THE FEASIBIILITY OF USING MODIFIED ATMOSPHERES TO CONTROL INSECT PESTS IN MUSEUMS

Michael K. Rust, Janice M. Kennedy, Vinod Daniel, James R. Druzik and Frank D. Preusser

Abstract: The mortality of all life stages of pests commonly found in museums was evaluated at 55% RH and 25.5°C in a nitrogen atmosphere (less than 0.1% oxygen). The insects studied were webbing clothes moths, furniture carpet beetles, firebrats, cabinet beetles, larder beetles, cigarette beetles, confused flour beetles, cockroaches, powderpost beetles and western drywood termites. The time required for 100% kill varied from three hours for the adult firebrats to 192 hours for the eggs of the cigarette beetle.

1 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 traditional chemicals is uncertain. The more we learn about many of them, the more questionable they become, to their operators (ethylene oxide) and 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]. Preslock has provided an annotated bibliography of literature pertaining to pest control in museums [6].

The primary objectives of our study were to determine if controlled or modified atmospheres were lethal 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 O_2 concentrations tested were 0.6-0.9%.

Marzke et ale found that as O_2 concentrations decreased from 21.0% to 0.6%, the mortality of adults and larvae of *Trogoderma glabrum* (Herbst) increased [7]. Mortality was also increased with increasing temperature. Three-day exposures at 0.5% O_2 at 26.7°C provided 100% kill of adults and larvae. Adults were more susceptible than larvae. Navarro found that exposure time was the critical factor for certain species [8], such as rice weevil *sitophilus orvzae* (L.), being almost independent of O_2 concentrations below 3%. However, as O_2 concentrations decreased, the time required to kill *Tribolium castaneum* (Herbst) also decreased.

Jay et ale found that as the relative humidity decreased, the mortality of three stored product insects exposed to low O_2 atmospheres (0.8-0.97%) increased [9]. Jay and Cuff found that mortality and water loss with *T. castaneum* was low at 97% N_2 and 3% O_2 but high at 99% N_2 and 1% O_2 suggesting that water loss is the major cause of death at high N_2 atmospheres [10].

In studies with insect pests frequently encountered in museums, Gilberg found that 7-day exposures at 30°C and 65-70% RH to 0.421% O_2 in nitrogen killed webbing clothes moths, cigarette beetles, drugstore beetles, carpet beetles and powderpost beetles [11]. The same insect exposed for 3 weeks in plastic bags were also killed [12]. Preliminary studies by Valentin showed that exposures to 1.0% O_2 atmospheres for 20 days killed deathwatch and powderpost beetles [13]. Valentin and Preusser found that 30-hour exposures to 0.5% O_2 and 99.5% N_2 atmospheres completely killed fruit flies [14]. Exposure time decreased as the temperature at which the exposures were conducted increased. Exposures of 5 days to 80% CO_2 atmospheres provided complete kill of West Indian drywood termites, *Cryptotermes brevin* (Walker), inside pieces of infested wood [15].

2 Experimental

2.1 *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 (381, 42,475 cm^3) that could be independently flushed with nitrogen and sealed to provide stable low oxygen atmospheres. A controllable humidifying apparatus for adjusting relative humidity (RH) and nitrogen flow was inserted between the pre-purified nitrogen cylinder (99.999% N_2, <20 ppm O_2) and the input manifold to the chambers. For aiding analytical sampling of the atmosphere in any given chamber without opening it, a gas chromatography septum was installed in each chamber.

The chambers, constructed of 0.63-cm thick methacrylate (35.6cm x 45.7cm x 26.7 cm), had a 14.6 cm diameter opening that could be quickly closed and sealed. A neoprene a-ring fitted door was placed over the opening and tightened to the chamber with six 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.

To humidify the nitrogen before flushing the chambers, the nitrogen after 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 exiting 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 RH sensor. The nitrogen then passed to the chambers. The schematic of the RH conditioning unit is shown in Figure 1.

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 reflushed with nitrogen.

To determine the RH of the mixed nitrogen flow, the RH sensor was plugged into a Shinyei temperature and humidity transmitter and LCD digital multimeter (Micronta). The accuracy was about ± 1%.

