CONTROLLED ATMOSPHERE TREATMENT OF TEXTILE PESTS IN ANTIQUE CURTAINS USING NITROGEN HYPOXIA – A CASE STUDY

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Abstract—A commercial controlled atmosphere treatment of wool/silk curtains infested with textile pests was carried out as part of a National Trust conservation project. The curtains, together with small cages containing 20 late instar larvae of the textile pests *Tineola bisselliella* (common clothes moth), *Tinea pellionella* (casebearing clothes moth) and *Anthrenus verbasci* (varied carpet beetle), were heat-sealed into a "bubble" of gas-impermeable sheeting (polyethylene-aluminium laminate) and exposed to a low oxygen atmosphere. The atmosphere was produced and maintained by flushing with high purity nitrogen and introduction of sachets of oxygen absorber. The oxygen concentration in the bubble was 0.6% v/v one day into the treatment, falling to 0.13% after 7 days, 0.03% after 11 days and 0.01% after 21 days, remaining at 0.01% until the bubble was opened after 73 days. Within the bubble, RH was maintained at about 50–70%. Temperature in the bubble was about 11–19°C up to day 11, ranging thereafter from 4–20°C. Cages of insects were retrieved from the enclosure after 4, 7, 11, 21 and 31 days. Five percent of the *T. pellionella* larvae and 50% of the *A. verbasci* larvae survived seven days hypoxia. Neither species survived 11 or more days hypoxia. Larvae of *T. bisselliella* required at least 11 days exposure to hypoxia to produce complete mortality. The practical implications of these findings are discussed.

INTRODUCTION

Carpet and fur beetles (*Anthrenus* and *Attagenus* species) and clothes moths (*Tinea* and *Tineola* species) can cause serious damage to textiles woven from animal fibres such as wool and silk (Morgan *et al*, 1993; Pinniger, 1994). It is possible to control textile pests by applying insecticidal sprays, dusts or fumigants to infested items. However, the insecticides may themselves damage artefacts (Brokerhof, 1989; Dawson, 1988; Linnie, 1987). This was the dilemma facing National Trust conservators when they discovered that deterioration of some 55 year old curtains was due in part to the depredations of textile pests.

A number of alternative "non-chemical" treatments have been investigated by various workers: these include controlled atmosphere treatment (CAT) and freezing (Pinniger, 1991). Although freezing has been used successfully to eradicate textile pests from artefacts (Hillyer and Blyth, 1992), it was felt that the extremely fragile condition of the curtains rendered freezing inadvisable. The CAT options most readily available in the UK entail exposure to 60% carbon dioxide atmosphere or to an hypoxic nitrogen atmosphere (<0.5% oxygen, balance nitrogen). Since nitrogen may be considered chemically inert, it was decided to use an hypoxic atmosphere to treat the curtains. After taking independent advice, the National Trust conservator specified that the oxygen concentration should be maintained at less than 0.4%, the temperature at 24°C and the RH at 50–65%.

This paper describes a controlled atmosphere treatment of curtains infested with textile pests. In order to validate the treatment and generate useful data on the efficacy of a commercial CAT, small cages of textile pest larvae were exposed to the same hypoxic atmosphere as were the curtains.

MATERIALS AND METHODS

The curtains and the insects infesting them

In 1938–39 Rex Whistler was commissioned to paint the new Drawing Room at Mottisfont Abbey, Hampshire, UK. The *trompe l'oeil* fantasy was enhanced by curtains, composed of emerald green

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silk velvet, lined and trimmed with mock ermine (combed white wool weft on a cotton warp, spotted with black). The ten curtains are each 4.2m long and 1.8–2.5 m wide. Housekeeping in the Drawing Room had not been vigilant, and the edges of the woollen Feltlux carpet had been grazed by carpet beetles (*Anthrenus* sp). The curtains were not in good condition; the silk had deteriorated and the velvet pile was breaking down into a fine dust. The curtains had also been attacked by carpet beetles (*Anthrenus* sp) which in places had penetrated the silk. In some areas the attack had caused loss of woollen weft from the mock ermine, leaving only the cotton warps. Other textile pests found on and near the curtains were identified as clothes moths (Tineidae) and fur beetles *Attagenus pellio* (Linnaeus). The curtains were taken down and cleaned, and the *Anthrenus* larvae removed by hand. The curtains were folded lengthwise two or three times, interleaved, padded and lined with acid-free tissue paper, then wrapped in downproof cambric fastened with brass pins. The wrapped curtains were stored flat in twos on purpose-built shelving in a conservation store on the first floor of the Stable Block. On a visit prior to the start of the controlled atmosphere treatment a large pale clothes moth *Tinea pallescentella* Stainton and a Guernsey carpet beetle *Anthrenus sarnicus* Mroczkowski were captured on and next to the wrapped curtains.

