

The Feasibility of Using Modified Atmospheres to Control Insect Pests in Museums

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INTRODUCTION

Surveys of natural history and art museums indicate that beetles belonging to the families Anobiidae and Dermestidae and moths belonging to the family Tineidae are major pests.¹ Schrock has provided a list of commonly damaged materials in museums and their associated pests.² Other groups such as termites and silverfish may also be extremely important, especially in southeast Asia.³ The future of fumigation in museums with conventional chemicals is uncertain. The more we learn about many of them, the more questionable their use becomes to operators (ethylene oxide) and to the environment (methyl bromide). In addition to the need to train museum personnel to use these insecticides, there is always the potential for damage to rare antiquities and artifacts.^{4,5} Preslock⁶ has provided an annotated bibliography of literature pertaining to pest control in museums.

The primary objectives of our study were to determine whether controlled or modified atmospheres were lethal to insects and the minimum time required to provide 100% kill of all developmental stages of insects likely to infest materials, objects and artifacts in museums.

Considerable research has been conducted with the use of modified atmospheres (MA) or controlled atmospheres (CA) to manage insect pests of stored grains and food. In most studies the lowest range of O₂ concentrations tested were 0.6–0.9%.

Marzke et al.⁷ found that, as O₂ concentrations decreased from 21.0% to 0.6%, the mortality of adults and larvae of *Trogoderma glabrum* (Herbst) increased. Mortality also increased with increasing temperature. Three-day exposures at 0.5% O₂ at 26.7°C resulted in 100% kill of adults and larvae. Adults were more susceptible than larvae. Navarro⁸ found that exposure time was the critical factor for certain species, such as rice weevil *Sitophilus oryzae* (L.), being almost independent of O₂ concentrations below 3%.

However, as O₂ concentrations decreased, the time required to kill the red flour beetle *Tribolium castaneum* (Herbst) also decreased.

Jay et al.⁹ found that, as the relative humidity decreased, the mortality of three stored-product insects exposed to low O₂ atmospheres (0.8–0.97%) increased. Jay & Cuff¹⁰ found that mortality and water loss with *T. castaneum* was low at 97% N₂ and 3% O₂ but high at 99% N₂ and 1% O₂, suggesting that water loss is the major cause of death at high N₂ atmospheres.

In studies with insect pests frequently encountered in museums, Gilberg found that 7-day exposures at 30°C and 65–70% relative humidity (RH) to 0.421% O₂ in nitrogen killed webbing clothes moths, cigarette beetles, drugstore beetles, carpet beetles and powderpost beetles.¹¹ The same insects exposed for 3 weeks in plastic bags were also killed.¹² Preliminary studies by Valentin¹³ showed that exposures to 1.0% O₂ atmospheres for 20 days killed deathwatch and powderpost beetles. Valentin & Preusser¹⁴ found that 30-hour exposures to 0.5% O₂ and 99.5% N₂ atmospheres produced 100% mortality in fruit flies. Exposure time decreased as the temperature at which the exposures were conducted increased. Exposures of 5 days to 80% CO₂ atmospheres provided complete kill of West Indian drywood termites, *Cryptotermes brevis* (Walker), inside pieces of infested wood.¹⁵

EXPERIMENTAL

Phase I: test system

In the current study controlled atmospheres (CA) were achieved by purging the chambers with pre-purified nitrogen. The test system consisted of 12 acrylic chambers each with a volume of 38 liters that could be independently flushed with nitrogen and sealed to provide stable low oxygen atmospheres. A controllable humidifying apparatus for adjusting relative humidity and nitrogen flow was inserted between the pre-purified nitrogen cylinder (99.999% N₂, <20 ppm O₂) and the input manifold to the chambers. For analytical sampling of the atmosphere in any given chamber without opening it, a gas chromatography septum was installed.

The chambers, constructed of 0.63-cm-thick methacrylate (35.6 cm × 45.7 cm × 26.7 cm), had a 14.6-cm diameter opening that could be quickly closed and sealed. A door fitted with a neoprene o-ring was placed over the opening and tightened to the chamber with 6 capscrews. Although each chamber was connected to the common nitrogen supply line with 0.63-cm copper tubing and an exhaust line, each of the inlet and outlet ports for the chambers was controlled by Whitey valves (Swagelok), making each chamber an independent experimental unit.

The schematic of the relative humidity conditioning unit is shown in Fig. 1. To humidify the nitrogen before flushing the chambers, the nitrogen af-

ter passing through (controlled by the (A), and the other leaving the water through the two metering bottle (B), fitted for analysis. From (C) equipped with the chambers.

To analyze the air dyne Oxygen Analyzer standardized by carbon dioxide nitrogen mixing bottle the chambers and above the nitrogen

To determine the relative humidity sensitive transmitter and L about ±1%.

Procedure

Mortality studies were stages. a) Each life cycle atmosphere in order testing phase II were placed in vials packed flour. Wood

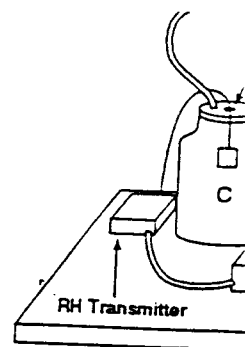


Fig. 1. Apparatus for hum

ter passing through the initial on/off valve, was split into two streams; one (controlled by the "wet" metering valve) bubbling through the first bottle (A), and the other to a T-tube where it joined the "wet" nitrogen stream leaving the water bottle. The ratio of wet to dry nitrogen was varied with the two metering valves. The combined flow of nitrogen entered a mixing bottle (B), fitted with a septum through which air samples were obtained for analysis. From the mixing bottle, the nitrogen passed to a third bottle (C) equipped with a relative humidity sensor. The nitrogen then passed to the chambers.