2.2 *Procedure*

Mortality studies were done for two different cases: a) Each life stage of the various pests studied were exposed to a nitrogen atmosphere in open containers, the procedure and results are given under testing Phase IIi b) To mimic an infested object non-wood boring insects were placed in vials, submerged in 0.9-liter jars covered with 10-13 cms of packed flour. While woodboring insects such as the powder post beetle and the western drywood termites, were placed in screened vials, inside 8 x 8 x 14 cm wooden blocks. The procedure and results are tabulated under testing Phase III.

2.21 *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., Inc.) [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.

2.22 *Phase III testing for non woodboring 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.

2.23 *Phase III testing for woodboring insects*

A simple wooden holding block was designed to confine the beetles deep inside the blocks during the exposure. Pieces of wood (8cm x 8cm x 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 2 1/2-inch bolts and wing nuts and six blocks were placed in each chamber for each test.

2.3 *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 live. All larvae that pupated or adults that emerged from cocoons were scored as live. The remaining cocoons were opened. If they moved, they were scored as live. The eggs were scored as live if the egg had hatched and a larvae could be found near the egg shell.

2.4 *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, U.S.A.

2.4a *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 cabinetry [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 650 larvae, 350 pupae, 80 eggs were tested in Phase II, plus controls.

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

2.4b *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 93 to 126 days.

Five different exposure periods tested with all life stage 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.

2.4c *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 sidings or paste [19]. The typical life cycle of firebrats at optimal rearing conditions (37- 39°C) is about 1.5 to 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 if 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 1,040 nymphs, 750 adults, and 1,500 eggs were tested in Phase II.

In Phase III the only exposure time tested in Phase III 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.

2.4d *The cabinet beetle*

The larvae of the cabinet beetle, *Trogoderrna inclusum* (LeConte), damages 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.

In Phase II, 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, 1,500 larvae, and 1,640 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, 1,150 larvae, and 740 eggs were tested in Phase III, plus controls.

2.4e *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 thelarder beetle may indicate rodent or bird carcass in buildings. In museums, it is frequently used to clean flesh off of bones. The typical life cycle from egg to adult is 60 to 90 days.

Seven different exposure periods were selected for testing in Phase II were 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.

2.4f *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, 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 were exposed for 168 hours only. Most exposures were replicated 2-6 times, all on different dates.

Adults, pupae, larvae, and cocoons were inspected for mortality 3 weeks after exposure to low oxygen atmospheres. Eggs were inspected at 5 weeks. Approximately 920 adults, 1,050 pupae, 1,590 larvae, 3,000 eggs, and 60 grams 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.

2.4g *The confused flour beetle*

The confused flour beetle, *Tribolium confusum* Jacqulin 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 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 was tested per replicate. The only exposure time tested in Phase III was 72 hours.

2.4h *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 (1 1/2 inches) long with fully developed reddish-brown wings. The American cockroach is found most commonly in restaurants, grocery stores, 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 100 cockroaches of each life stage were tested, 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 fly readily when disturbed. It prefers warm temperatures and is found in areas of the structure where the temperatures exceed 26.5°C (80°F) 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 and parchment. The complete life cycle takes an average of 161 days. Fifteen to 20 cockroaches of each life stage were selected for each low oxygen exposure, totaling 75 to 100 cockroaches of each life stage tested in each replicate. 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 (5/8 inch)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 21°C (70°F). The life cycle (egg to adult) varies from 55 to 68 days. The selection procedure was identical to that described for brownbanded cockroaches.

In Phase II, 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 (egg capsule) of the American cockroach was tested in Phase III because it was 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 was tested in Phase III, with two different exposure periods of 96 and 120 hours. The oothecae were the most tolerant of stage of brownbanded cockroach examined in Phase II. Exposures were replicated 2 times.

In Phase 111, 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. Tests were replicated 5 times.

2.4i *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 commonly 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. Three species used in the tests were *Lyctus brunneus* (Stephens), *Lyctus linearis* (Goeze), and *Trogoxylon prostomoides* (Gorham). *Lyctus 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 the adult *T. prostomoides* were 48-, 96-, and 120-hour exposures. The adult *Lyctus brunneus* was 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 Lyctus spp. were tested.

2.4j *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 1,400 nymphs were tested in this phase plus controls.

Three exposure periods of 48, 72 and 96 hours were tested in the next phase. Approximately 1,650 nymphs were tested in Phase III, plus controls.

3 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 Figure 2 for Phase II and Figure 3 for Phase III. A brief discussion of the results for all the insects tested are given below.