Bioassay insects

The *Anthrenus verbasci* (Linnaeus) used in this study were obtained from cultures reared in the CSL Insectary at 20°C 70% RH on a diet of fishmeal, yeast and cholesterol (38:9:1 m/m) plus wool felt. The *Tineola bisselliella* (Hummel) and *Tinea pellionella* (Linnaeus) were from Rentokil R&D cultures reared at 25°C 50% RH on a diet of fishmeal and yeast (16:1 m/m) plus wool felt. Small, fine mesh cages (about $20cm^3$) containing 20 mixed late instar larvae of *A. verbasci*, *T. bisselliella* or *T. pellionella* were set up a few days before the start of the controlled atmosphere treatment. The cages were provisioned with about 5g of the diet appropriate to the species.

Construction of treatment enclosure ("bubble")

On "day zero" a 5.7 m×2.5 m×0.5 m bubble of M10 barrier foil (last dimension is uninflated height of bubble) was constructed in the conservation store, around the curtains . The M10 barrier foil comprises a base fabric of 60μm low density polyethylene (LDPE) coated with 12μm polyethylene terephthalate and 9μm aluminium foil. A large sheet of foil had been prefabricated from lengths of 0.8m wide foil, and prefitted with sampling and inlet/outlet ports in the corners. The foil sheet was larger than required so a central section was cut out and discarded, and the cut edges joined by heat sealer using the technique described below. The cut down sheet was inspected for imperfections, then laid LDPE face upwards on cloth-covered trestle tables in the conservation store. The wrapped curtains were laid carefully on the foil sheet, the sheet was folded over the curtains, and the edges of the sheet were aligned. Along the margins of the folded foil sheet the LDPE coated faces of the foil were now in contact. The sheet margins were then joined by grasping the two layers of foil between the jaws of a heat sealer, which produced a seam by fusing together the layers of LDPE (Figure 1). For reasons of safety an "impulse" type heat sealer (Hulme-Martin HM 1000P) was used, in which the 24V heating bar switches off automatically after a few seconds. Continuous seams were carefully fabricated along the short edges of the bubble (Figure 2). Along the long edge, a discontinuous seam was fabricated, running parallel to and about 15cm from the sheet edges. The cages of insects (in batches comprising one cage of *T. bisselliella*, one cage of *T. pellionella* and two cages of *A. verbasci*) were secured with adhesive tape onto the sheet margin outside the discontinuous seam. The free edges of the sheet were then carefully joined in a continuous seam running outside the row of batches of cages, and intersecting the seams along the short edges of the bubble. This produced a gas-tight bubble of foil enclosing the cages of insects and the curtains.

Production of hypoxic atmosphere

The internal atmosphere of the newly sealed bubble was partially exhausted using a pump attached to the outlet port (Figure 2); care was taken not to exhaust the bubble to the point where the foil exerted damaging pressure on the curtains within. Oxygen-free nitrogen ex BOC Ltd (minimum