To analyze the amount of oxygen in the mixing bottle or the chambers, a Teledyne Oxygen Analyzer (model 316) was used. The Teledyne Analyzer was standardized by calibrating it with air and zeroing it with samples from the nitrogen mixing bottle. The needle was then inserted through the septum into the chambers and an oxygen reading determined. If the reading was $>0.1\%$ above the nitrogen zero, the chamber was refushed with nitrogen.

To determine the relative humidity of the mixed nitrogen flow, the relative humidity sensor was plugged into a Shinyei temperature and humidity transmitter and LCD digital multimeter (Micronata). The accuracy was about $\pm 1\%$.

Procedure

Mortality studies were done in two different series of experiments phases or stages. a) Each life stage of the various pests studied was exposed to a nitrogen atmosphere in open containers; the procedure and results are given under testing phase II. b) To mimic an infested object, non-wood-boring insects were placed in vials, and submerged in 0.9-liter jars covered with 10–13 cm of packed flour. Wood-boring insects such as the powderpost beetle and the

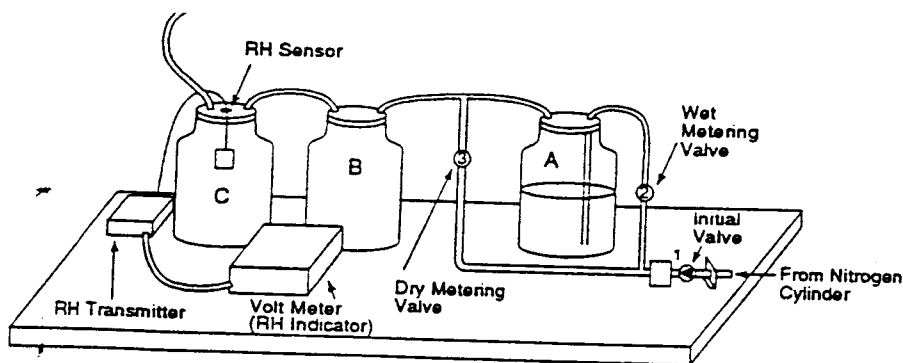


Fig. 1. Apparatus for humidifying the nitrogen flow. RH=relative humidity.

western drywood termites were placed in glass vials covered with a piece of screen to permit air exchange. The vials were placed inside 8 × 8 × 14 cm wooden blocks. The procedure and results are tabulated under testing phase III.

Testing phase II

The vials containing insects or eggs to be tested were transferred to the chambers. The relative humidity inside the chamber was maintained at 55% with 25 ml of a saturated solution of magnesium nitrate in a small plastic box. Excess magnesium nitrate (25 g) was added to the saturated solution so that any excess moisture in the chamber was absorbed. Two packets (7 g) of Z-1000 Ageless™ were placed in each chamber. Ageless™ is an oxygen scavenger prepared from moist powdered iron oxide and alkali metal salts (Mitsubishi Gas Chemical Co.).¹⁶ After transferring all insects to the test chamber, the chamber door was loosely sealed. The chamber was flooded for 30 minutes with 99.999% pure nitrogen preconditioned to 55% RH. The chamber was tightly sealed and the flow of nitrogen discontinued.

If the oxygen content inside the chamber was greater than 0.1%, the chamber was flushed again for an additional 5 to 10 minutes. The oxygen content was again analyzed. Every morning the chambers were analyzed for oxygen content. Whenever the oxygen level was greater than 0.1%, the chamber was flushed as described above.

Phase III testing for non-wood-boring insects

The procedure for sorting and preparing the insects was identical to those in phase II except the vials were placed in 0.9-liter glass jars and covered with 10 to 13 cm of flour to simulate conditions where the insects might be buried underneath articles or items.

Phase III testing for wood-boring insects

A simple wooden holding block was designed to confine the beetles deep inside the blocks during the exposure. Pieces of wood (8 cm × 8 cm × 14 cm) were cut from a post of Douglas fir. Each block was cut in half, and the center of each block hollowed to hold a 10-ml glass vial, leaving 1.27 to 2.54 cm of solid wood surrounding each insect vial. Two holes were drilled through the two blocks so that bolts could pass through both blocks. A sheet of parafilm was placed on either block so that when pressing the two halves firmly together, the blocks were sealed. The blocks were held with 6.35-cm bolts and wing nuts and 6 blocks were placed in each chamber for each test.

Mortality evaluation

The insects were transferred to a microscope. Adults and nymphs were picked up with forceps. If they moved, they were considered alive. If they did not move, the cocoons were opened. If the cocoon was opened and scored as alive if the egg was visible inside the egg shell.

Description of insects tested

A brief description of the species and number of insects and termites have included in the study. For the species tested, the dates of exposure and the dates. A detailed report is available from the University of California, Institute, 4503 Glencoe

The webbing clothes moth

The webbing clothes moth is a common clothes moth found in homes. It is uncommon to find a webbing clothes moth in boxes, textile storage boxes, etc.

The five different exposure periods were 24, 48, 72, 96 and 96 hours. The number of insects tested because of the difficulty in finding all stages were held in the chamber during exposures. The insects were tested in phase II.

The three exposure periods were 24, 48 and 96 hours. Approximately 540 pupae were tested in phase III, plus controls.

The furniture carpet beetle

The furniture carpet beetle is a wide variety of household pest. In particular, they attack upholstery and carpets. Other materials such as books and glue of book covers are attacked if they are contaminated.

Mortality evaluation

The insects were transferred to a petri dish to be counted with the aid of a microscope. Adults and larvae were individually probed with a pair of soft forceps. If they moved, they were scored as alive. All larvae that pupated or adults that emerged from cocoons were scored as alive. The remaining cocoons were opened. If they moved, they were scored as alive. The eggs were scored as alive if the egg had hatched and a larvae could be found near the egg shell.