3.1 *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 provided 100% kill of the eggs.

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

3.2 *The furniture carpet beetle*

In Phase II, exposures for 24 hours provided 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 provide 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, exposures of 72 hours provided 100% mortality. The use of 72-hour exposures should provide sufficient margin of error to insure complete kill of all life stages

3.3 *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-hours exposure should provide sufficient margin of error to insure complete kill of all stages.

3.4 *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. Adults were killed with a 72 hour exposure.

In Phase III, the 120-hour exposures provided 100% kill of all life stages. The flour did not increase the exposure time required to provide complete kill.

3.5 *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 was the most tolerant stage in that 24-hour exposures resulting in 70.1% mortality compared with 98.9% kill of larvae and complete kill of eggs and pupae. 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.

3.6 *Cigarette beetle*

Adult cigarette beetles were killed with 120-hour exposures. 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 exposures of 144 hours, the egg stage is the most tolerant stage tested, requiring 192 hours to provide 100% kill.

All stages of the cigarette beetle were killed with 192-hour exposures in Phase III.

3.7 *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 exposures to low oxygen atmospheres.
It is extremely unlikely that *T. confusum* will rapidly develop resistance to low O_2 treatments as reported by Donahaye [21]. He exposed red flour beetles to 0.5% O_2 for 40 generations at 95% RH. The lethal times increased from 36 hours in the 2nd generation to 190 hours in the 26th generation. It is unlikely that this would ever be achieved under practical condition

3.8 *The American cockroach, brownbanded cockroach and German cockroach*

Adult cockroaches are the most susceptible stage to low oxygen atmospheres, requiring 6-hour exposures to provide 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 *B. americana*, *S. longipalpa,* and *B. germanica,* respectively.

In Phase III, exposures of 120 hours were necessary to kill 100% of the *B. americana* oothecae. There was no apparent effect of burying the capsules in the flour.

3.9 *The powderpost beetle*

In Phase II, a 48-hour exposure produced a 97% kill of adult beetles. a 96-hour or longer exposure produced 100% mortality. A 90% kill of the *Lyctus* larvae within 24 hours was achieved, all other life stages were completely killed. At least a 96-hour exposure in Phase II with *Trogoxvlon prostomoides* was necessary to provide 100% kill. In Phase II, a 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.

3.10 The western drywood *termite*
Exposures 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. Clearly 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 100% kill within 24 hours.

4 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, exposures less than 72 hours were required to insure complete kill. certain stages such as eggs of cigarette beetles may require up to a-day exposures to insure complete kill. Preliminary tests indicated that the addition of CO_2 to the nitrogen slightly decreased the exposure time required to kill the insects. However, if increased temperatures or decreased relative humidities could be tolerated by the objects, they would probably have a much greater effect than using CO_2 and N_2 mixtures in reducing the exposure times.

The time required to kill the most resistant stages of each insect tested did not significantly increase in stage 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 O_2 atmosphere [22,23]. Hence the use of low oxygen atmospheres can replace the current use of insecticide sprays and fumigants effectively.

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6 Suppliers of Materials

Swagelok tubing fittings and valves: Swagelok Co., 31400 Aurora road, Solon, Ohio 44139
Ageless™: Conservation Materials, Ltd., P.O.Box 2884, Sparks, Nevada 89432
Teledyne Model 316: Teledyne Analytical Instruments, P.O. Box 1580, City of Industry, California 91749
Shinyei Temperature and Relative Humidity Transmitter: Shinyei Kaisha, 1-10-7, Shinbashi, Minato-ku, Tokyo, Japan

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Dr. Rust received his B.A. in Biology from Hiram College and his M.S. and Ph.D. from the University of Kansas. He joined the faculty at the University of California, Riverside, in 1975 to teach, conduct research, and develop a graduate program in urban entomology. He is currently Professor of Entomology and Acting Chairman. His primary areas of research include the integrated pest management of urban pests such as ants, cockroaches, fleas, termites, and wood-destroying organisms; physiological ecology; insecticide resistance; and the isolation of natural products with biological activity.