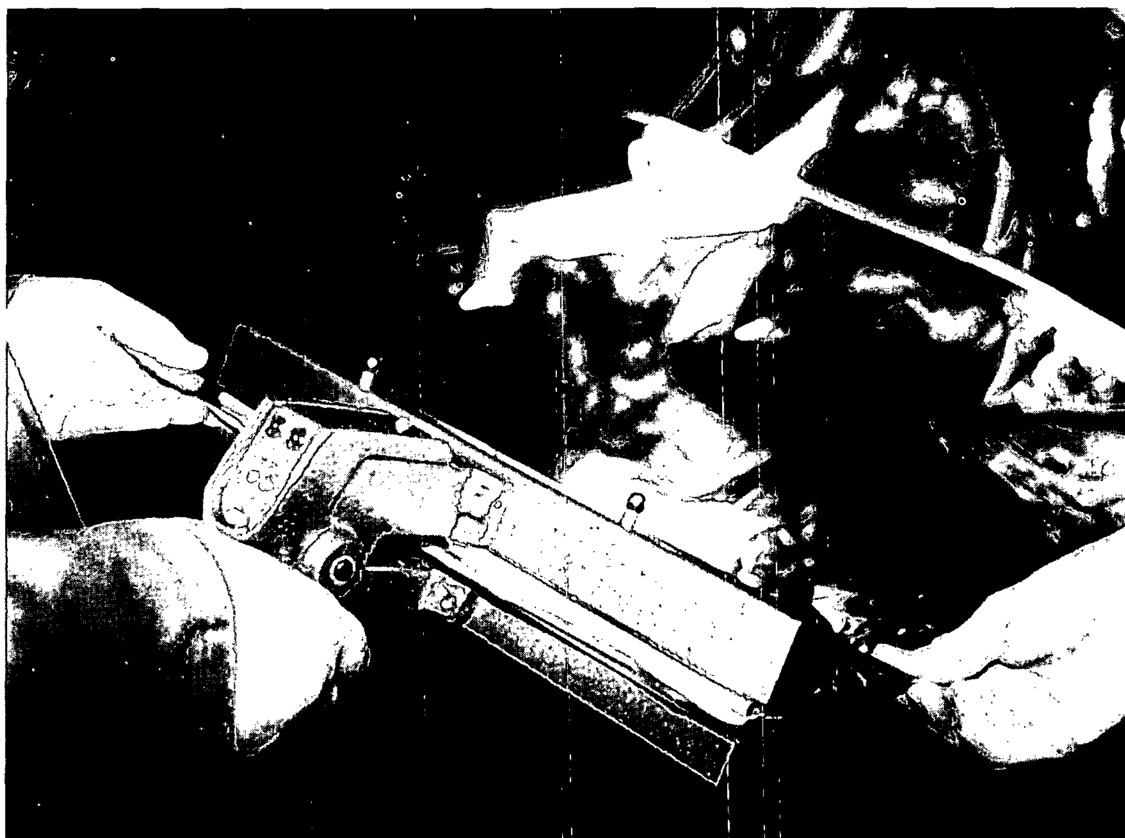

Figure 1. Sealing the bubble using an impulse heat sealer. (Photograph by D B Pinniger).

purity 99.998% m/m) was dispensed via a pressure regulator from a compressed gas cylinder (175 bar, nominal capacity 9.2kg/7.8m^3 of gas at atmospheric pressure). The size K cylinders used were relatively cumbersome (0.23m$\times$1.46m, net weight 65kg) and were handled using a cylinder trolley. The nitrogen was humidified to the required RH by passing it through a split stream humidifier (Figure 3). This mixed humidified and dry streams of gas. The temperature and RH of the gas in the humidifier outlet chamber were continuously monitored by a digital thermohygrometer. The humidified nitrogen was introduced into the bubble via a small inlet port at the opposite end of the bubble from the outlet port (Figure 2) until the bubble was fully inflated (Figure 4). Over-inflation was avoided as this would have subjected the seams to undue stress.

In the two hours following sealing, the bubble was "flushed" (partially exhausted then reinflated with humidified nitrogen) four times. After the second flushing the oxygen concentration in the bubble was 1.3% (v/v) and rising; after the fourth it was 0.25% and rising (oxygen concentrations measured using a Trace Oxygen Analyser, see below).

On the following day (day 1) the bubble was flushed twice. At this point (18 hours after initial sealing of the bubble) the oxygen concentration was 0.38%. Sachets of oxygen absorber were then introduced into the bubble via the two corners lacking inlet/outlet ports, as follows. One corner of the bubble was cut off to provide a 10cm wide entry aperture. Through this were introduced oxygen absorber sachets; these were placed along the edges of the bubble well away from the curtains. The corner was then carefully resealed using the heat sealer. This procedure was repeated at the other corner (Figure 2). The oxygen absorbers comprised in total one pack of twenty-five 80g sachets of Mitsubishi Ageless® Z and one pack of twenty Atco® LH3000 sachets. After insertion of the oxygen absorbers the oxygen concentration was 0.56%. On day 4 and at intervals thereafter the oxygen concentration was measured and the bubble flushed. In order to quarantine the treated curtains, the bubble was not opened until access to the curtain was required. On day 73 the bubble was partially exhausted, reinflated with air, then carefully cut open.

