out the lowering of light intensity, the reduction of lighting time and the elimination of infrared rays which produce heat.

Another aspect of this parameter concerns its relation with insects. The larvae and the termites avoid light while the most adults of insects can see the UV rays. The light traps are just based on the insects capability of being attracted also by this radiation.

Outdoor environment

The outdoor interventions on humidity, water, temperature and light can be carried out in few cases but they can help in limiting the biological growth. The covers (e.g. in an archaeological area) reduce the humidity in the air and into the materials as well as the stagnant water; the protective treatments can be useful because, reducing stone porosity, make it more water-repellent. Finally, the periodic maintenance is the main way to prevent a biological colonisation in an outdoor environment.

A particular aspect of outdoor prevention concerns the problem of birds. Metallic needles or nets are usually set to prevent their rest. Anti-stop gels have been applied on the bulges of monuments; these products, causing birds to lose their balance, were quite successful but they can interfere with stone. In other cases sounding systems were used; they provoke the removal of birds producing particular sounds (e.g. of a predator) at intermitted times.

The most successful method recently applied is based on electrostatic impulses. An equipment gives out electrostatic impulses along cables made of stainless steel which are placed on the areas to be protected.

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THE CONTROL OF BIODETERIORATION

Ornella Salvadori

Soprintendenza speciale per il Polo Museale Veneziano, Italy

The aim of treatments against biodeteriogens is to control or to eradicate their growth. The effectiveness of these operations depends on the methods and the products chosen, on the species that have to be killed and their stage of development (e.g. for insects). Generally the treatment can kill all organisms and microorganisms but does not give any kind of protection for future recolonisation. Prevention strategies are necessary to avoid new and rapid growth; this is often the principal, and sometimes the only way of preventing biological colonization. Recently some products where the biocide is held in a resin or in a mortar were developed for the restoration of stone with the purpose of realeasing the biocide with time and improving the efficacy of these compounds over long periods (Nugari and Salvadori, 2002).

The control of biological growth requires further in-depth analysis, which should fulfill the following aims:

- evaluate the effectiveness of methods and products against macro- and microorganisms deteriorating artifacts (target biodeteriogens)
- assess their harmlessness on substrate
- define methods for testing and evaluating methods and products
- define the best method of treatment
- evaluate long-term effects of treatments and interactions with other products which can be used during restoration
- single out new, alternative and non-toxic methods to disinfect and disinfest.

Any treatments should be recommended only after accurate diagnosis to detect the colonizing macro- and microflora and evaluate their role in the deterioration process. When organisms and/or microorganisms are not responsible for serious damage, or the effectiveness of the treatment is uncertain, no treatment should be carried out. Moreover the risk of repeated treatments should be carefully evaluated and avoided.

A certain treatment can be indicate for controlling biodeterioration in several materials and its application on different or composite materials must be carefully evaluated. The knowledge of the physiology of organisms is particularly useful in the case of physical treatments. Moreover moisture content of the substrate, temperature and time/exposure may often influence the effectiveness of many methods. Tests of effectiveness against the biodeteriogen should be performed in the laboratory and/or *in situ*. Selected procedures can strongly influence the results, and a diverse pattern of behavior of chemicals has frequently been found between laboratory and *in situ* conditions, depending on the type of microorganisms as well as on practical conditions. Laboratory tests may therefore have a limited prediction value with regard to the microbicidal activity of biocides on stone surfaces (Koestler and Salvadori, 1996). Isolated microorganisms used in efficacy tests are much more sensitive than those present in biofilms, which are far less susceptible to biocides, so the spectrum of activity of chemicals could be significantly affected.

A careful appraisal of harmlessness on the substrate in the short and/or long-term should be made, and then chemical and physical effects of the treatments on the materials should be attentively evaluated. Many factors affect the interaction of chemicals with materials. The most significant, as in the case of efficacy, are the chemical composition of the product, the conditions of use (concentration, method of application, duration on substrate, etc.), the physical and chemical properties, as well as the state of conservation of the object and the environmental conditions during the treatment.

