkov-Oldenbourg Office of Public Works and Perry Lithgow Partnership	Katkov-Oldenbourg undertook the conservation of the badly deteriorated wall painting of the 'Three Living and Three Dead' on the north wall of the chancel. The work was completed in 1990. The treatment at Abbeyknockmoy consisted of 'limited UV exposure in combination with direct surface cleaning using de-natured alcohol swabs'. In November and December 2015, the Perry Lithgow Partnership carried out further UVC irradiation treatment of the same painting. They used similar techniques to those employed at Cashel, County Tipperary, and Jerpoint Abbey, County Kilkenny (see below).
		Reference: Unpublished conservation reports
1990s–2001 **2016**	Clare Abbey, Clare Island, County Mayo, Éire Katkov-Oldenbourg Office of Public Works and Perry Lithgow Partnership	The wall paintings in the chancel date from the mid to late 15th century and they were treated extensively with UVC irradiation in the 1990s by Katkov- Oldenbourg. The treatment is assumed to be similar to that carried out at Abbeyknockmoy in 1989. A trial using UVC irradiation to clean an area in the south-east corner of the chancel, directed by the Perry Lithgow Partnership, was undertaken by the Office of Public Works in 2016 The treatment used the same units as at Jerpoint Abbey. Following a site inspection in 2023, further UVC treatment was recommended by the Perry Lithgow Partnership, and it was due to be carried out by the Office of Public Works in the chancel later that year. However, this work was never undertaken, due to constraints on the access/usage of the abbey.
		Reference: Oldenbourg, C 2005 'Conservation of the paintings', *New Survey of Clare Island, Volume 4: The Abbey*. Dublin: Royal Irish Academy, 46–60 Unpublished conservation reports

Pre-2000	Church of San Clemente, Rome, Italy	The subterranean temple of Mithras (c 200) is characterised by high levels of humidity and stagnant ventilation, deep below the church. It contains a marble altar coated with cyanobacteria and green algae. Treatment used two 36W lamps on a lamp holder with aluminium reflectors, placed 250mm away from the surface. Three 10-hour cycles of irradiation were carried out during the night. A biocide was applied for comparative purposes. Optical microscopy (morphological examination) confirmed living cells had been almost totally eradicated after 30 hours. In comparison, the biocide did not attain the same level of success.
		Reference: Bartolini, M, Pietrini, A M and Ricci, S 1999 'Use of UVC irradiation on artistic stonework for control of algae and cyanobacteria'. *An International Conference on Microbiology and Conservation (ICMC '99). Of Microbes and Art. The Role of Microbial Communities in the Degradation and Protection of Cultural Heritage*. Florence, 221–7
c 2000	Basilica of Aquileia, Italy	The crypt of the Basilica of Aquileia in Italy has a magnificent late antique mosaic. High humidity, combined with some natural light, created the ideal environment for moss to grow on the pavement. During the reinstallation of services, UVC lamps were introduced in the standard lighting design. As the problem here was primarily vegetation (in the form of moss) and not microorganisms, wider spectrum UVB lamps were deployed. This is presumably because UVB irradiation damages plant tissue, as it does human tissue (sun burn and skin cancer). The ceiling was fitted with wide-spectrum UVB fluorescent lamps, one every 25m^2 to 30m^2. The lamps are only switched on at night, when no staff or visitors are present. Good results have reportedly been obtained.
		Reference: Ottavio di Blasi Associati 2000 'Nuova apertura e percorsi di visita in vetro per l'aula nord della Basilica di Aquileia'. Progetto Restauro, **7** (16), 28–32
2002 **2009** **2010-18**	Chedworth Roman Villa, National Trust, UK	UVC irradiation trials of fragile wall plaster (cold plunge bath) were carried out in 2002 and of the underfloor heating system of a mosaic in 2009. These trials were judged to be effective. The wall plaster was treated with UVC irradiation by Oldenburg in 2009. Maintenance prior to a redevelopment project involved treating the regrowth in the cold plunge bath in 2010. This work was carried out by the house steward in consultation with Richard Lithgow (National Trust adviser on wall painting conservation). Sporadic UVC maintenance was carried out by National Trust staff in consultation with Richard Lithgow until c 2018.
		Reference: Unpublished conservation reports

2007 **2009** **2011** **2014**	Cormac's Chapel, Cashel, County Tipperary, Éire Office of Public Works and Perry Lithgow Partnership	After a 10-year programme of conservation in the 12th-century chapel, maintenance with MUVUs began in 2007. Units had 75W lamps mounted in housing, with reflectors to concentrate the radiation, on adjustable light stands. Irradiation was carried out for a minimum of four days at a distance of 150mm to 200mm from the surface. Photographs were taken under UVA illumination to monitor the treatment's success. These images suggested all growth had been killed. The UVC treatment within the chancel effectively vapourised the microbiological growths, meaning that no further cleaning with brushes, swabs and so on was necessary. Poor environmental conditions in the chapel at the time made it likely that microbiological growth would reoccur, but irradiation has dramatically lessened the rate of growth. Since then, extensive building repairs have been carried out, and a programme of environmental monitoring and internal climate control has been installed by Tobit Curteis Associates. In 2014, the Office of Public Works, supervised by Perry Lithgow Partnership, carried out UVC irradiation of the entire nave (walls and ceiling) using lamps mounted in units, as used at Jerpoint Abbey. There has been no significant regrowth in any area in the chapel since 2014.
		Reference: Unpublished conservation reports
2007 to 2018	Newport Roman Villa, Historic England, Isle of Wight County Council and University of Portsmouth, UK	See Appendix C
2008 and 2011	St Patrick's Cathedral, Cashel, County Tipperary, Éire Office of Public Works and Perry Lithgow Partnership	The c 1500 Crucifixion painting on the east wall of the south transept and the coeval wall painting of an archbishop in the niche above were treated with UVC irradiation to remove microbiological growths in two phases: 2008 and 2011. The process used the same equipment and methods as for the chancel in Cormac's Chapel. The less controllable external environment has meant localised mould growth has reoccurred, first noted in 2019. Further surface cleaning is due to take place, with additional UVC irradiation if necessary. Discussions with the Office of Public Works to improve the immediate environment are ongoing.
		Reference: Unpublished conservation reports