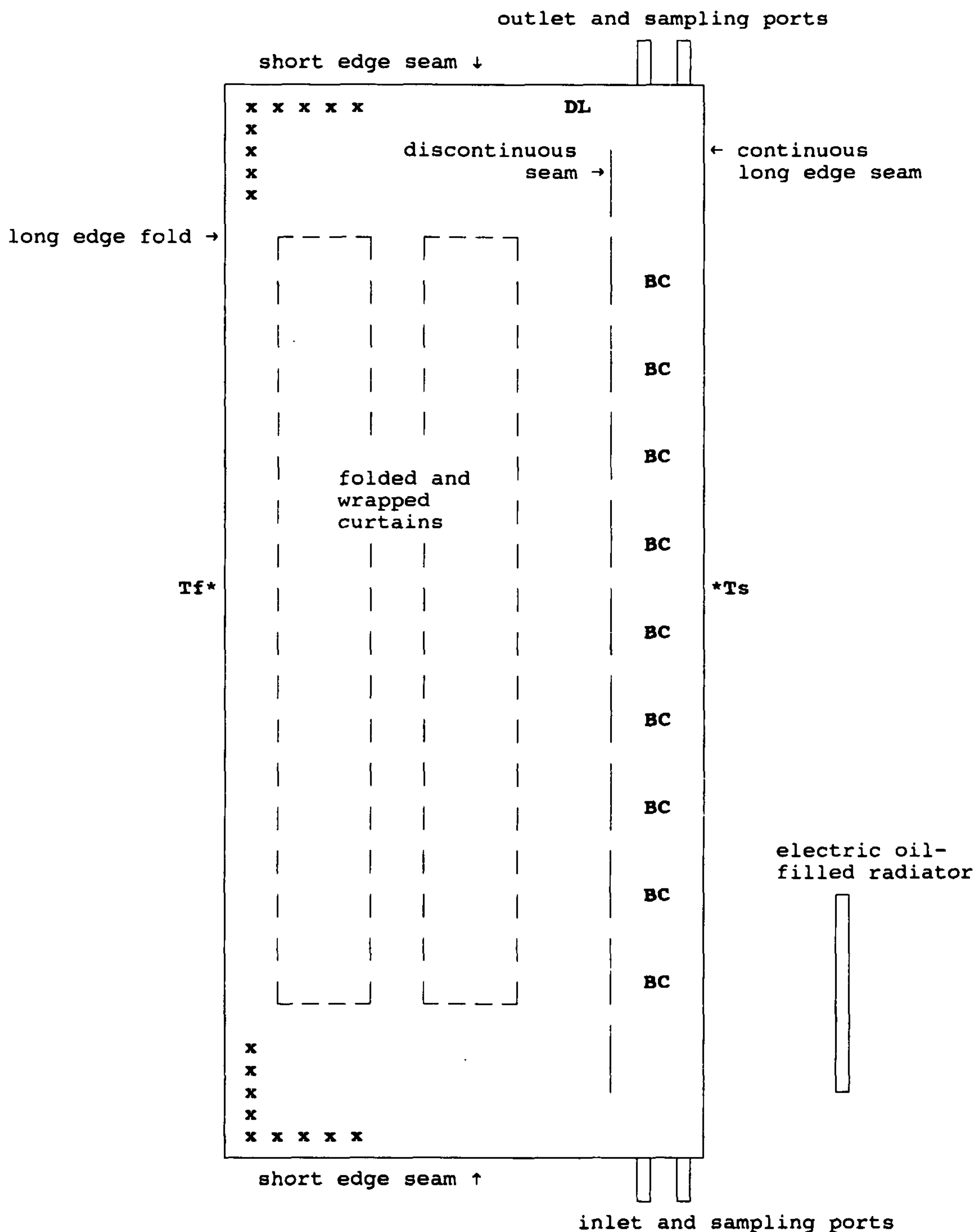

Figure 2. Diagrammatic plan view of bubble. x = oxygen absorber sachets; BC = batch of insect bioassay cages; DL = data logger; * = thermocouple probes (Tf at bubble fold & Ts at seam).

Measurement of temperature and humidity in conservation store

At the start of the treatment, the temperature and humidity in the conservation store were measured almost daily using a Novasina MIK 3000 hand-held thermohygrometer. From day four the temperature was measured using an inexpensive digital twin thermocouple maximum-minimum thermometer. The thermocouple probes were located half way along the two long sides of the

