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Controlled atmospheres against insect pests in museums: a review and some considerations

Abstract - Controlled atmospheres using nitrogen represent a safe and effective method for both objects and human health. The use of this technique against pests in museums has received an increasing amount of interest during the last twenty years. This paper looks at the researches into anoxic treatments that use nitrogen from the late '80s until now.

At the moment, the recommended protocol suggests an oxygen percentage below 1% for at least three weeks. Considering that the major practical problems of controlled atmospheres are connected to treatment time and low oxygen percentage, it is very important to develop more flexible protocols that consider higher oxygen percentages or shorter treatment times, exploiting temperature and/or relative humidity. At oxygen percentage higher than those commonly used, temperature and relative humidity are very critical to insects' development and success. Preliminary data (unpublished) show that it is possible to adapt the application of the controlled atmospheres to different situations, taking advantage of favorable conditions already present in the considered situation and at the same time to use the other parameters at more favorable levels.

Key words: cultural heritage, relative humidity, protocol.

INTRODUCTION

Control of insect pests in conservation institutions was based on pesticide applications at least until the eighties. Of course the high use of chemicals has led to accumulations of residues in the environment (Glastrup, 1987; Koestler *et al.*, 1993). Reviews concerning problems caused by biocides used on cultural objects can be found in Allsopp & Seal (1985), Story (1985), Dawson (1988), Caneva *et al.* (1991), and Pinniger (1994). Biocides are reactive products and many, if not all, can cause alterations in some kinds of works of art.

An array of preventive and "non chemical" control methods should represent the rule to be adopted to solve pest problems (Strang, 1998). Controlled atmospheres using nitrogen represent a safe and effective method for both objects and human health. Nitrogen is nontoxic, non-flammable, and non-reactive. This technique, in fact, is particularly useful for very vulnerable objects, which might be damaged by low or high

temperature treatments (Pinniger, 2010). After 150 days of treatment, painting materials showed no visual effects as a consequence of exposure to nitrogen (Koestler *et al.*, 1993; Koestler *et al.*, 2004). Despite the fact that an inert atmosphere “retards color fading” of most organic colorants (Arney *et al.*, 1979; Burke, 1992), a possible negative effect, due to oxygen deprivation, is a change in specific pigments (e.g. Prussian blue) (Rowe, 2004).

Use of controlled atmospheres against pests in museums has received an increasing amount of interest during the last twenty years (Gilberg, 1989; Valentin, 1990; Gilberg, 1991; Daniel *et al.*, 1993; Hanlon *et al.*, 1993; Reichmuth *et al.*, 1993; Valentin, 1993; Kaplan & Schulte, 1996; Newton *et al.*, 1996; Reirson *et al.*, 1996; Rust *et al.*, 1996; Grassi, 1997; Nielse, 1998; Selwitz and Maekawa, 1998; Kigawa *et al.*, 2001; Valentin *et al.*, 2002; Bergh *et al.*, 2003; Brandon & Hanlon, 2003; Child, 2007; Child & Pinniger, 2008). This research especially addressed two aspects of the method: the oxygen percentage (but always very low, between 0.03% and 1.0%) (Child & Pinniger, 2008) and the treatment time, which varied from a few days to weeks (Gilberg, 1991; Grassi, 1997; Daniel *et al.*, 1993; Hanlon *et al.*, 1993; Pinniger & Child, 1996; Valentin *et al.*, 2002; Bergh *et al.*, 2003).

At the moment, the recommended protocol, which Gilberg (1991) validated for *Tineola bisselliella* (Hummel), *Lasioderma serricornis* (Fabricius), *Stegobium paniceum* (Linnaeus), *Anthrenus vorax* (Linnaeus), recommends an oxygen percentage below 1% for at least three weeks.

According to professionals, the most common problems are: 1) long treatment times that, together with low oxygen percentages, cause high costs and difficulties to the management of conservation institutions (Selwitz & Maekawa, 1998), 2) difficulty in achieving and maintaining such low oxygen concentrations; if the oxygen level increases during the treatment, it has to be repeated.