He has authored or co-authored more than 90 publications and has presented more than 70 technical papers at scientific meetings and seminars. Dr. Rust is a member of the Entomological Society of America, Sigma Xi (national research fraternity), Gamma Sigma Delta (national honorary fraternity of agricultural sciences), and Pi Chi Omega. *Authors address: Department of Entomology, University of California, Riverside, CA 92521-0314*

Janice M. Kennedy retired December 1991 as Staff Research Associate II from University of California, Riverside. She never attended college, but she taught herself extremely difficult techniques and concepts in physiology and entomology. She was a junior author of 13 publications regarding the physiology and toxicology of insecticides against pink bollworms in cotton.

Vinod Daniel received his M.Tech degree in chemical engineering from Indian Institute of Technology, Madras, India in 1986, where he worked on the rheological characteristics of polymer blends. He also received his M.S degree in physical chemistry from Texas Christian University in 1991, where his thesis was in diffusion in liquids. He is presently working as a Senior Research Fellow in the environmental sciences division at the Getty Conservation r Institute. His research involves museum cases, moisture buffers in display cases, non-toxic fumigation, environmental data acquisition and moisture transfer in porous objects. *Author's Address: Getty Conservation Institute, 4503 Glencoe Avenue, Marina Del Rey, CA 90292.*

James R. Druzik has been Conservation scientist at the Getty Conservation Institute since 1985. He is responsible for managing the Institute's contract research program. This program focuses on experimental studies within, (1) the museum indoor environment, (2) the material science of new and traditional

conservation products and methods, (3) architectural and archaeological conservation and (4) new technology. Prior to the GCI, Druzik was an associate scientist in the Conservation Center of the Los Angeles County Museum of Art. He has over 40 publications from his personal research to his credit and has a B.S. in Chemistry. *Author's Address: Getty Conservation Institute, 4503 Glencoe Avenue, Marina Del Rey, CA 90292.*

Frank D. Preusser received his Ph.D in polymer and physical chemistry in 1973 from the Technical University in Munich. From 1973-1983 he was Head of the Scientific Laboratory of the Doerner Institute in Munich. In 1983 he joined the Getty Museum as Conservation Scientist and developed the research program and the laboratories for the Museum and the Getty Conservation Institute.

From 1985 to 1990 he was Director of the Scientific Research Program of the Getty Conservation Institute and since 1990 he is Associate Director for Programs, Head of Publications, and since 1991 Acting Director of the Scientific Research Program of the GCI. Preusser, who has published some 55 technical articles, works in five areas of the GCI: the scientific examination of paintings, architectural preservation, museum environment, evaluation of conservation materials and techniques and preservation of archaeological sites. *Author's address: Getty Conservation Institute, 4503 Glencoe Avenue, Marina Del Rey, CA 90292*