2013 and 2018	Jerpoint Abbey, County Kilkenny, Éire Office of Public Works and Perry Lithgow Partnership	All areas of microbiological growth that were affecting the painted and unpainted plaster on the north and east walls of the chancel were treated in 2013. The method largely followed that used at Cormac's Chapel and St Patrick's Cathedral, albeit with several significant design adaptations to improve delivery and safety. The germicidal lamps and housings were mounted on plywood boards in pairs or groups of four, with brackets added for suspension from the scaffold. The electrical supply was relayed from a circuit board sited outside the scaffold area, with separate outputs for each unit. Exposure was for 24 hours a day for four days. Initial concern about the warmth generated was alleviated by increasing the ventilation at the top and bottom of the scaffold. No heat-generated surface salts were evident after treatment. The thickness of the mould and the unevenness of the surface meant the microbiological growth was not completely removed by the irradiation treatment alone, as at Cashel. Further surface cleaning was carried out by dry brushing to remove the dead dry mould and additional wet cleaning using swabs of denatured alcohol to remove any further residue. The building repair works to improve the environment were carried out by the Office of Public Works between 2014 and 2017. A second phase of UVC irradiation was done by the Office of Public Works in April 2018, immediately before the final remedial conservation works to the wall paintings.
		Reference: Unpublished conservation reports
Pre-2014	Moidons Cave, Jura, France	The green algae ***Chlorella minutissima*** biofilms were harvested and sub-cultured in the laboratory under conditions similar to those in the cave. After one or two treatments of UVC (150kJ/m^2 or 300kJ/m^2), the samples were incubated for 21 days, and the pigment concentrations and photosynthetic activity were monitored every seven days. The results showed that all UVC treatments caused chlorophyll bleaching and completely blocked metabolic activity.
		Reference: Borderie, F et al 2014 'Cellular and molecular damage caused by high UV-C irradiation of the cave-harvested green alga Chlorella minutissima: Implications for cave management'. International Biodeterioration & Biodegradation, 93, 118–30 sciencedirect.com/science/article/abs/pii/S0964830514001498
2014	Fort Brockhurst, Gosport, English Heritage Trust, UK	See Appendix D.

Pre-2017	La Glacière Cave, Chaux-lès-Passavant, France	Biofilms were initially treated with UVC irradiation. Colorimetric measurements were then carried out for 21 months. Similar tests were done in laboratory conditions. Effects on prehistoric pigments were also investigated. Results showed complete eradication of cave biofilms, with no further algae proliferation observed after 21 months. Also, no changes in pigment colour or chemical and crystalline properties were recorded.
		Reference: Pfendler, S et al 2017 'UVC as an efficient means to combat biofilm formation in show caves: Evidence from the La Glacière Cave (France) and laboratory experiments'. *Environmental Science and Pollution Research*, **24** (31), 24611–23
2018	Church of Vicherey, France	Treatments of cyanobacteria and algae with biocides or UVC irradiation were compared. The UVC treatment was applied using eight UVC lamps (25W each = 200W, max = 254nm) placed 200mm from the biofilm. A single irradiation treatment lasting 14 hours was applied, corresponding to 646kJ/m^2. However, six months later, fungal colonisation occurred in the treated area, indicating that a second round of UVC exposure was necessary to avoid recolonisation. These results were better than those from biocide treatments.
		Reference: Pfendler, S et al 2018 'Comparison of biocides, allelopathic substances and UVC as treatments for biofilm proliferation on heritage monuments'. Journal of Cultural Heritage, 33, 117–24
Pre-2020	Wall paintings, Porta Nocera, Pompeii, Italy	Biofilms from the wall paintings were extracted, and detached fragments of wall paintings were used to identify pigments. The test samples were then exposed to two UVC lamps (9W each = 18W total, max = 254nm) at four distances (1.2m, 1.0m, 0.80m, 0.60m), for eight hours a day every other day, totalling 24 hours of exposure. The studies demonstrated that using UVC irradiation can eliminate biofilms under weaker exposure than previously reported in the literature. Intensities of 10kJ/m^2, 20kJ/m^2 and 30kJ/m^2 were sufficient to eradicate all organisms, without causing changes to the inorganic pigments of the substrate. It was also found that the degree of bleaching was inversely proportional to the distance of exposition. The best results were achieved at distances of 0.80m and 0.60m. For a more flexible range of applications, using 30W lamps, rather than 18W lamps, is recommended.
		Reference: Cennamo, P et al 2020 'UVC irradiation as a tool to reduce biofilm growth on Pompeii wall paintings'. *International Journal of Environmental Research and Public Health*, **17 (**22), 8392. doi:10.3390/ijerph17228392

Appendix C: UVC trials at Newport Roman Villa

Background

Newport Roman Villa at Newport, Isle of Wight, dates from the late 3rd century. It was discovered in 1926. A year later, the villa was protected by a structure of concrete block walls and a flat roof. This covers various rooms and five mosaics.