Description of insects tested

A brief description of the various insects tested as well as the exposure times and number of insects tested are detailed below. The cockroach, firebrats and termites have incomplete metamorphosis and lack a pupal stage. For all the species tested, the experiments were replicated 3-5 times on 3-5 different dates. A detailed report can be requested from The Getty Conservation Institute, 4503 Glencoe Avenue, Marina Del Rey, CA 90292, USA.

The webbing clothes moth

The webbing clothes moth, *Tineola bisselliella* (Hummel), is the most common clothes moth found in the United States. In museum storage, it is not uncommon to find active infestations inside acid-free boxes, Hollinger boxes, textile storage boxes and even dressers and closets.^{17,18}

The five different exposure periods selected for testing were 3, 24, 48, 72 and 96 hours. The number of insects tested varied with each exposure because of the difficulty in obtaining certain stages. In the untreated control, all stages were held in the 55% RH holding box on top of the testing chamber during exposures. Approximately 350 pupae, 650 larvae, and 80 eggs were tested in phase II, plus controls.

The three exposure times tested in phase III were 48, 72 and 96 hours. Approximately 540 pupae, 400 larvae and 1270 eggs pupae were tested in phase III, plus controls.

The furniture carpet beetle

The furniture carpet beetle, *Anthrenus flavipes* (LeConte), is destructive to a wide variety of household and museum articles made of animal products. In particular, they attack upholstered furniture, hair, feathers, natural brushes, and carpets. Other materials damaged include wool, fur, leather bindings of books and glue of book bindings. Fabrics such as silk, and cotton may be attacked if they are contaminated with perspiration, blood or urine.

The typical life cycle of the furniture carpet beetle at optimal rearing conditions from egg to adult is about 3 to 4 months.

Five different exposure periods tested with all life stages were 6, 16, 24, 48 and 72 hours. Each test chamber contained four vials of adults, pupae, and larvae with 20 insects per vial totalling approximately 240 insects per test plus the control insects in phase II.

The only exposure time tested in phase III was 72 hours, which was the minimum time required to produce 100% mortality in phase II. Approximately 630 adults, 190 pupae, 650 larvae and 200 eggs were tested in phase III, plus control insects.

The firebrat

The firebrat, *Thermobia domestica* (Packard), is a primitive wingless group of insects belonging to the order Thysanura. Firebrats feed on numerous items found in museums and libraries, especially those made with starch, paste, glue (as in bookbinding), and starched cotton, linen, rayon or lisle. They are pests of paper, especially those with a glaze or sizings consisting of starch, dextrin, casein, gum or glue. Occasionally, synthetic items will be attacked if they are coated with sizings or paste.¹⁹ The typical life cycle of firebrats at optimal rearing conditions (37–39°C) is about 1.5–3.5 months.

In phase II, nymphs and adults were exposed for 0.5, 1, 2, 3, 16 and 24 hours. Eggs were exposed for 3, 16 and 24 hours. To determine whether the exposures were lethal, the contents of each vial were placed into a petri dish. Nymphs and adults were examined 24 and 168 hours after the exposure. Eggs were inspected at 24, 48 and 168 hours after exposure. The eggs were held for an additional 9 weeks before a final count was made. Approximately 1040 nymphs, 750 adults and 1500 eggs were tested in phase II.

In phase III the only exposure time tested was 48 hours because it equalled the minimum time required to produce 100% mortality in phase II plus 24 hours. Approximately 150 nymphs, 250 adults and 120 eggs were tested.

The cabinet beetle

The larvae of the cabinet beetle, *Trogoderma inclusum* (LeConte) damage insect collections, hides, skins, wool and feathers. The larvae are more likely to be a pest of processed dry foods, animal feeds and storage facilities than a serious pest of stored grains. The distribution of *T. inclusum* is influenced by climate, being encountered in areas with the relative humidity in excess of 35%.²⁰ The typical life cycle of cabinet beetles under normal rearing conditions is about 5.5 to 7 months.

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The larder beetle

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Adults, larvae and cc exposure to low oxygen. proximately 920 adults. coons were tested.

In phase II, the five different exposure periods selected for testing with the pupal, larval, and egg stages were 24, 48, 72, 96 and 120 hours. Approximately 290 adults, 670 pupae, 1500 larvae and 1640 eggs were tested in phase II, plus controls.

The two exposure times tested in phase III were 96 hours and 120 hours (the minimum time required to produce 100% mortality determined in phase II). The tests were replicated three times. Approximately 270 adults, 530 pupae, 1150 larvae and 740 eggs were tested in phase III, plus controls.

The larder beetle

The larder beetle, *Dermestes lardarius* L., feeds on ham, bacon, dried beef or fish, cheese, hair, horn, feathers, fur and carcasses. With the discontinuance of curing meats at home, the larder beetle has become less important in recent years. However, the presence of the larder beetle may indicate rodent or bird carcasses in buildings. The typical life cycle from egg to adult is 3 to 4 months.

Seven different exposure periods were selected for testing in phase II: 6, 18, 21, 24, 48, 72 and 96 hours. Approximately 650 adults, 320 pupae, 650 larvae and 750 eggs were tested in phase II, plus controls.

The only exposure time tested in phase III was 96 hours. Approximately 100 adults, 200 pupae, 560 larvae, and 500 eggs were tested in phase III, plus controls.

The cigarette beetle

The cigarette beetle, *Lasioderma serricorne* (F.), is the most destructive pest found in stored tobacco but will attack a variety of stored products. It also causes minor to serious damage to the binding and leaves of books while in storage or on shelves of libraries. The larvae feed on upholstered furniture, particularly stuffing. Other items it feeds on are seeds, paper, spices, drugs, grain, cereal products, botanical specimens, insect specimens, silk, rodent bait and dried plants.¹⁷ It is an important pest of books, damaging the binding and leaves.¹⁴ The life cycle (egg to adult) is 7 to 14 weeks.