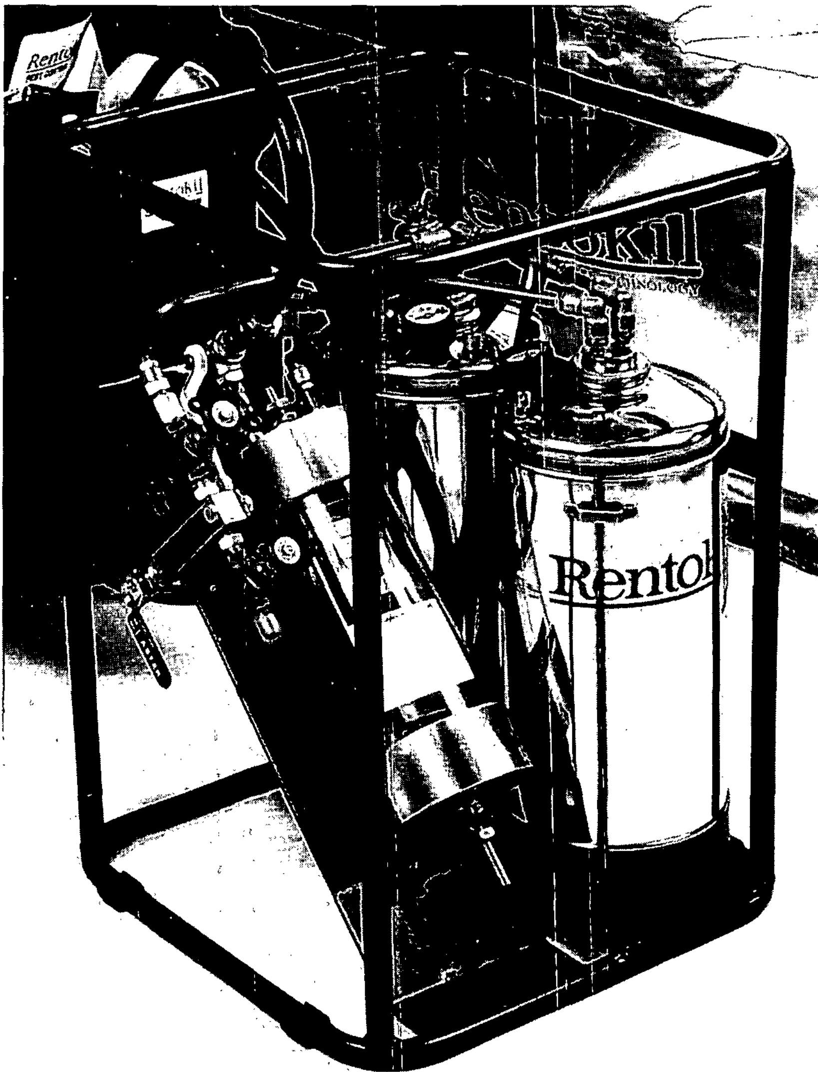

Figure 3. Split stream nitrogen humidifier; *front left*: transparent outlet chamber with thermohygrometer; *back centre*: humidifying tank; *front right*: dry and humidified gas mixing tank.

bubble (Tf and Ts, Figure 2). The readings from this instrument were subsequently checked against those of a calibrated precision instrument (KM45 digital thermocouple thermometer, Comark Ltd., UK) and adjusted as necessary. Humidity in the holding room was measured at intervals using the Novasina MIK 3000.

When the weather became cold an oil-filled electric radiator was used to heat the room (Figure 2).

Measurement of temperature, humidity and oxygen concentration inside bubble

The concentration of oxygen within the bubble was measured at intervals using a Bedfont Scientific Instruments BT 2000 Trace Oxygen Analyzer connected between a sampling port (near the inlet port, see Figure 2) and a small exhaust pump.

On days 7 and 11 the temperature and RH of the bubble atmosphere were measured (prior to inflation with humidified nitrogen) using the Novasina MIK 3000. This was positioned inside a transparent pipe fastened to the bubble outlet port, through which the bubble atmosphere was expelled by gentle hand pressure on the bubble. On day 11 a SmartReader 02 data logger (ACR Systems Inc., Canada) preset to record RH and temperature at 30 minute intervals was introduced into the bubble near the outlet port (Figure 2), using the cut and reseal technique described above.

Figure 4. General view of fully inflated bubble in conservation store. Note: nitrogen cylinder, and doors open for ventilation (visible behind lefthand end of bubble). (Photograph by D B Pinniger)

Removal of exposed insects and assessment of mortality

On days 4, 7, 11, 21 and 31, batches of insects were removed from the bubble using a technique designed not to compromise its gas-tightness. The heat sealer was used to fabricate two seams (one on each side of a batch of insects) running between the bubble's continuous long edge seam and a short unbroken section of the discontinuous inner seam. The piece of sealed-off bubble thus formed around the batch of insects was cut into from the edge of the bubble, exposing the insects to the air and leaving a zigzag gas-tight seam along the bubble edge. The insects were returned to the laboratory and held with their cage food at 25°C 50% RH until assessment of mortality. Unexposed control batches of insects were held with cage food at 25°C 50% RH until assessment of mortality.

Mortality of exposed insects was assessed one and five weeks after removal from the bubble. Unexposed controls were assessed two, five and 11.5 weeks after day zero. Insects showing no signs of movement after gentle probing were presumed dead. Larvae of *T. bisselliella* and *T. pellionella* are generally found within silk tubes or short silk cases respectively, intrusive examination of which might injure the occupants. For these species therefore, the initial (one or two weeks) assessment was superficial, while the final (five or 11.5 weeks) assessment entailed teasing open the silk tubes or cases. Any live or dead moths found must have developed from the original larvae, and so were counted as survivors. Assessment of mortality of *A. verbasci* larvae is known to be problematic (Morgan *et al* 1993): larvae which appeared to be dead one week after exposure were therefore retained for reassessment at five weeks.

RESULTS

Conditions in conservation store

The temperatures recorded ranged between 3 and 22°C (Table 1). The eight humidity readings taken between day zero and day 21 ranged from 63–71% RH.

Conditions inside bubble

The bubble was flushed (*ie* partially exhausted, then inflated with humidified nitrogen) four times on day zero, twice on day 1, once on day 4 and once on day 7. The ninth and final flushing was carried out on day 11. On day 21 the bubble appeared to be slightly deflated, and was topped up with a little humidified nitrogen. During the course of the treatment, the temperature of the nitrogen passing through the humidifier outlet chamber ranged from 10–19°C and the relative humidity from 46–66% (Table 2). The bulk of the nitrogen used (in four flushings on day zero) was preconditioned to about 11°C and 50% RH. A total of four cylinders of gas (each containing a nominal 7.8m^3 of nitrogen at atmospheric pressure) was consumed during the course of the treatment.

The oxygen concentration in the bubble was reduced from atmospheric (20.9%) to below 1% on day zero, subsequently falling to 0.132% by day 7, to 0.031% by day 11 and to 0.12% by day 21 (Table 2). The oxygen level remained at or below 0.012% from day 21 to day 73. It was noted that the oxygen absorber sachets retrieved from the bubble became warm when exposed to air. Evidently they were not fully spent, and were absorbing oxygen from the air (an exothermic reaction). This indicates that the bubble was initially well sealed and had remained gas-tight, so that there had not been any significant ingress of oxygen.