The site is located on the flood plain of the River Medina, about 400m away. The villa is certainly damp, as evidenced by dense concentrations of microorganisms within the hypocausts and on mosaics in direct contact with the ground. It is thought that the high humidity is caused by the high water table rather than by intrinsic problems with building drainage. The temperature and relative humidity within and outside the cover building are monitored by dataloggers.

The mosaics are in good condition, despite persistent salt efflorescence. From the late 20th century, they were wet cleaned on an annual basis. No biocides were used because of concerns about long-term effects. Cleaning approximately 75m^2 of mosaic surface took one conservator four to five days per year. However, this was of little benefit. Microorganisms were not entirely removed in very dense concentrations, and they reappeared within four to five months. Therefore, an alternative and more effective method of control would be extremely useful.

Phase 1 UVC trials (2008)

The initial trials were carried out by English Heritage (now Historic England) and Isle of Wight Heritage Service, the latter of which manages the site. They attempted to define the range of issues that needed to be addressed in further controlled treatments. These were:

- identifying microorganisms present
- designing and constructing the UVC irradiation box
- using irradiation over different durations.

The microorganisms were provisionally identified, by visual means, as photosynthetic cyanobacteria (blue-green algae) and lichen-forming fungi. Both are commonly found on calcareous rocks with low levels of light and a source of moisture. Periods of light deprivation may, therefore, have little impact. In fact, Newport Roman Villa is closed to the public for four months each winter. The mosaics are in complete darkness, but microorganisms quickly rebloom when the villa reopens.

Irradiation was delivered via lamps in a lightweight box (it can be carried by one person). The box was designed by a professional building services engineer. It was of simple construction, made of MDF, and covered an area of approximately 0.50m^2. The box housed ten 11W germicidal lamps that emit UVC radiation peaking at 254nm. They were fixed in the box 100mm from the base. The lamps were sourced from specialist suppliers, and all other components were bought from retail shops (see Figure C1).

Security risks were managed by restricting access to the treatment area. In addition, UVC radiation was prevented from leaking out of the bottom of the box by two means. Gaps between the box and the mosaic pavement were filled with foam, and a fitted cover was made to slip over the box, with flaps folding along the floor. The cover was made of UVC-resistant polypropylene, lined with blackout fabric.

Dosage calculations are less reliable in a natural context where more complex biofilms may be present, so some experimentation was required. The preliminary trials sought to quantify two extremes of exposure, one with high UVC dosage (trial area 1) and one with low UVC dosage (trial area 2).

Figure C1: The UVC box designed and built for the initial trials is shown here upside-down. The inside of the box was lined with polished aluminium sheet, to reflect maximum radiation from the lamps onto the mosaic.

Trial area 1

The mosaic surface of the first trial area included various densities of visibly green organisms. Because of the dense growth, a high level of irradiation using all 10 lamps was applied over a period of seven days.

After treatment, there was no visible presence of microorganisms, but the irradiated surface was covered with a salt bloom. Enough heat had been generated from the electrical apparatus to dry the mosaic and cause this efflorescence. Also, some condensation had formed under the impermeable polypropylene cover on top of the box. Fortunately, the salt bloom caused no damage. It was easily removed in one hour, by wet cleaning with a mixture of distilled water and alcohol (50:50), to impart a sterilising effect. Irradiation and wet cleaning restored the natural appearance of the mosaic surface.

A visual assessment of the results was very positive, particularly in comparison with adjacent areas of dense microbiological growth. For comparative purposes, an area of dense growth that had not been exposed to irradiation was cleaned using the same method. There, the results of manual cleaning were very poor.

Trial area 2

The second trial used low levels of irradiation, with only four UVC lamps and an exposure time of 24 hours. This surface had considerably less microbiological growth than trial area 1. A datalogger was placed within the box to record temperature and relative humidity. This was not done in trial area 1 out of concern for the effect of very high UVC radiation on the plastic housing of the datalogger.

Irradiation reduced most, but not all, visible microorganisms. Some remained prominent within mortar joints. There was also a light salt bloom beneath the lamps. Temperature peaked and stabilised at 23°C after 12 hours (see Figure C2).

Four months after irradiation, and throughout the damp winter months, both trial areas maintained their clean appearance and had no visible regrowth of microorganisms. There was no recorded change in normal environmental conditions within the building compared to the previous year.

Clearly, there is a need to distinguish between the effect of UVC irradiation and heat. Propagules of some microorganisms, such as algae, can survive exceedingly high external temperatures and soon reappear when moisture levels are sufficiently restored. This has not yet occurred in the trial areas.

Figure C2: Trial area 1 (left) and trial area 2 (right), demarcated by tape, after UVC irradiation and wet cleaning.

Phase 2 UVC trials (2016 and 2018)

Historic England's other corporate priorities prevented progress on this project for a number of years. When the project resumed, an opportunity arose to collaborate with the University of Portsmouth, School of Biological Sciences, and this offered a scientific basis for the renewed trials.

2016 trial

Two locations at Newport were studied: the hypocaust (see Figure C3) and the kitchen. The hypocaust (nine monitored sites, H1 to H9) had a rich green mat of algae covering the compacted soil base, with occasional areas where the mineral surface could be seen. The kitchen (eight sites, K1 to K8) had a mosaic floor composed of red tesserae tiles. The algal cover was discontinuous and confined mainly to the mortar between the tiles. A paper label was placed within each site, with its number. As this blocked UVC radiation to the surface below, this provided a useful measure of the difference between adjacent irradiated and non-irradiated surfaces.