In phase II, the five different exposure periods selected for testing with the adult, pupal, and larval life stages were 48, 72, 120, 144 and 168 hours. In addition, the egg stage was exposed for 192 hours. Cocoons containing pupae were exposed for 168 hours only. Most exposures were replicated 2-6 times, all on different dates.

Adults, larvae and cocoons were inspected for mortality 3 weeks after exposure to low oxygen atmospheres. Eggs were inspected at 5 weeks. Approximately 920 adults, 1050 pupae, 1590 larvae, 3000 eggs and 60 g of cocoons were tested.

The only exposure time tested in phase III was 192 hours because it equalled the minimum time required to produce 100% mortality of phase II, plus 24 hours. The tests were replicated twice on different dates.

The confused flour beetle

The confused flour beetle, *Tribolium confusum* Jacquelin du Val, is considered to be one of the most important pests of stored food. Confused flour beetles feed on broken grains, beans, nuts, spices, drugs, and herbarium and museum specimens. They are unable to feed on unbroken grains, but readily attack processed food.

The typical life cycle of *T. confusum* in heated warehouses or structures is about 3 months, with 4 to 5 generations of beetles yearly.

In phase II, the six different exposure periods selected for testing with all life stages were 6, 18, 21, 24, 48 and 72 hours. Three to four open dishes (20 insects per dish) of each life stage were tested per replicate. The only exposure time tested in phase III was 72 hours.

The American cockroach, brownbanded cockroach and German cockroach

The American cockroach, *Periplaneta americana* L., is the largest of the common structural infesting cockroaches, being 38 mm long with fully developed reddish-brown wings. The American cockroach is found most commonly in restaurants, grocery stores and bakeries, wherever food is prepared and stored. They are also attracted to fermenting liquid. They are occasionally found in museums in north America and commonly found in museums in southeast Asia.³ In museums they feed on starchy materials, sugary or fermented foods, leather, and parchment. In addition to sighting live insects, they can be detected by feeding damage, excrement and egg cases. Fifty to 60 adult males, adult females without oothecae (egg capsules), small nymphs (6 mm long), large nymphs (20 mm long) and oothecae were tested at each exposure period, totalling approximately 250 to 500 cockroaches, including controls.

The brownbanded cockroach, *Supella longipalpa* (F.), is a cosmopolitan cockroach pest, occurring both outdoors and indoors. In Egypt, this species is often referred to as the furniture cockroach. The brownbanded cockroach is tan to brown with light yellow crossbands on the dorsal side, especially prominent in nymphs. The adult is small, up to 12.5 mm long, active and flies readily when disturbed. It prefers warm temperatures and is found in areas of the structure where the temperatures exceed 26.5°C for most of the year. It prefers high locations such as shelves, behind picture moldings, etc. The damaging stages are the nymphs and adults. In museums they feed on starch materials, sugary or fermented foods, leather

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The powderpost beetle

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and parchment. The complete life cycle takes an average of 5.5 months. Fifteen to 20 adult male, adult female without oothecae, small nymphs (3 mm long), large nymphs (6 mm long) and oothecae were selected for each low oxygen exposure. Four hundred to 500 cockroaches, including controls, were tested.

The German cockroach, *Blattella germanica* (L.), is a cosmopolitan species occurring primarily indoors in areas where food is prepared or served. Adult German cockroaches are about 16 mm in length, brown in color, with two dark longitudinal streaks on the pronotum. They breed throughout the year indoors, especially in a humid environment averaging approximately 25°C. The life cycle (egg to adult) is approximately 2 months. The selection procedure was identical to that described for brownbanded cockroaches, with the exception of one additional adult stage. Since the German female carries the oothecae until 1-2 hours before it is ready to hatch, females with oothecae were also selected.

In phase II, the five different exposure periods selected for testing with adults and nymphs of *P. americana* were 1, 4, 6, 8 and 24 hours. Egg capsules of American cockroaches were also exposed for 92 and 120 hours. For brownbanded cockroaches, five different exposure periods, 1, 2, 3, 6, and 24 hours, were selected for testing with all nymphs and adults. Two additional exposure periods, 96 and 120 hours, were tested against the egg capsules. Four exposure periods, 1, 3, 6, 1 and 24 hours, were selected for testing with all life stages of *B. germanica*.

Only the oothecae of the American cockroach were tested in phase III because it was the most tolerant stage. Three different exposure periods, 72, 96 and 120 hours, were selected for testing. Four replicates were tested at the 120-hour exposure.

Only the egg capsules of the brownbanded cockroach were tested in phase III, with two different exposure periods of 96 and 120 hours. The oothecae were the most tolerant stage of brownbanded cockroach examined in phase II. Exposures were replicated 2 times.

In phase III, 70 female and male adult German cockroaches were exposed for 48 hours. Females with oothecae and large and small nymphs were tested with 10 to 20 insects per life stage per chamber. The tests were replicated 5 times.

The powderpost beetle

Beetles belonging to the family Lyctidae are collectively referred to as true powderpost beetles. The larval stage of powderpost beetles limit their feeding to hard woods such as ash, oak, hickory, mahogany, walnut, wild cherry, locust, poplar, sycamore, orange, eucalyptus and other open grained woods. Articles made of bamboo are also frequently infested. Infestations are com-

monly found in hardwood floors, furniture, antiques, tool handles, gunstocks, picture frames, packing crates and ornamental pieces such as grape canes and figurines.¹⁷ The entire life cycle of powderpost beetles range from 3 months to a year or longer.