Comparison of Tables 1 and 2 shows reasonable agreement between the temperature in the room and the temperature inside the bubble. From this it can be inferred that the temperature inside the bubble from day zero to day 7 was in the region of 11–18°C, and from day 7 to day 11 about 14–19°C. From day 11 onwards the temperature in the bubble ranged between 3.8 and 20.2°C (data logger readings, Table 2).

Table 1. Temperature and relative humidity in conservation store in which bubble installed at Mottisfont Abbey

Day Number	Temperature (°C)			Relative Humidity [N] (%)
	By long seam of bubble [Ts]	By long fold of bubble [Tf]	Elsewhere in room	
zero	–	–	16	64
1–3	–	–	14–16[†]	–
4	16	16	12	–
	–	–	15.5	63
4–7	12–18	11–18	-	-
7	–	–	14.7	67
8	15	15	14.8	68
9	18	17	16.9	70
10	15	14	14.7	68
7–11	15–19	14–19	–	–
11	16	15	15.3	69
11–21	16–22	15–22	-	–
21	19	19	18.3	71
21–31	12–21	11–19	–	–
21*-73	4–21	3–19	–	–
73	6	4	–	–

*maximum-minimum memories not cleared on day 31.
[Ts] and [Tf] measurements using twin thermocouple maximum-minimum thermometer; temperature ranges are minima-maxima over periods indicated.
[N] measurements using Novasina MIK 3000.
[†]range of three readings.

Table 2. Oxygen concentration, temperature and relative humidity of atmosphere in bubble

Day No.	Atmosphere in bubble: Oxygen concn. (% v/v)	Temp. (°C)	% RH	Timing of measurements of bubble atmosphere in relation to nitrogen flushing	Temperature (°C) and % RH of nitrogen used in flushing*
zero	0.25†	–	–	After four flushings	10–12°, 46–52%
1	0.56	–	–	After two flushings and insertion of oxygen absorbers	–
4	0.59	–	–	Initial reading	
	0.17	–	–	After single flushing	14°, 50–60%
7	0.132	17	63	Initial readings	–
	0.046	-	–	After single flushing	15°, 57%
11	0.031	15	66	Initial readings	–
	0.022	–	–	After single flushing	16–17°, 55–66%
11–21	-	15.7–20.2	64–68	Readings from data logger	–
21	0.012	–	–	Initial reading, before topping up with nitrogen	18–19°, 56–58%
21–31	–	11.3–18.1	65–68	Readings from data logger	–
31	0.010	–	–	-	–
31–73	–	3.8–15.7	65–68	Readings from data logger	–
73	0.010	–	–	-	–

*where ranges are given they are based on two or three sets of readings
†concentration rising at time of reading

From the RH of the humidified nitrogen (Table 2) and the tendency from day 11 onwards of the RH to equilibrate at 64–68% (Table 2) it can be inferred that the RH inside the bubble from day zero to day 7 was in the region of 50–65%. On day 7 and day 11 the bubble RH was respectively 63% and 66%, while from day 11 onwards the RH ranged between 64 and 68% (Table 2).

Mortality of insects exposed to hypoxia

Based on mortality at final assessment, *Tinea* and *Anthrenus* larvae survived exposure for seven days, *Tinea* larvae suffering 95% mortality, but *Anthrenus* larvae only 50% (Table 3). During this seven day period the bubble atmosphere was at about 11–18°C, 50–65% RH and (from day 4) ≤0.17% v/v oxygen (Table 2). Eleven days exposure produced 100% mortality in *Tinea* and *Anthrenus*. Bubble conditions during this eleven day period were about 11–19°C, 50–66% RH, and (from day 7) <0.05% v/v oxygen. Mortality of unexposed controls was acceptably low for *T. pellionella* (30%) and *A. verbasci* (12.5%). Mortality of unexposed *T. bisselliella* larvae was extremely high (90%); the reasons for this are unknown. Mortality of exposed *T. bisselliella* was 90% after four days, 95% after seven days and 100% after eleven or more days. Overestimation of mortality of *Tinea* larvae at the initial assessment was due to failure to find all the survivors during the necessarily superficial initial examination. Although there had been concern about the difficulty of assessing mortality of *A. verbasci* larvae, there was no evidence that any were erroneously declared dead at initial assessment.