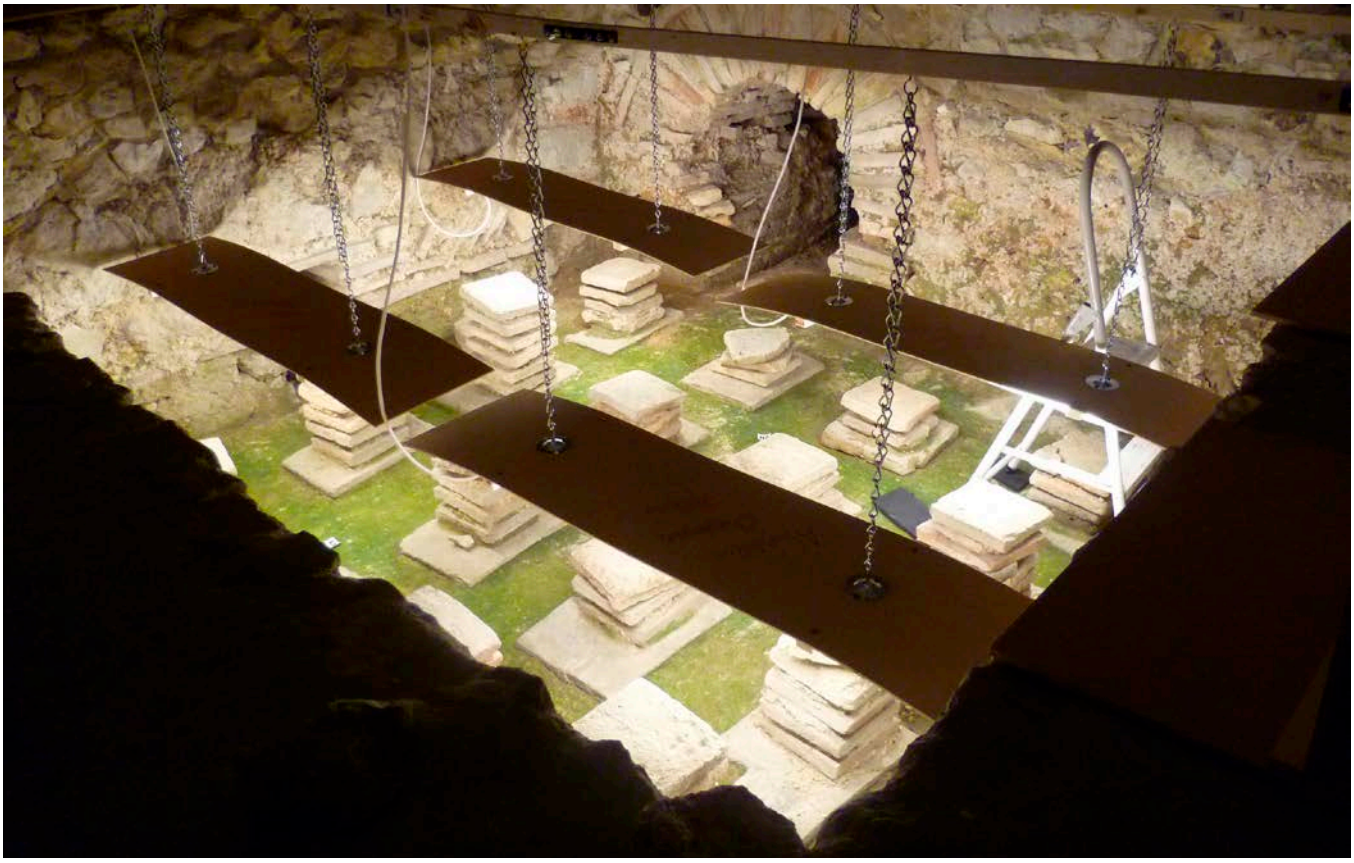


Figure C3: UVC irradiation within the hypocaust was provided by lamps fixed to the underside of timber panels, suspended from timber battens supported by lateral walls. (The lamps operating here for setting-up purposes are the ordinary white fluorescent tubes supplied with the batten fittings.) The hypocaust piers are very fragile and great care was required not to disturb them when installing and removing treatment infrastructure and kit.

Samples were taken from each site and examined using the procedures described in Chapter 7.

Filamentous algae were the most widely distributed type of alga in the hypocaust. These organisms had a deep green pigment and were mostly found in large masses, often in combination with single-celled types. Coccoid spherical algae with a yellow-green pigment were the next most common type. Although the filamentous algae appeared to be one species, the spherical types were probably two, possibly three, different species.

The algal growths were much less evenly distributed in the kitchen. It is likely that moisture from the groundwater below was a factor in growth promotion. The most striking feature of the kitchen microflora was the lack of filamentous algae that were so common in the hypocaust. Samples taken from the kitchen were far more heterogenous, reflecting a patchy and uneven distribution. Algal populations were far more diverse, with green and yellow-green coccoid algae being the most common.

The algal cover in the hypocaust area was exposed to UVC light for three days in March 2016. Experiments conducted in the kitchen area were done over three days in (K1 to K4) and one

day (K5 to K8) in March 2016. In the hypocaust, all sites were originally green and healthy-looking, but the three-day UVC exposure caused a visible reduction in the green colour. Deliberately shaded areas under site labels remained more or less the same green colour as they were before UVC exposure.

For the hypocaust, the extent of colour change was analysed using ERDAS software. This showed that green growth cover (varying from 36 to 95 per cent across nine sites) after UVC treatment was rarely more than 5 per cent of the original cover. UVC treatment achieved at best a 98 per cent reduction, never less than 75 per cent reduction, and an average 89 per cent reduction over the nine sites. (see Figure C4).

