Efficacy of Methoprene Applied at Different Temperatures and Rates on Surface Substrates to Control Eggs and Fifth Instars of *Plodia interpunctella*

EMILY A. JENSON,[1] FRANK H. ARTHUR,[2] AND JAMES R. NECHOLS[1]

J. Econ. Entomol. 102(5): 1992–2002 (2009)

ABSTRACT A series of studies was conducted to determine the effects of temperature on toxicity of the insect growth regulator methoprene to eggs and larvae of *Plodia interpunctella* (Hübner), the Indianmeal moth. When methoprene was applied to Kraft paper at the rate of 0.0003 mg of active ingredient [(AI)] / cm^2, there was little direct toxicity against eggs of *P. interpunctella*, and temperature did not affect insecticide efficacy. Similarly, exposure of eggs on a paperboard surface treated with different rates of methoprene resulted in delayed adult emergence but not a reduction in adult emergence. However, wandering-phase larvae of *P. interpuctella* were susceptible to methoprene, and exposure of larvae for 0.5, 1, and 2 h on different packaging materials resulted in reduced adult emergence. There was variation in emergence depending on the specific surface, but temperature had no effect on resulting adult emergence from exposed larvae. A partial budget analysis described treatment costs and reduction of risks associated with control of eggs and larvae of *P. interpunctella*. Results indicate methoprene could be used in management programs to control larvae of *P. interpunctella*, but eggs may be able to compensate for exposure to methoprene residues on treated surfaces.

KEY WORDS temperature, methoprene, packaging materials, *P. interpunctella*

In recent years there has been increased interest in the use of insect growth regulators (IGRs) to control insect pests in raw grain commodities, processed food warehouses, and in milling and storage facilities (Mondal and Parween 2000, Campbell et al. 2004). Methoprene, a juvenile hormone analog, affects growth and development of immature stages of stored-product insects and prevents maturation to the adult stage (Oberlander et al. 1997, Henrick 2007). Several studies have demonstrated that methoprene incorporated into the diet of stored-product insects will result in reduced or delayed adult emergence (Strong and Diekman 1973, McGregor and Kramer 1975, Loschiavo 1976, Firstenberg and Silhacek 1976, Mian and Mulla 1982, Manzelli 1982). In the United States, methoprene is labeled for direct application to stored grains, as well as a contact insecticide and as an aerosol space application inside mills, warehouses, and indoor food storage facilities.

Plodia interpunctella (Hübner), the Indianmeal moth, can infest many different food products and can occur throughout the manufacturing and distribution process (Doud and Phillips 2000, Johnson et al. 2003, Mahroof and Subramanyam 2006). The number of days required for *P. interpunctella* to complete the life cycle (and subsequent population dynamics) is influenced by several factors, including diet (Johnson et al. 1992), relative humidity (Bell 1975), and temperature (Cline 1970). Temperature can influence fecundity and development of *P. interpunctella* (Tzanakakis 1959, Mohandass et al. 2007), as well as the toxicity of insecticides (Arthur et al. 2004). There are published studies evaluating the IGR hydroprene for toxicity against *P. interpunctella* at different temperatures (Mohandass et al. 2006a,b), but similar studies on methoprene have not been published in the scientific literature.

Eggs of stored-product pest species are often the life stage most tolerant to fumigants (Weller and Morton 2001, Armstrong and Whitehand 2005). The eggs of *P. interpunctella* are relatively heat- and cold-tolerant, making this life stage an important target for control of populations (Mahroof and Subramanyam 2006, Johnson 2007). When an insecticide is applied to packaging material, shelving, flooring, or on spilled products, eggs deposited on that surface could come into contact with the insecticide. The last instar of *P. interpuctella* will often leave the food source and wander in search of a pupation site and thus would come into contact with insecticide residues on a treated surface. This particular life stage is difficult to kill with contact insecticides, especially compared with adult stored-

This article reports the results of research only. Mention of a proprietary product or trade name does not constitute a recommendation or endorsement by the U.S. Department of Agriculture or by Kansas State University.

[1] Department of Entomology, 123 West Waters Hall, Kansas State University, Manhattan, KS 66506.