The time of action of a treatment varies in relation to the products, the methods, the organisms or microorganisms to be removed, as well as the temperature and relative humidity.

Control methods which can be employed against biodeterioration of cultural heritage are mechanical, physical, chemical and biological.

Mechanical methods

They involve the physical removal of biodeteriogens by hand or simple tools such as scalpels, scrapers, brushes, vacuum cleaners etc. These methods do not completely solve the problems as it is almost impossible to remove completely biodeteriogens and can often damage the substrate. When properly employed by restorers, they can be useful coupled with chemical methods.

Physical methods

The suitability of control methods based on physical factors are attentively evaluated and used as possible replacements to chemical control especially in museums and archives. The methods more frequently used to date are: electromagnetic radiation (gamma, Röntgen (X), and far ultraviolet (200-280 nm)), freezing, heat and low-frequency electrical current.

They are more used for indoor treatments on organic materials; they frequently induce less interactions with the constitutive materials of objects than those induced by the use of chemicals but they also present some adverse effects.

Electromagnetic radiation

Gamma radiation is effective against insects in all stages of development and microorganisms including spores depending on the dose (Brokerhof, 1989; Pointing et al., 1998). Lower organisms are more resistant to radiation than higher ones: the lethal dose for insects (adults are more sensitive than larvae and eggs) is 1 kGy, while fungi are killed with a dose from 5 to 18 kGy. Recommeded dosage for complete sterilization is 25 kGy; temperature during irradiation is very important, higher temperature can reduce the required doses. *Advantages*: good penetration power, simple and rapid operations, possibility of treating a lot of material at one time. *Disadvantages*: effective doses can cause cellulose depolimerization and degradation of proteic materials, paper and leather become more susceptible to microbial attack after treatment, and the effects of radiation are cumulative

Röntgen (X) radiation has similar effects to gamma irradiation but was not so largerly used. *Disadvantages*: can induce change in lead pigments and reduction of tensile strenght in cotton.

Ultraviolet rays have been used especially against microorganisms on stone and plasters with good results (Bartolini et al., 1999). They have germicidal activity between 200-280 nm (UV-C) with a maximum of efficiency at 253,7 nm. They cannot be used on organic materials. *Advantages*: very simple to use, low cost. *Disadvantages*: poor penetration power, they cause a photo-oxidation of some materials (cellulose, proteins) and interact with several pigments.

Freezing

The use of sub-zero temperatures (freezing) is used for eradication of insects. When living cells (80-90% water content) are subjected to low temperature ice crystals may form. Freezing is time/temperature dependent. A period of 48 hours at −20°C should be sufficient, but a treatment for 72 hours is now generally recommended (Florian, 1997).

Heat

Dry or wet heat has traditionally been used in the disinfection and disinfestation of organic materials. Most insects are killed at 55°C for at least 1 hour. With lower temperatures higher exposure time (some hours) is necessary (Stengaard Hansen and Vagn Jensen, 1996). Many materials are negatively affected with long exposures to high temperature.

Low-frequency electrical current systems are used to keep birds from roosting on monuments.

Chemical methods

Chemical substances, biocides or pesticides, are used. They are classified depending on their chemical nature (organic and inorganic compounds, quaternary ammonium compounds, phenolics, nitrogen containing compounds, urea derivatives, etc.) or on the target pest species (bactericides, fungicides, algicides, insecticides, etc.). Products with a wide-spectrum of action are generally used. In choosing chemicals, the following characteristics have to be considered: high efficiency against biodeteriogens, harmlessness on the physico-chemical characteristics of materials, low toxicity for the operators, low risk of environmental pollution (Caneva et al., 1991).

The efficiency is in relation to the dose of product (quantity of pesticide/unit of surface or volume of air), the spectrum and the persistence of action. Other factors may affect the effectiveness of biocides, among which there are the utilized concentrations, the type of substrate, the solvent used (e.g. water hardness can reduce the activity of quaternary ammonium compounds, while alcoholic solutions can increase their penetration power and sometimes their stability), the contact time, temperature and relative humidity during the treatment, weather conditions (wind, rain) for outdoor applications and light intensity.