Light microscopy provided further evidence of the impact of UVC light on the algal populations. UVC-exposed populations were shrunken and contracted, with much reduced pigmentation. Filaments appeared withered, and coccoid cells were misshapen and distorted. In contrast, cells embedded in large masses or clumps were seen to be protected from UVC irradiation, similar to non-irradiated zones under the site labels that had healthy cells of both filamentous and coccoid cells.

For the kitchen, adhesive tape samples showed that all shaded sites were green and supported healthy populations. Samples exposed to UVC for two days were less green than those exposed for one day. The latter were almost similar to healthy populations from shaded zones. Light microscopy confirmed that sites treated for two days showed shrunken and contracted growth, with loss of pigmentation. However, some healthy cells were still present. After only one day of exposure, many more healthy cells were evident. The uneven distribution of algal growth in the kitchen did not allow ERDAS analysis.

The photography and microscopy clearly showed that the length of exposure to UVC irradiation affected the viability and survival of the algal cells.

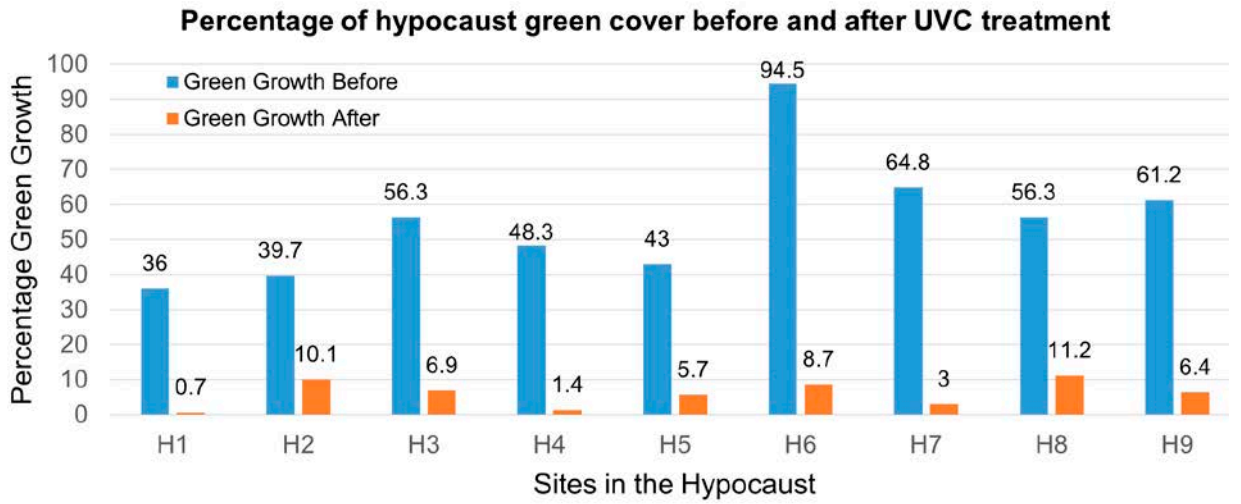


Figure C4: Bar chart expressing percentage of green growth before and after UVC treatment at nine sites in the hypocaust, using ERDAS imaging software.

2018 trial

Trials were done during February and March 2018. They set out to further develop the treatment technology and extend biological understanding of the treatment process. UVC treatment was via suspended lamps in the hypocaust. In the kitchen, a large light box (used in the 2016 trial, but raised to reduce the build-up of heat) and a mobile box were used to deliver UVC treatment (see Figure C5).

Figure C5: The mobile delivery device (made of Meccano parts) and a tin plate box containing UVC lamps. This design enabled the box to be raised or lowered to adjust dosage.

The hypocaust had a mat of green algae covering the compacted soil base. It was visually patchier in its coverage than it had been in 2016. In the hypocaust, five areas were chosen for study. Each one was exposed to UVC treatment for a different amount of time, and each had four sampling points – for biological analysis and surface evaluation. Experiments were done over a four-day period, with different areas receiving 24, 48, 72 or 96 hours of exposure. The zone chosen for the 48-hour treatment had less growth than the others. Pigments extracted from the hypocaust confirmed the presence of green algae and cyanobacteria. Molecular analysis confirmed that the green cover was probably due to cyanobacteria.

After UVC irradiation, all sites within the treated zones, except the control zone, had visually less green cover than they did before treatment. Green cover was still evident in the 24-hour zone, but it was difficult to distinguish between the zones that had been treated for 48, 72 and 96 hours. Spectral analysis of photographic images using ERDAS, obtained before and after UVC irradiation, confirmed that a clear reduction in green growth had occurred for all areas of the hypocaust, except the one that had had only 24 hours of UVC exposure.

The extent of regrowth or regression of green algal cover was monitored in March (one month later) and April (six weeks later), but little change in the distribution of algal cover was seen.

For the 2016 trial, the impact of UVC light exposure for three days was uniform across all the sites: between 75 and 98 per cent reduction. For the 2018 trial, the percentage reduction varied from 0 per cent (no exposure) to 87 per cent (96-hour treatment). There was little difference between areas exposed for 72 and 96 hours. The percentage reduction for 24 and 48 hours was much less than for 72 and 96 hours. The results for 72 hours treatment were relatively equal in all of the 2016 results. This indicates that the best reductions were obtained by delivering UVC treatment for 72 hours – with no added advantage for longer treatment (*see* Figure C6). ERDAS analysis suggests that the algal mat in the hypocaust recovered well over the two-year period, although visually there appeared to be a qualitative difference. Populations that had developed between 2016 and 2018 may be different to those found in 2016.