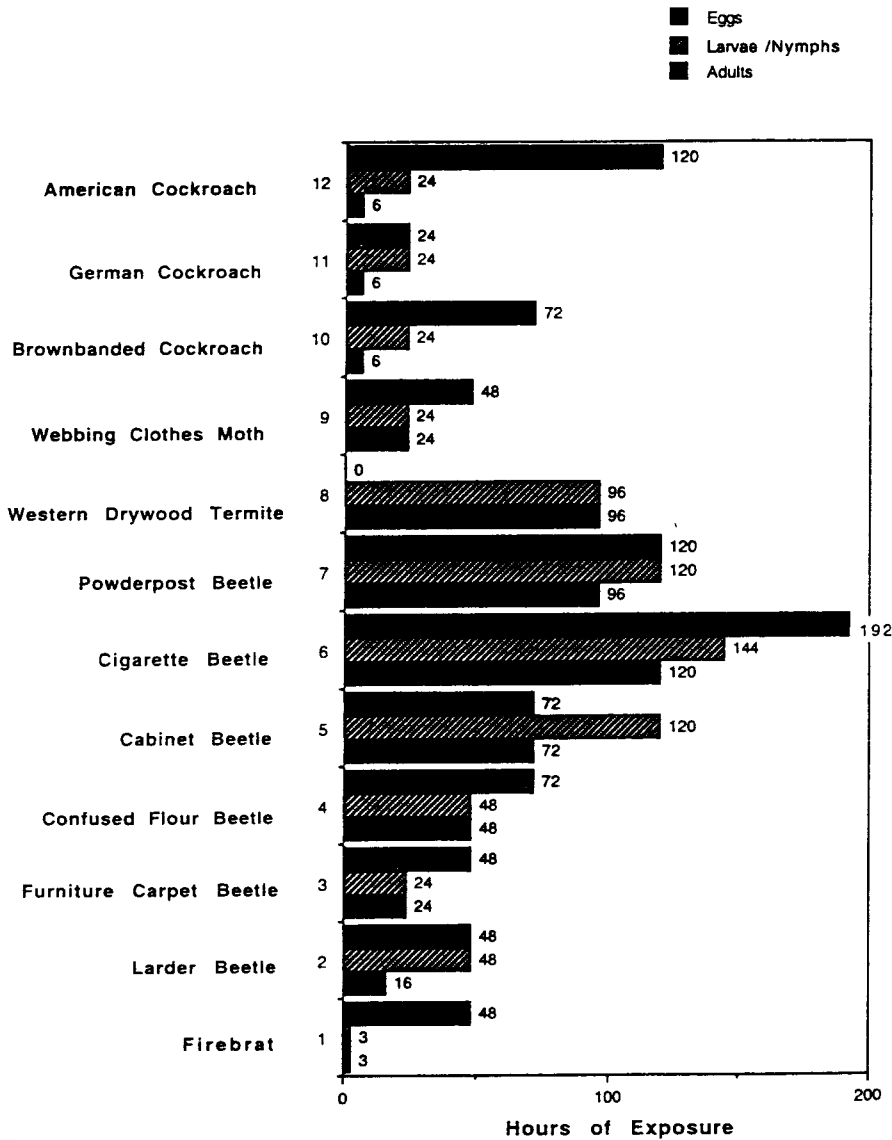


Fig. 2. Hours of exposure to achieve 100% mortality for ten commonly found insect pests exposed to nitrogen (<0.1% oxygen) in open containers at 25.5°C and 55% RH.

Three species used in this study (*Trogus*, *Leptinotarsus*, and *Blattella germanica*) are cosmopolitan species. *Blattella germanica* has been found in

Three different experiments were conducted: 96- and 120-hour exposures and 144 hours.

Approximately 50 adults, 20 larvae and 20

- Cigarette Beetle
- Powderpost Beetle
- Cabinet Beetle
- American Cockroach
- Confused Flour Beetle
- Larder Beetle
- Western Drywood Termite
- Webbing Clothes Moth
- Furniture Carpet Beetle
- Firebrat

Fig. 3. Hours of exposure to nitrogen for ten commonly found insect pests exposed to nitrogen (<0.1% oxygen) in open containers at 25.5°C and 55% RH.

Three species used in the tests were *Lyctus brunneus* (Stephens), *Lyctus linearis* (Goeze) and *Trogoxylon prostomoides* (Gorham). *L. brunneus* and *L. linearis* are cosmopolitan species, found in a wide variety of hardwoods. *T. prostomoides* has been found infesting toys, furniture, herbwood and bamboo.

Three different exposure periods tested with adult *T. prostomoides* were 48-, 96- and 120-hour exposures. Adult *L. brunneus* were exposed for 24, 120 and 144 hours.

Approximately 50 adult *T. prostomoides* were tested in phase II. About 50 adults, 20 larvae and 20 pupae of the *L. brunneus* were tested.