Regarding the first point, the total time required for treatment is the sum of the time necessary for the controlled atmosphere to permeate the substrate plus the time needed to obtain total mortality of the insects. Therefore, the exposure time is affected by the oxygen drop time, not only in the “bubble” where the treatment is done, but especially within the object in which the insect lives. The oxygen desorption time of objects depends intrinsically on the nature of the materials, on the thickness of the objects to be treated (normally, wood needs more time for a uniform distribution than textiles) (Reichmuth, 1993), on their volume and on the anoxia chamber volume. In addition, it varies as a function of the permeability of the materials to the gas mixture that replaces oxygen in the material. Gunn *et al.* (2006) elaborated a modelling of nitrogen diffusion in porous objects that makes it possible to predict oxygen desorption time, in relation to the nature of the material and the size of the objects, and therefore to estimate achievement of anoxia at the core of a treated object. They concluded that the length of treatment depends closely on the desorption time and that the oxygen drop time is between 1 and 2 days for most objects. It is therefore advisable that this aspect is studied by both an entomologist and a physicist.

With regard to the second point (use of very low oxygen concentrations), some considerations are necessary on the way oxygen deprivation acts on insects. The effects

of different oxygen percentages in the controlled atmosphere on insect metabolism are different. At oxygen concentrations below 3%, in order to meet their energy requirements, insects adopt an anaerobic metabolism (Edwards, 1953; Wegener, 1993; Mitcham *et al.*, 2006). With oxygen levels ranging from 3% to 5%, insects face the reduced availability of oxygen by reducing the oxidative metabolism. Neither strategy produces enough energy to maintain a standard metabolic level, obliging the insects to reduce this and, as a consequence, their energy demand (Hochachka *et al.*, 1993; Mitcham *et al.*, 2006). An accumulation of toxic end products, together with a very slow metabolism, is the cause of stress that results in death (Ofuya & Reichmuth, 2002).

At oxygen concentrations above 5%, the insects increase their respiratory rate in order to take in the same amount of oxygen. The increase in respiratory rate results in dehydration due to prolonged opening of the stigma, especially at high temperatures and low humidity (Emekci *et al.*, 2002; Mitcham *et al.*, 2006). Jay *et al.* (1971) studied the relationship between mortality and R.H., by examining the death rate of red flour beetles *Tribolium castaneum* (Herbst) and confused flour beetles *Tribolium confusum* Jacquelin du Val in a nitrogen atmosphere, containing between 0.8% and 1% oxygen, after 24 hours at R.H. of 9%, 33%, 54%, and 68%. Both species showed a marked increase in mortality as the R.H. decreased, but they died also at high R.H. (68%). Considering the possibility of using controlled atmospheres with higher oxygen percentages, anoxia treatments were shown to be effective at oxygen percentages from 3 to 10%, in at most one week, at temperatures between 20°C and 40°C (Chiappini *et al.*, 2009), taking advantage of the “positive influence of a temperature increase in order to compensate for the effects of the reduced anoxia”.

In this case, the efficacy of treatments with oxygen concentrations higher than 5% was certainly due also to the low R.H. registered in the experiments, always lower than 15% (Chiappini *et al.*, 2009).

Humidity influences the survival of insects and dry conditions generally appear to be highly unfavourable to most insects (Child, 2007). Controlled atmospheres increase the action of low humidity, by prolonging opening of the spiracles, thereby permitting rapid loss of water. In the same way, high humidity suppresses the desiccation mechanism (Gullan & Cranston, 1994; Emekci *et al.*, 2002; Mitcham *et al.*, 2006).

DISCUSSION AND CONCLUSIONS

Considering that the major practical problems of controlled atmospheres are connected to treatment time and low oxygen percentage, and that these parameters are strictly related to each other and to those of the microclimate (temperature and relative humidity), it is very important to develop more flexible protocols that consider higher oxygen percentages or shorter treatment times, exploiting temperature and/or relative humidity.

The availability of these data also allows us to adapt to different situations, even to take advantage of favourable conditions already present and to use the other parameters at more favourable levels.

Temperature and relative humidity are critical to insects' developmental success. Considering the positive correlation between metabolic rate and temperature in insects (Calderwood, 1961), anoxic treatment is, of course, temperature-dependent to a high degree. It is generally agreed to be relatively ineffective at temperatures below 15°C (Child, 2007). The effect of high temperatures can be useful for speeding up the treatment time (Navarro & Calderon, 1980; Chapman, 1998).