Growth was already sparse and unevenly distributed in the kitchen, but the impact of UVC was greatest for sites treated with the large box. For the mobile box, the effects were less dramatic but still observable. Comparisons before and after treatment, and under the site labels, showed that UVC treatment with the large box had a marked lightening effect on the mosaic. This was not the case for the mobile unit, which had a higher operational height. In the latter case, although algal growth was reduced, the final appearance was more like the original patina.

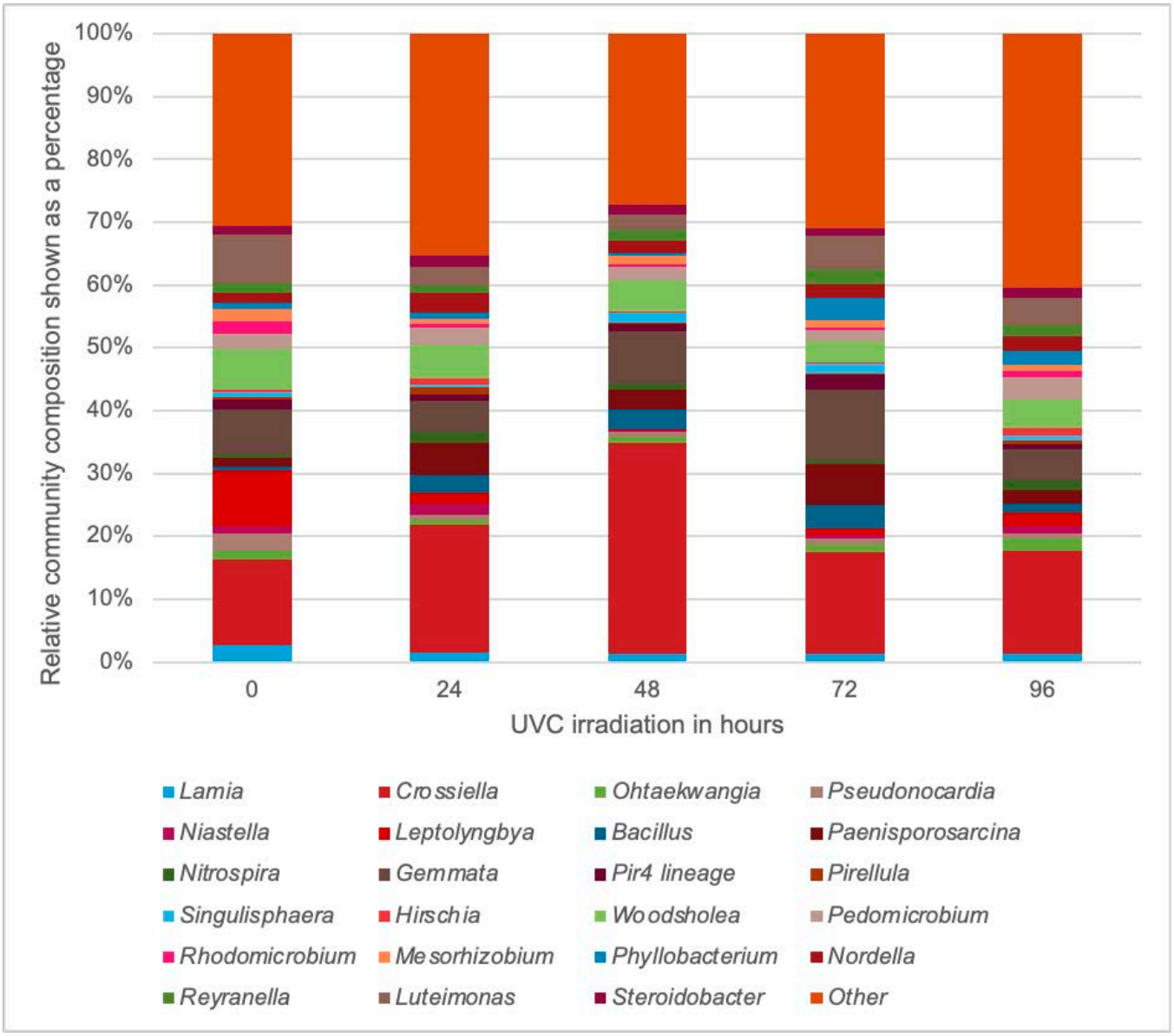


Figure C6: The concentration of microorganisms identified in samples from the hypocaust, after 24, 48, 72 and 96 hours of UVC exposure. They were identified by genomic sequencing. A key change is that the predominant *Leptolyngbya* (shown in red) is greatly reduced after 24 hours of treatment, falling from about 9 to 2 per cent of the total bacterial population.

The versatility of the mobile UVC unit (see Figure C5) was tested in a second trial in a second hypocaust that had retained a luxurious green growth. A transect was chosen for study and showed that the effects of the UVC light extended over a wide area and that shaded parts were dramatically unaffected.

Appendix D: UVC treatments at Fort Brockhurst

A practical and effective method of treating mould-contaminated stonework

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English Heritage Trust

Introduction

Almost one-third of English Heritage's archaeological collections are stored in several areas of Fort Brockhurst, Gosport. For the last decade, an adequate environment was maintained in these areas. However, during the summer of 2014, a combination of extreme moisture ingress from heavy rainfall patterns and the catastrophic failure of the industrial dehumidification units caused a widespread mould outbreak in one of these spaces.