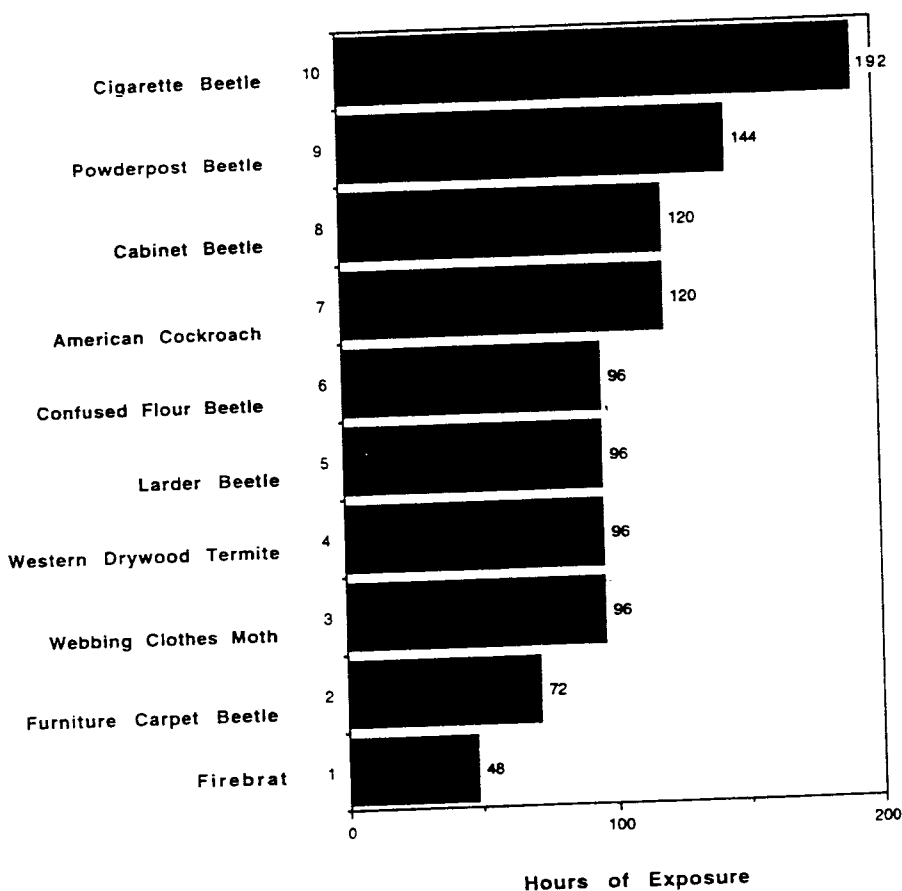


Fig. 3. Hours of exposure to achieve 100% mortality for the most tolerant stage of ten commonly found insect pests exposed to nitrogen (<0.1% oxygen) in closed containers at 25.5°C and 55% RH.

The western drywood termite

The western drywood termite, *Incisitermes minor* (Hagen), is the most destructive drywood termite in the United States. The drywood termites are aptly named because they establish themselves in wood that is not decayed or in contact with ground moisture. They frequently attack softwoods used in framing structures which is perfectly dry, but they occasionally infest hardwoods used in furniture construction.¹⁷

In phase II, five exposure periods were selected: 15, 24, 48, 72 and 96 hours. Approximately 1400 nymphs were tested in this phase, plus controls.

Three exposure periods of 48, 72 and 96 hours were tested in the next phase. Approximately 1650 nymphs were tested in phase III, plus controls.

RESULTS AND DISCUSSION

The exposure times for 100% mortality of all life stages of pests studied at 55% RH and 25.5°C are tabulated in Fig. 2 for phase II and Fig. 3 for phase III. A brief discussion of the results for all the insects tested are given below.

Webbing clothes moth

In phase II, the larvae and cocoons (containing resting larvae, and pupae) were readily killed when exposed to the low oxygen atmospheres for 24 hours. Three-hour exposures killed 71–75% of the larvae and cocoons. A 48-hour exposure produced 100% kill of the eggs.

The 48-hour exposures resulted in 100% kill of all stages tested in phase III, but only 98.7% of the cocoons were killed with a 72-hour exposure. All stages were killed with a 96-hour exposure.

The furniture carpet beetle

In phase II, exposure for 24 hours produced 100% kill of adult carpet beetles. The adults are short-lived, 25% being dead at day 7 in the untreated controls. The egg was the most tolerant stage, only 50% being killed with a 24-hour exposure. Exposures for 48 hours were required to produce 100% kill of the eggs and pupae. Larvae were the most susceptible stage, requiring only a 24-hour exposure to give 100% kill.

In phase III, exposure of 72 hours produced 100% mortality. The use of 72-hour exposure should provide a sufficient margin of error to ensure complete kill of all life stages.

The firebrat

In phase II, firebrat nymphs died in the low oxygen atmospheres within 24 hours. Exposures of 29.8 hours produced 100% mortality.

Brief exposures of 15 and 24 hours were sufficient to kill firebrats when firebrats were exposed to the low oxygen atmosphere.

In phase III, the 48-hour exposure was quickly displaced by the use of 48-hour exposure to produce complete kill of all life stages.

The cabinet beetle

The cabinet beetle was the most tolerant stage to 120-hour exposures to the low oxygen atmosphere. Pupae and 72-hour exposures produced 100% mortality.

In phase III, the 48-hour exposure did not increase the exposure time to 100% mortality.

The larder beetle

The adults were the most tolerant stage to the low oxygen atmosphere. In phase II, the pupae were the most tolerant stage to mortality compared with the adults. All stages were killed with a 96-hour exposure.

In phase III, 96-hour exposure produced 100% mortality.

Cigarette beetle

Adult cigarette beetles and pupal cigarette beetles were the most tolerant stages to the low oxygen atmosphere. Control mortality was 25% after 144 hours, and 100% after 192 hours to produce 100% mortality.

All stages of the cigarette beetle were killed with a 96-hour exposure in phase III.

The firebrat

In phase II, firebrat nymphs and adults were readily killed when exposed to the low oxygen atmospheres. As short as a 3-hour exposure killed all the stages within 24 hours. Eggs were the most resistant life stage, requiring exposures of 29.8 hours to provide complete kill.

Brief exposures of 0.5 or 1 hour provided significant latent mortality when firebrats were examined after 168 hours. The mode of action is unknown.

In phase III, the 48-hour exposure produced 100% kill of all stages. Oxygen was quickly displaced from the flour and replaced with nitrogen. The use of 48-hour exposure should provide sufficient margin of error to ensure complete kill of all stages.

The cabinet beetle

The cabinet beetle was the only species tested in which the larvae was the most tolerant stage to low oxygen atmospheres. In phase II, larvae required 120-hour exposures to produce 100% mortality, compared with 48 hours for pupae and 72 hours for the eggs and adults.

In phase III, the 120-hour exposures provided 100% kill. The flour did not increase the exposure time required to completely kill larvae.

The larder beetle

The adults were the most susceptible life stage tested with the low oxygen atmosphere. In phase II, 16-hour exposure resulting in 100% kill. The pupae were the most tolerant stage in that 24-hour exposure resulted in 70.1% mortality compared with 98.9% kill of larvae and complete kill of eggs and adults. All stages were killed with 48- or 72-hour exposures.