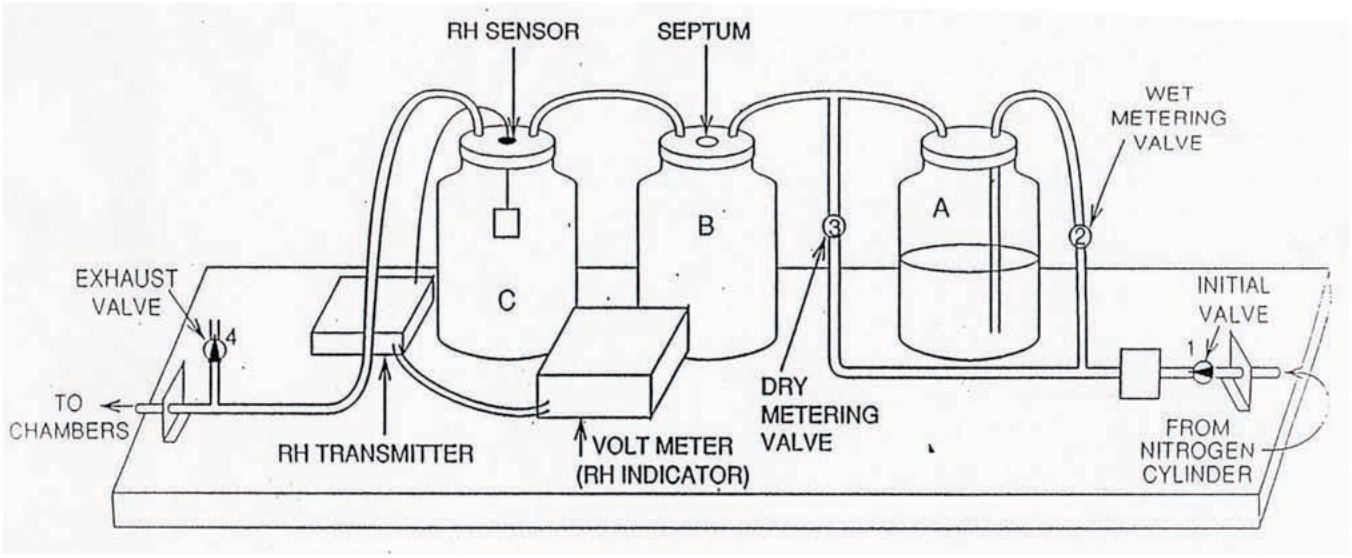

Figure 1. Apparatus for humidifying the nitrogen flow

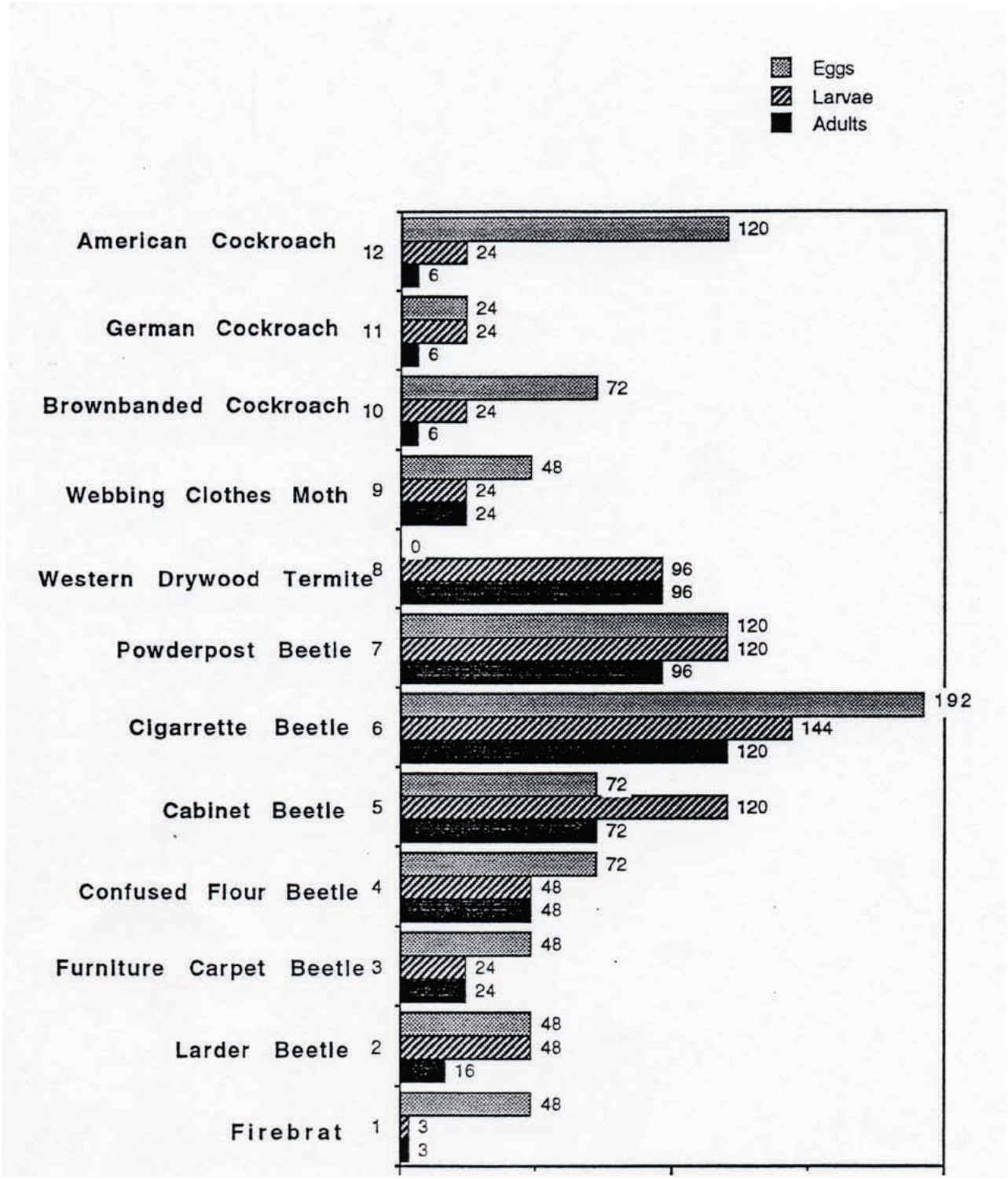

Figure 2. Phase II (open container) mortality with nitrogen (<0.1% oxygen)