Figure D1: Fort Brockhurst from above, with the store in the bottom left area.

Figure D2: External view of the store.

The spaces at Fort Brockhurst are turf-roof, brick-built casemates. Although these are not typical storage spaces, they have maintained adequate environmental conditions for robust collections. The rapid speed of the mould outbreak led to the contamination of approximately 1,400 stone items, which were stored on wooden pallets, but not crated due to their size. The majority of the stonework was limestone, although sandstone and granite were also present.

Figure D3: The store in use.

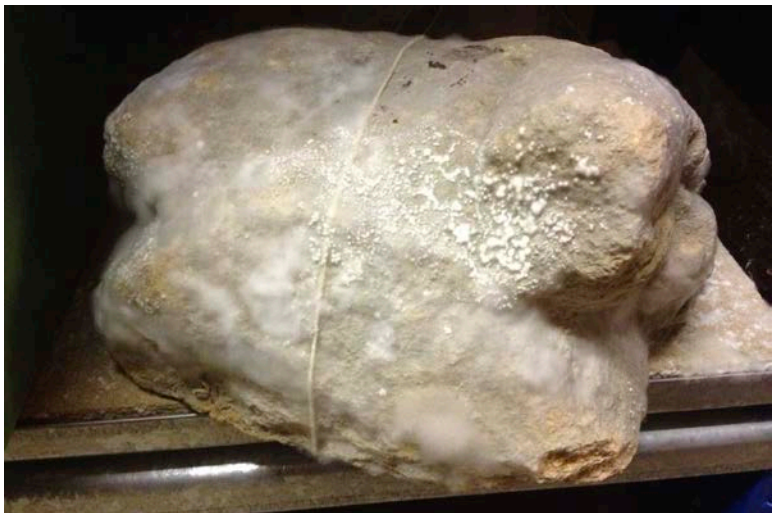

Figure D4: An example of the mould, which appeared as a white surface bloom on stonework, pallets and shelving in storage.

Mould species analysis

The most prevalent species were isolated from the environmental swabs and sorted morphologically. *Aspergillus* was found to be the primary genera (*see* Table D1). Those with varying colony morphologies were sequenced using a common DNA barcode region for a good chance of identification (Schoch et al 2012). Air sample readings indicated a colony-forming unit (CFU) count of more than 10 times the recommended limit. This posed a particular concern because some *Aspergillus* strains can have severe health risks (Englehart et al 2002). As a xerophilic fungi, these strains can grow at a reduced rate: below 65 per cent relative humidity, the 'safe' figure often quoted for environmental control.

Table D1: Results from air testing in a number of storage areas (October 2014). Most inside areas have higher counts than the outside measurement.

Location	Av CFU per m²	% *Aspergillus*	% *Penicillin*	% *Cladosporium*	% *Yeast*
Bay 9	1850	10	10	15	4
Bay 2	4383	57	18	18	3
Bay 4	4600	46	2	10	2
Bay 6	2550	35	2	12	2
Bay 8	6650	80	2	2	0
Wood Store	2600	40	3	5	2
Object Store	5367	26	7	3	0
Air Museum	3467	38	8	3	2
Outside	883	36	11	6	0

A common problem is that the literature focuses on identifying the species present without commenting on their removal (Ciferri 1999; Jurado et al 2008; Montanari et al 2012) or on possible treatments without having identified the species (Rodrigues and Valero 2003; Gatenby 1990; Severson 2010). Little information is available on successful treatment methods for specific species. Assessments of the efficacy of a treatment have started to appear in the conservation literature (Masen and Scheerer 2014).

Preliminary cleaning trials

Hydrogen peroxide was trialled initially. At safe concentrations for limestone (1.2%), it was found to be ineffective without multiple applications and long drying times. The solution would potentially fizz in the presence of biological factors (mould), but also if the limestone was reacting with the solution. This made it very difficult to visually check for signs of damage.

Thorough cleaning using natural bristle brushes, extracted into a HEPA filter vacuum, with no further surface treatment, was also trialled. This method is used extensively to treat localised mould, such as on the underside of a piece of furniture. Dry dusting was also considered as a potential practical treatment for collections that were not robust enough to be treated by any of the UVC systems tested, and particularly where the display or storage environment was likely to be more controlled. Interestingly, this method was found to be quite effective, with a 50 to 60 per cent reduction of spore germination on the lab cultures. Regular cleaning would help to reduce the likelihood of dust or organic matter collecting on the surfaces of open displays, including stonework. In turn, this may prevent mould growth.

Figure D5: Stonework treated with 1.2% hydrogen peroxide solution.

Figure D6: Cultured swabs from before and after cleaning with 1.2% hydrogen peroxide: on limestone.

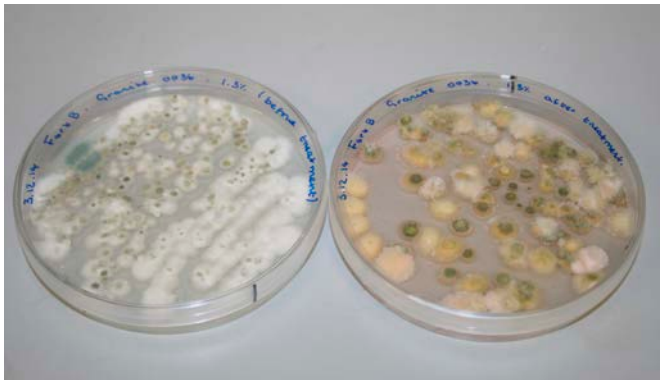

Figure D7: Cultured swabs from before and after cleaning with 1.2% hydrogen peroxide: on granite.