In phase III, 96-hour exposures killed 100% of all stages buried in the flour.

Cigarette beetle

Adult cigarette beetles were killed with 120-hour exposure. All of the adult and pupal cigarette beetles were killed with 144-hour exposure in phase II. Control mortality was extremely high at 3 weeks (>97%). Larvae required exposure of 144 hours, the egg stage was the most tolerant stage tested, requiring 192 hours to produce 100% kill.

All stages of the cigarette beetle were killed with 192-hour exposure in phase III.

The confused flour beetle

The adults and larvae were completely killed with 48-hour exposures in phase II. All developmental stages were killed with a 72-hour exposure. The reason for the significant increase in mortality of larvae and pupae between 7 and 21 days after exposure is unknown.

In phase III, all stages were killed with 96-hour exposure to low oxygen atmospheres.

It is extremely unlikely that *T. confusum* will develop resistance to low O₂ treatments as reported by Donahaye.²¹ He exposed red flour beetles to 0.5% O₂ for 40 generations at 95% RH. The lethal times increased from 36 hours in the second generation to 190 hours in generation 26. It is unlikely that this degree of selection would ever be achieved under practical conditions.

The American cockroach, brownbanded cockroach and German cockroach

Adult cockroaches are the most susceptible stage to low oxygen atmospheres, requiring 6-hour exposure to produced 100% kill of all 3 species tested in phase II. The nymphal cockroaches of all 3 species are somewhat more tolerant of low oxygen atmospheres, requiring 8-24 hours to kill 100%.

The oothecae are the most tolerant life stage. Exposures of 120, 72 and 24 hours were required to kill 100% of the developing nymphs of *P. americana*, *S. longipalpa* and *B. germanica*, respectively.

In phase III, exposure of 120 hours was necessary to kill 100% of the *P. americana* oothecae. There was no apparent effect of burying the capsules in the flour.

The powderpost beetle

In phase II, 48-hour exposure produced 97% kill of adult beetles, 96-hour or longer exposure produced 100% mortality and 90% kill of the *Lyctus* larvae within 24 hours was achieved, all other life stages being completely killed. At least a 96-hour exposure in phase II with *T. prostomoides* was necessary to provide 100% kill. In phase II, 120-hour exposure produced only a 90% kill of the *Lyctus* with the larval stage, indicating a need for a longer exposure period to achieve 100% mortality.

The colonies were too small and thus it was not possible to test sufficient replicates. Phase III provided final results for *Lyctus* larvae.

In phase III, the only exposure period tested for adult beetles was 144 hours, which provided 100% kill. Two exposures were tested for *Lyctus* larvae, 120 and 144 hours, all resulting in 100% kill.

The western drywood termite

Exposure for 96 hours in phase II. A 72-hour exposure was necessary for the exposure.

When termites were exposed to low oxygen atmospheres, there was a significant increase in mortality.

In phase III, 48-, 72- and 144-hour exposures were tested. The wooden blocks were killed in 14 days. The 96-hour exposure was necessary for the nitrogen. The 96-hour exposure was necessary for the nitrogen.

CONCLUSION

The use of low-oxygen atmospheres is extremely promising. (<0.1%) for at least 8-14 days. The wooden blocks were killed in 14 days. The 96-hour exposure was necessary for the nitrogen. The 96-hour exposure was necessary for the nitrogen. The 96-hour exposure was necessary for the nitrogen.

The time required to kill the insects was dependent on the nature of the insect. The time required to kill the insects was dependent on the nature of the insect.

The Getty Conservation Institute has developed special bags for the storage of paintings and still life objects. The use of low oxygen atmospheres and fumigants effective for the protection of these objects.

The western drywood termite

Exposure for 96 hours resulted in a 100% kill of nymphs within 24 hours in phase II. A 72-hour exposure killed 100% of the nymphs within 14 days after the exposure.

When termites were exposed for 15, 24 or 48 hours, there was a significant increase in mortality between day 1 and day 7. The exposure to the low oxygen atmospheres produced some latent effects.

In phase III, 48-, 72- and 96-hour exposures produced 100% kill within 14 days. The wooden block was not a barrier to displacement of oxygen by nitrogen. The 96-hour exposure produced a 100% kill within 24 hours.

CONCLUSION

The use of low-oxygen atmospheres to control insect pests in museums looks extremely promising. It was possible to maintain low-oxygen atmospheres (<0.1%) for at least 8-10 days with only an occasional flushing of pre/purified N₂ and several packets of Ageless™ oxygen scavenger. The results showed that the time required to kill 100% of the insects varied between species and even between the developmental stages of a given species. For most insects tested, exposure of less than 96 hours was required to ensure complete kill. Certain stages such as eggs of cigarette beetles may require up to 8-day exposure to ensure complete kill. Preliminary tests indicated that the addition of CO₂ to the nitrogen slightly decreased the exposure time required to kill the insects. It is likely that the exposure time in the low-oxygen atmosphere would be dramatically decreased by increasing the temperature above 25.5°C and lowering the relative humidity below 55%. However, the upper temperature limits and lower relative humidity limits would depend on the nature of the object.

The time required to kill the most resistant stages of each insect tested did not substantially increase in phase III testing. The oxygen was quickly displaced and removed by the Ageless™, killing the insects buried deep in the wood or flour. Consequently, it will probably not be necessary to specially prepare or stack items for treatment.

The Getty Conservation Institute and the J. Paul Getty Museum have developed special bags capable of enclosing larger items such as furniture and paintings and still maintaining the low-O₂ atmosphere.²²⁻²⁴ Hence the use of low oxygen atmospheres can replace the current use of insecticide sprays and fumigants effectively.