Reinstatement of curtains

After treatment the curtains were again cleaned, and the dead carpet beetle larvae were removed. Meanwhile the Feltlux carpet had been removed from the Drawing Room, and the room had been thoroughly vacuum-cleaned, particular attention being paid to the skirting areas, window bays, doorways and entrance corridors. A week before the reinstatement of the curtains the same areas were sprayed with Ficam W (bendiocarb wettable powder), a low-odour non-staining insecticide which has been shown to be effective against *Anthrenus* larvae (Morgan *et al*, 1993). The whole area

Table 3. Percent mortality of larvae of *A. verbasci* and *T. pellionella* exposed to hypoxic atmosphere in bubble

Species	Interval between removal from hypoxia and mortality assessment (weeks)	% mortality					
		Duration of exposure to hypoxic atmosphere (days)					
		0*	4	7	11	21	31
Tinea pellionella	1	40[†]	95	100	100	100	100
	5	75	100	95	100	100	100[‡]
	11.5	30	–	–	–	–	–
Anthrenus verbasci	1	1.3[†]	7.5	45	100	100	100
	5	3.8	20	50	100	100	100[‡]
	11.5	12.5	–	–	–	–	–

*unexposed control; [†]assessed at 2 weeks; [‡] assessed at 6 weeks.
Mortality based on numbers of live larvae and live or dead moths found at stated intervals.
T. pellionella: 20 insects per treatment.
A. verbasci: 40 insects per hypoxia treatment, 80 insects in unexposed control.

was vacuumed daily and three weeks later the new Feltlux carpet and Defender Plus underlay were laid. The cleanliness regime continues: the whole area, particularly the skirting and window areas, are vacuum-cleaned daily. When last assessed, a month after rehanging, the curtains looked "excellent", and no physical change was apparent.

DISCUSSION

The oxygen concentration within the bubble was lowered to the specified <0.4% by the flushing on day 4, and was maintained well below 0.4% until the bubble was opened on day 73. The RH was maintained above the specified 50% minimum and breached the 65% maximum by only 3%. Detailed examination of the printout from the data logger revealed circadian cycles in temperature and RH within the bubble. Temperature was peaking at about 19.00h and troughing at about 09.00h. RH was peaking at about 12.00h and troughing at about 19.00h. This is what might be expected in a sealed enclosure: a relatively constant mass per volume of water vapour more nearly saturates an atmosphere at lower temperatures (giving a higher RH) than it does at higher temperatures. The specified temperature of 24°C was never reached. The treatment was carried out between September and December, and 24°C would have been attained only by installing a substantial source of heat in the conservation store. As the main reason for specifying 24°C was to ensure eradication of the insects at a higher oxygen concentration and shorter exposure period than eventuated, the lower temperatures experienced did not prevent a successful outcome. All the test insects were killed by the first 11 days of exposure, and no live insects were found on the curtains when they were removed from the bubble after 71 days in the hypoxic atmosphere. However, because of the extremely high mortality in unexposed controls of *T. bisselliella*, it is not possible to estimate the exposure period required to control larvae of this species.

In hypoxic atmospheres, speed of mortality increases as temperature increases (Annis, 1987). Bearing this in mind, the findings in the present study (100% mortality after 11 days at 11–19°C and 50–66% RH) are consistent with other published data. For most of the species of stored product moth and beetle for which data were reviewed by Annis (1987), less than ten days exposure at 20–29°C to atmospheres containing either 1% or <0.1% oxygen was required to achieve ≥95% mortality. Complete mortality of mixed stage cultures of *Anthrenus vorax* and *T. bisselliella* was achieved by exposure for one week to 0.42% oxygen in nitrogen at 30°C and 65–70% RH (Gilberg, 1989). Exposure at 25.5°C and 55% RH to an atmosphere containing <0.1% oxygen in nitrogen achieved complete control of all stages of *T. bisselliella* and of *Anthrenus flavipes* in two days (Rust

and Kennedy, 1993). In unpublished work*, complete mortality of pupae and mature larvae of *T. bisselliella*, and of mature larvae of *A. verbasci* was achieved by exposure for one week to 0.2–0.3% oxygen in nitrogen at 55–87% RH and 20°C (in this work, exposure was at atmospheric pressure, although the hypoxic atmosphere was produced by hypobaric flushing).

The CAT options most readily available in the UK utilise either a 60% carbon dioxide atmosphere or an hypoxic nitrogen atmosphere (≤0.5% oxygen). The degree of gas-tightness required to maintain the carbon dioxide atmosphere is less than that required to maintain hypoxia. Larvae of *A. verbasci* can be controlled by 14 days exposure to 60% carbon dioxide at 15°C (Newton, 1991). Cylinders of liquefied carbon dioxide are readily available, and are smaller, lighter and therefore less cumbersome than cylinders of compressed nitrogen containing comparable amounts of gas. From a purely practical point of view, carbon dioxide CAT would appear to be the first choice. Carbon dioxide CAT has been used commercially to treat museum artefacts in mainland Europe since at least 1993 (Newton, 1993). It is *in theory* possible that carbon dioxide could damage artefacts. Carbonic acid formed under extremely humid conditions could cause corrosion of susceptible materials or colour changes in pH sensitive dyes or pigments. However, no documented cases of such damage have come to the attention of the authors. In any case, exposure of artefacts to very high humidity is of itself likely to lead to bacterial or fungal damage.