Valentin (1993) studied the possibility of shortening treatment time, rising the temperature, at a very low oxygen percentage (0.03%). Complete eradication of *Anobium punctatum* (DeGeer) was achieved after 5 days at 30°C (50% R.H.), *L. serricornis*, required 8 days at 25°C (50% R.H.), or 9 days at 20°C (40% R.H.), while for *Hylotrupes bajulus* an exposure time of 10 days at 30°C (40% R.H.) or 20 days at 20°C was necessary (Valentin, 1993), thus demonstrating the efficacy of exposure times much shorter than the standard of 21 days.

In some cases, at low oxygen percentages, a total mortality was reported even at not very high temperatures. It was reached in less than 4 days at 25.5°C (55% R.H., < 0.1% oxygen percentage) for adults, larvae, and eggs of Tineidae (Rust *et al.*, 1996) and in only 3 days at 25°C (55% R.H., 0.3% oxygen percentage) for six Dermestidae species (Bergh *et al.*, 2003).

If higher oxygen percentages are taken into account, at which, as we have already clarified, water loss becomes a key factor for mortality, relative humidity should also be considered.

Some preliminary results on adults of the food pest, *T. confusum*, are extremely promising. At $3 \pm 0.1\%$ oxygen, total mortality was obtained in 5 days of treatment at $32 \pm 1^\circ\text{C}$ and $30 \pm 2\%$ R.H., while lower mortality (86%) was registered at the same treatment time (5 days), oxygen percentage ($3 \pm 0.1\%$) and temperature ($32 \pm 1^\circ\text{C}$) but at higher relative humidity ($50 \pm 2\%$ R.H.). A similar result was obtained also at a higher oxygen percentage; at $5 \pm 0.1\%$ oxygen total mortality was obtained in 4 days of treatment at $35 \pm 1^\circ\text{C}$ and $30 \pm 2\%$ R.H.. These data demonstrate the high correlation existing between temperature and relative humidity for controlled atmosphere efficacy (unpublished data), especially at higher oxygen percentages.

In many conservation institutions all over the world, recommended temperature and relative humidity conditions (25°C, 45-50% R.H.) are not sustainable; moreover, many times a wide range of relative humidity could be suitable; for paper conservation a R.H. from 35% to 50% is acceptable, as pointed out by Dean (www.nyalgro.org/enemies%20of%20paper05.ppt). However, low humidity is preferable to high. Miller in 1993 (<http://www.artframe.us/Article-EnemiesofPaper.pdf>), talking about the conservation of paper, underlines that 50% is the ideal value, but the most important factor is not 50% R.H., but that it remains constant. Humidity changes are in fact the main cause of paper materials damage.

From his experience Michalski (1993) identifies real examples of incorrect relative humidity in museums, falling into one of four categories: "damp, above or below a critical humidity, any humidity over 0%, and humidity fluctuations".

Also in particular situations, such as moving or building restoration, the "correct"

temperature or humidity could be temporarily lost. In addition some institutions (e.g. Canadian libraries and archives) opt to achieve mass desiccation for free during the winter by using heating systems with no humidifiers (Michalski, 1993).

Therefore, why not considering the opportunity of treatment under more favourable conditions?

With respect to relative humidity and oxygen percentage also the technique chosen could acquire importance. A static approach can be optimal when the previous R.H. is low and therefore useful for enhancement of treatment efficacy while a dynamic approach, which requires humidification to avoid hygrometric shock to museum objects during treatment (Child & Pinniger, 2008), could be used when the R.H. is relatively high and does not have to be lowered.

Some additional considerations are necessary. Considering that survival parameters for many insect pest species have been studied and are well understood and that for holometabolous insects the ability to live in hypoxia is stage-specific (Hoback & Stanley, 2001), a systematic study is necessary in which the museum insect mortality, of various species is determined following exposure to a range of oxygen concentrations for varying periods of time at different temperatures and relative humidity.

Furthermore, most of the tests on the mortality of the insects in cultural property in an anoxic environment have been done not on laboratory reared insects, but on “natural populations” in objects to be treated, not knowing their precise age or even their health. Therefore, in literature it is often not basic research on the insects that is presented, but treatments to test the functionality of a specific instrument (Gilberg, 1990; Brandon & Hanlon, 2003; Valentin, 2002).

Information in literature on respiration rates of the various developmental stages of insects is very rare. Gilberg (1991), Hoback & Stanley (2001), and Child (2007), underline that it appears that investigation into insect adaptations to hypoxic and anoxic environments is an emerging field of inquiry, but these challenges are still evident today.

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