Über die Möglichkeit, Insektenbefall in Museen durch modifizierte Umluft zu bekämpfen

Es wurde die Sterblichkeit aller Stadien von Schadinsekten, die in Museen begegnen, bei 25,5°C 55% rF in Stickstoff-Atmosphäre (<0,1% Sauerstoff) untersucht. Gegenstand der Untersuchung waren Kleidermotten, Teppichkäfer, Ofenfischchen, Kabinettkäfer, Speckkäfer, Amerikanischer Reismehlkäfer, Amerikanische Schabe, Braunbandschabe, Hausschabe, Splintkäfer und "Kleine Trockenholzkalotermite" (*Incisitermes minor*). Die Zeit bis zum vollständigen Abtöten betrug zwischen drei Stunden für entwickelte Ofenfischchen und 192 Stunden für die Eier des Tabakkäfers.

REFERENCES

1. Bailey, S. W. & Banks, H. J.: *A review of recent studies of the effects of controlled atmospheres on stored product pests*. Controlled atmosphere storage of grains. Amsterdam: Elsevier Scientific Publishing Co., 1980: 101-18.
2. Schrock, J. R.: *List of insect pests by material or apparent damage*. A guide to museum pest control. Washington, DC: Association of Systematic Collections, 1988: 113-20.
3. Quek, L. C., Razak, M. & Ballard, M. W.: *Pest control for temperature vs. tropical museums: North America vs. Southeast Asia*. Ninth Triennial Meeting of the International Council of Museums, Committee for Conservation (1990): 817-820.
4. Florian, M. L.: *Ethylene oxide fumigation: a literature review of the problems and interactions with materials and substances in artifacts*. Zycherman, L. A. & Schrock, J. R. ed. A guide to museum pest control. Washington, DC: Association of Systematic Collections, 1988: 151-58.
5. Dawson, J.: *The effects of insecticides on museum artifacts and materials*. Zycherman, L. A. & Schrock, J. R. ed. A guide to museum pest control. Washington, DC: Association of Systematic Collections, 1988: 135-150.
6. Preslock, K.: *Pest control in museums a partially annotated bibliography*. Zycherman, L. A. & Schrock, J. R. ed. A guide to museum pest control. Washington, DC: Association of Systematic Collections, 1988: 177-98.
7. Marzke, F. O., Press, A. F. Jr. & Pearman, G. C. Jr.: *Mortality of the rice weevil, the Indian-meal moth, and *Trogoderma glabrum* exposed to mixtures of atmospheric gases at various temperatures*. Journal of Economics and Entomology 63 (1970): 570-4.
8. Navarro, S.: *The effects of low oxygen tensions on three stored-product insect pests*. Phytoparasitica 6 (1978): 51-8.
9. Jay, E. G., Arbogast, R. T. & Peraman, G. G. Jr.: *Relative humidity: its importance in the control of store-product insects with modified atmospheric gas concentrations*. Journal of Stored Product Research 6 (1971): 325-9.
10. Jay, E. G. & Cuff, W.: *Weight loss and mortality of three life stages of *Tribolium castaneum* (Herbst) when exposed to four modified atmospheres*. Journal of Stored Product Research 17 (1981): 117-24.
11. Gilberg, M.: *Inert atmosphere fumigation of museum objects*. Studies in Conservation 34 (1989): 80-4.
12. Gilberg, M.: *Inert atmosphere disinfestation using Ageless oxygen scavenger*. Ninth Triennial Meeting of the International Council of Museums, Committee for Conservation (1990): 812-6.
13. Valentin, N.: *Insect eradication in museums and archives by oxygen replacement, a pilot project*. Ninth Triennial Meeting of the International Council of Museums, Committee for Conservation (1990): 821-3.
14. Valentin, N. & Preusser, F. D.: *Insect control by inert gases in museums, archives and libraries*. Restaurator 11 (1990): 22-33.

Modified Atmospheres and Insect Pests

15. Paton, R. & Creffield, J. W.: *The tolerance of some timber insect pests to atmospheres of carbon dioxide in air*. International Pest Control 29, 1/2 (1987): 1072.
16. Lambert, F. L., Daniel, V. & Preusser, F. D.: *The rate of absorption of oxygen by Ageless™; the utility of an oxygen scavenger in sealed cases*. Studies in Conservation 37 (1992): 267-274.
17. Ebeling, W.: *Urban entomology*. Berkeley, CA: University of California Division of Agricultural Science (1975).
18. Parker, T. A.: *Clothes moths*. Storey K, ed. Handbook of pest control. Cleveland, OH: Franzak & Foster Co., 1990: 347-75.
19. Carr, R. C.: *Silverfish and booklice*. Storey, K., ed. Handbook of pest control. Cleveland, OH: Franzak & Foster Co., 1990: 87-9.
20. Strong, R. G.: *Comparative studies on the biologies of six species of Triogoderma: T. inclusum*. Annals of the Entomology Society of America 68 (1975): 91-104.
21. Ezra Donahave, Volcani Center, P.O.B. 6, Bet-Dagan 50 250 (Private communication).
22. Hanlon, G., Daniel, V., Ravenel, N. & Maekawa, S.: *Dynamic system for nitrogen anoxia of large museum objects: a pest eradication case study*. Second International Conference on Biodeterioration of Cultural Property, Oct 5-8, Yokohama.
23. Daniel, V., Hanlon, G., Maekawa, S. & Preusser, F. D.: *Nitrogen anoxia: a viable alternative*. International Council of Museums 10th triennial meeting preprints. Washington DC. August 22-27, 1993.
24. Daniel, V., Hanlon, G. & Maekawa, S.: *Eradication of insect pests in museums using nitrogen*. Western Association for Art Conservation Newsletter 3 (1993): 15-9.

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2. Hon, D. N.-S.: *Yellowing of historic and artistic value II*. Chemical Society, 1981: 11

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