Figure D8: Cultured swabs from before and after cleaning with 1.2% hydrogen peroxide: on wood.

Figure D9: Cultured swabs from before and after cleaning with 1.2% hydrogen peroxide: on plaster.

UVC trial

Previous work on UVC treatment notes the appearance of a salt bloom caused by salt efflorescence as a result of heating and drying (Stewart et al 2008). However, there is sparse information regarding light sources, methodology and treatment times. Product literature for UVC lamps (Philips Lighting 2004) gives values of the rate constant (used in the calculation process) and required dose for different bacteria, yeasts, mould spores, viruses, protozoa and algae. It also provides calculations to determine the required dose for different UVC lamps and treatment parameters. Variables include the effective irradiance (lamp dependent) and the survival rate.

To test UVC treatment, a pallet of stonework with mould contamination was identified. It had a range of differing stone types: limestone, chalky limestone, limestone with extensive pitting and moss and lichen growth, sandstone and granite. Each item of stonework was thoroughly dry dusted and placed on a plastic pallet (*see* Figure D10). The test area used existing pallet racking shelves to support the light source, positioned 1m above the stonework. The lights were left on for 24 hours, after which the stonework was turned.

The process was then repeated. A second pallet of stonework was tested using a two-hour exposure. (Calculations demonstrated that to reduce the survival rate for *Aspergillus niger* from 10 per cent to 1 per cent, the treatment time needed to be doubled – from 57 to 114 minutes). The difference in performance after two hours and 24 hours of treatment was negligible (see Table D2), but a treatment time of two hours allowed a batch of stonework to be treated each day.

Figure D10: UVC trial set-up. Pallet with stones that have been brush vacuumed and are awaiting UVC treatment.

Table D2: Test results.

Location	Treatment	Colony count (approx.)	Improvement from control (%)
SO1	UV 2	0	-
SO2	UV 2	0	-
SO3	UV 3	2	-
OS1	No cleaning	166	-
OS1	Dry dusting	36	78.3
OS1	UV 1 top	8	95.2
OS1	UV 1 bottom	0	100
OS2	No cleaning	439	-
OS2	Dry dusting	152	65.4
OS2	UV 1 top	3	99.3
OS3	No cleaning	127	-
OS3	Dry dusting	89	29.9
OS3	UV 1 top	0	100

UVC treatment

A room was set up for large-scale treatments to optimise the process. A marquee frame with battening was used to fix fluorescent lighting, with Osram UVC 51V, 15W, G13 (T8) lamps fitted. Thirty-five lights were dispersed around the frame (see Figure D11). The windows were covered with black stage curtain fabric to prevent radiation bleed, and signage was displayed outside. A risk assessment, including PPE requirements, locking-up procedure and operational safety, was shared with all staff. Twenty-five pallets could be treated each time. It was possible to fit more pallets into the space, but this would have made the process of turning the stonework very difficult and time consuming.

All stonework has now been treated: a total of 486 pallets, or just under 36 tonnes of stonework. Swabs were taken at different points during the treatment, on different collections and types of stone. With the exception of one sample (it is assumed that human error meant this sample was not turned over), all readings gave a reassuringly low result. This is particularly relevant because the distance between the pallets and the lights was increased from approximately 1m to 2m, and treatment times should have been recalculated accordingly.

Figure D11: Stones being irradiated with UVC bulbs fitted to the marquee frame.

Conclusions

Many positives have come from the unfortunate situation at Fort Brockhurst. It has created an opportunity to investigate more effective ways to deal with mould on robust collections and to quantify their effectiveness on real objects, as well as in the laboratory. It is also reassuring to know that good housekeeping can reduce the likelihood of mould germination. Furthermore, the situation at Fort Brockhurst has enabled a reassessment of other protocols. For example, the collections team will revise storage procedures to avoid substrates that are attractive to mould, such as wooden pallets, and they will include mould outbreaks in their integrated emergency management activities.

Acknowledgements

A number of individuals have assisted during this project to bring the treatments to a successful conclusion. Particular thanks go to Timothy Hill and Adrian Braddock, who carried out the works on site. Also to the following English Heritage staff: Andrew More (now with Historic England), Paul Lankester, Dave Thickett, Amber Xavier-Rowe, Kirsty Huggett, Emma Hallums, Ann Katrin Koester, Pam Braddock, Cameron Moffett and Martin Allfrey. Thanks also to Jane Nicklin and Krystina Merka-Richards from Birkbeck College.

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Acknowledgements

The authors thank the following individuals for their contribution to the UVC research: Chris Chilcott, former MSc student at the University of Portsmouth; at the Isle of Wight Heritage Service, Isle of Wight Council: Paul Simpson, formerly Conservator of Historic Objects; Corina Westwood, Libraries and Heritage Service Manager; John Fletcher, Exhibitions and Museums Officer.

Where to get advice

Finding a conservation professional

Building Conservation Directory
buildingconservation.com

ICON Conservation Register
conservationregister.com

IHBC Database of Accredited Practitioners
ihbc.org.uk/accredited

Register of Architects Accredited in Building Conservation (AABC)
aabc-register.co.uk

The Royal Institute of British Architects (RIBA) Conservation Register
architecture.com/working-with-an-architect/conservation-register

Royal Institution of Chartered Surveyors (RICS)
rics.org/surveyor-careers/career-development/accreditations/building-conservation-accreditation

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United Kingdom Accreditation Service
ukas.com

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Publication date: v1.0 July 2026 © Historic England

Design: Historic England