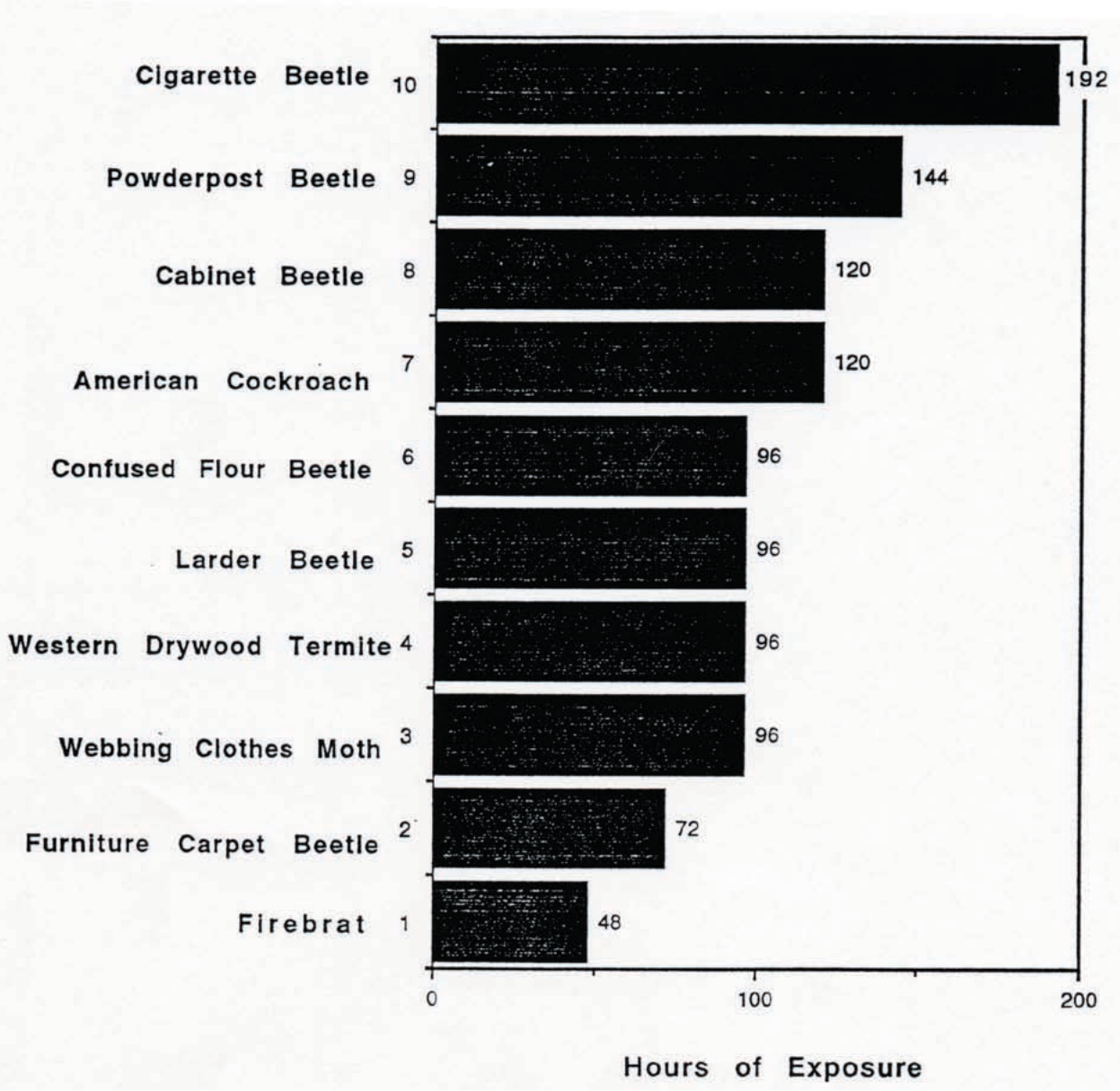

Figure 3. Phase III (closed container) mortality with nitrogen. Most resistant stages tested for each species.