Although nitrogen is intrinsically non-toxic, breathing an atmosphere in which excess nitrogen has displaced oxygen may be hazardous. The recommended minimum oxygen content for breathed air is 18% v/v (Anon, 1995). Self-contained breathing apparatus and a person trained in its use should be on hand whenever substantial volumes of nitrogen are used indoors. In the present study the exterior first floor doors of the conservation store were opened to provide ventilation whenever nitrogen flushing was in progress. The outlet hose from the pump was directed out through these doors whenever the bubble was exhausted.

The present study demonstrates that it is possible by careful sealing and use of the appropriate equipment to fabricate a temporary gas-tight enclosure around artefacts requiring disinfestation by hypoxic CAT. The RH and oxygen concentration within the enclosure can be controlled within specified limits for a period well in excess of that required to ensure eradication of the infestation. It should be noted that CAT confers no residual protection on the treated artefacts; retention of the artefacts within the bubble until required provides a useful means of quarantine. Perforation of the bubble by rough handling will be indicated by rising oxygen levels within. In cases where the contents of a bubble are less fragile than were the curtains, or where bubble contents are protected by a frame within the bubble, the gas-tightness of a sealed bubble can be checked by exhausting the atmosphere until the foil is tightly stretched against the contents of the bubble or the bubble frame. A visible reduction in the tension of the foil, or the sound of air entering the bubble indicates a failure of the seams or perforation of the foil. This approach was used when treating 43 oil paintings in three bubbles up to $90m^3$ in volume, in the south of France (Smith, 1995).

The classical fumigants methyl bromide, phosphine, sulphuryl fluoride and ethylene oxide have all been associated with damage to fumigated articles (Brokerhof, 1989). CAT with an hypoxic nitrogen atmosphere provides an effective and practical non-damaging alternative to the use of the classical fumigants.

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REFERENCES

Annis, P. C. (1987). Towards rational controlled atmosphere dosage schedules: a review of current knowledge. *Proc. 4th Int. Working Conf. on Stored-Product Protection.* Tel Aviv, Israel September 1986 (ed. Donahaye, E. and Navarro, S.) pp 128–148

Anon (1995). *EH 40/95 Occupational exposure limits 1995.* (Health and Safety Executive) Publ. HMSO, London, UK. Appendix 4: asphyxiants.

Brokerhof, A. W. (1989). *Control of fungi and insects in objects and collections of cultural value.* Publ. Central Research Laboratory for Objects of Art and Science, Amsterdam, Netherlands. 77pp

Dawson, J. E. (1988). The effects of insecticides on museum artifacts and materials. In *A guide to museum pest control* (ed. Zycherman, L. A. and Schrock, J. R.) Assocn. of Syst. Collections, Washington D.C.

Gilberg, M. (1989). Inert atmosphere fumigation of museum objects. *Studies in Conservation* 34: 80–84

Hillyer, L. and Blyth, V. (1992). Carpet beetle - a pilot study in detection and control. *Conservator* No. 16: 65–77

Linnie, M. J. (1987). Pest Control - A survey of Natural History Museums in Great Britain and Ireland. *Int. J. Museum Mgmt. and Curatorship* 6:277–290

Morgan, C. P., Pinniger, D. B. and Bowden, N. S. (1993). The effectiveness of residual insecticides against the varied carpet beetle *Anthrenus verbasci* (L.) and the implications for control of this pest in museums. *Proc. 1st Int. Conf. on Insect Pests in the Urban Environment* Cambridge, UK, 1993 (ed. Wildey, K. B. and Robinson, W. H.) pp 373–379

Newton, J. (1991). Carbon dioxide fumigation in a heated portable enclosure. *Proc. 5th Int. Working Conf. on Stored-Product Protection.* Bordeaux, France, September 1990 (ed. Fleurat-Lessard, F. and Ducom, P.) pp 877–885

Newton, J. (1993). Carbon dioxide as a fumigant to replace methyl bromide in the control of insects and mites damaging stored products and artefacts. *Proc. 1st Int. Conf. on Insect Pests in the Urban Environment* Cambridge, UK, 1993 (ed. Wildey, K. B. and Robinson, W. H.) pp 329–338

Pinniger, D. B. (1994). *Insect pests in Museums* (3rd edn.) Archetype Publications, 58pp

Pinniger, D. B. (1991). New developments in the detection and control of insects which damage museum collections. *Biodeterioration Abstracts* 5 (2): 125–130

Rust, M. K. and Kennedy, J. (1993). The feasibility of using modified atmospheres to control insect pests in museums. *Getty Conservation Institute Scientific Program Report*

Smith, C. P. (1995). Developments in large scale anoxia treatments with nitrogen. A case study: oil paintings Marseilles, France. *Proceedings of meeting of ICOM working group on icons* Athens, Greece, October 1995 (in press)