The mode of action of biocides is too frequently unknown and consequently the timing of the application is often wrong, or recommended concentrations are doubled or trebled in an attempt to improve effectiveness sometimes with negative and irreversible consequences on the final result. Biocides can be divided into two main categories: those that act through contact and those able to inhibit some metabolic activity of target microorganisms, and consequently need more time to exploit their action. Thus a better knowledge of chemical and physical properties, such as solubility, stability, incompatibility with other chemicals etc., of the active ingredients and/or of the commercial products employed should be acquired by restorers.

All pesticides are characterized by a certain toxicity. Generally the use of chemicals with low toxicity is preferred, but operators must always take several precautions according to the level of toxicity of the products they are using. Many pesticides used in the past are now forbidden; legislation of different countries regulate and restricte the methods and products which can be used avoiding most toxic ones and those representing severe environmental pollution problems.

Non-gaseous biocidal compounds are generally diluted in distilled water or organic solvents at low concentrations (usually 0.1-3%). The method of application varies according to the biocide formulations, the constituent materials and the state of conservation of the artwork and usually consists in spraying, brushing, application of poultices, injection, thermal fogging or fumigation. Thermal fogging can be used for aerial disinfection in archives and libraries. The biocide is aerosolized by means of an aerosol electrical generator and diffuse in the atmosphere as very fine fog composed by microdroplets (average diameter of about 1 µm). Thermal fogging is more effective on fungal spores suspended in the air than fumigation (Rakotonirainy et al., 1999).

Fumigation

Fumigation is a method of eradicating fungi and insects by exposing objects (especially organic materials) to a toxic gas in an airtight chamber or in perfectly sealed spaces. The main advantage of fumigation is the better penetration of the active compound into the material than liquid compounds, pressure can be reduced increasing even better penetration, and the short time necessary for the treatment (generally one or two days). Moreover a large amount of materials can be treated at the same time, and thus this method is particularly useful for museum collections. Fumigants require highly trained applicators because of their toxicity and hazard. Ethylene oxide, methyl bromide, sulphuryl fluoride, hydrogen cyanide, phosphine, formaldehyde and thymol are the compounds more commonly used in the past. Nowadays their use is more and more rare, restricted or forbidden in some countries for toxicological reasons (some of them have carcinogenic properties). Several gases can react with the materials inducing polymerization, oxidization, corrosion, shifting the colours of pigments, etc. (Raychaudhuri and Brimblecombe, 2000) and can be retained by objects for long time representing a health risk for people working in archives and museums.

Anoxic atmospheres

They represent a viable alternative to conventional fumigation with toxic gases and consist in a reduction of oxygen concentration generating an anoxic atmosphere (Valentin, 1993; Florian, 1997; Hanlon and Daniel, 1998). They are suitable especially to eradicate insects adult, larva, pupa and egg; fungi are sensitive but fungal spores can survive. The oxygen concentration is generally reduced less than 0.1-0.2% by chemical oxygen scavengers or by the replacement of oxygen with other inert gases like nitrogen, carbon dioxide, argon or, more rarely, helium; nitrogen is currently the preferred gas. Temperature, relative humidity and exposure time are strictly related to the mortality rate. Oxygen concentration, temperature and relative humidity in the bags containing the artifacts should be constantly monitored. The exposure period is considerably longer (several weeks) than that generally used with toxic fumigants and varies depending on the species of insect pest, the dimensions of objects and the temperature during the treatments. Although no analyses were performed it is supposed that anoxic eradication treatments do not cause any kind of damage to materials because no alterations in their appearance has been noticed, but further researches are necessary to definitively clarify the matter.

Biological methods

They are based on the use of antagonistic or parasitic species controlling target pests. They are applied especially in agriculture; their use in the field of cultutal heritage is almost limited to the introduction of pheromones for monitoring insects in museum and archives (Ackery et al., 1999).

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