[2] Corresponding author: USDA–ARS Grain Marketing and Production Research Center, Manhattan, KS 66502 (e-mail: frank.arthur@ars.usda.gov).

product beetles (Arthur, 1997, 1989, 1995). Although incorporation of methoprene into the food source of stored-product insect pests will often prevent adult emergence, this approach may not be an option for use inside a facility with finished food products. An alternative strategy would be to apply methoprene onto the surface of packaging materials.

The economic costs associated with control and treatment of stored-product insects is an area that needs to be more fully developed. Tilley et al. (2007) described an approach called target minimization of total absolute deviations (MOTAD). In this procedure, risk levels are associated with damage risk, and control is assumed to give a reduction in risk levels, and thereby provide an economic benefit. The target MOTAD procedure was used to evaluate different types of heaters for potential disinfestaion of empty grain bins. There are no comparable studies evaluating the costs of insecticide treatment in relation to control of *P. interpunctella.*

Currently, there is little published research regarding efficacy of methoprene as a contact insecticide on packaging materials against *P. interpunctella,* or the economic aspects of control. Therefore, the objectives of this study were to determine 1) whether eggs of *P. interpunctella* are susceptible to methoprene, 2) temperature effects on eggs and larvae exposed to methoprene, and 3) efficacy of methoprene on different packaging surfaces. A further objective was to construct a partial budget analysis for use of methoprene as a control strategy for *P. interpunctella.*

Materials and Methods

General Procedures. The *P. interpunctella* population that was used in all experiments was derived from a laboratory colony established in June 1988 from individuals collected in Riley County, KS, and periodically supplemented with wild-type individuals captured in Riley County. This colony has been maintained on an enriched wheat diet of cracked wheat and wheat shorts (4.4 kg), brewer's yeast (22 g), sorbic and benzoic acid (9.5 g each), honey (240 ml), glycerin (240 ml), and water (120 ml) inside environmental growth chambers (Forma-Scientific, Thermo Fisher Scientific, Waltham, MA) at 27 ± 1°C, ≈50% RH., and in darkness (0:24 [L:D] h) at the USDA–Agricultural Research Service Grain Marketing and Production Research Center (GMPRC) in Manhattan, KS. Voucher specimens have been deposited in the Kansas State University Museum of Entomological and Prairie Arthropod Research under lot no. 208. Experiments were conducted in environmental chambers at the same physical conditions as the colony. Humidity chambers were constructed for the temperature experiment using acrylic boxes with lids that contained a saturated solution of distilled water and NaBr, which maintains a constant 57% RH (Greenspan 1977). Detailed procedures for construction and use of these boxes to maintain relative humidity were described previously (Arthur 2000). The units were ≈26- by 36.5- by 15-cm rectangular boxes with a waffle-style plastic grid cut to fit the bottom. Separate humidity chambers were used for the various methoprene treatments and the untreated controls. Humidity boxes and environmental chambers were selected randomly for each experiment and rerandomized between blocks of each experiment. Temperature was monitored using digital thermometers checked frequently. Temperature and relative humidity also were recorded using a HOBO data logger (Onset Computer Corporation, Bourne, MA) placed in humidity chambers.

Experiment 1. Adult Emergence From Eggs Exposed to Methoprene at Different Temperatures. Treatment arenas were constructed by gluing a 100-mm petri dish inside of a 150-mm petri dish using industrial adhesive. Approximately 75 g of standard wheat diet was placed uniformly into the outer ring. Preliminary tests showed that the amount of diet in each arena was sufficient for normal development of 100 eggs of *P. interpunctella.* The inner petri dish was lined with uncoated brown Kraft paper, obtained from the Smurfit-Stone Company, KS City, MO.. Lids on the 150-mm petri dish were altered to have a 5.1-cm-diameter vent cut in the top with a standard filter paper secured with a nontoxic adhesive to allow air movement. The inner dish had an actual measured area of 62 cm^2. The construction of these treatment arenas allowed for movement between the smaller and larger dish.

The methoprene used in the experiments was a formulation of Diacon II, 33.6% active ingredient (AI), 300 mg (AI)/ml, obtained from Central Sciences International (formerly Wellmark International, Dallas, TX). Individual treatments consisted of a piece of Kraft paper measuring 19 by 13 cm. Solutions of methoprene were formulated at the label rate used in the United States, which was 0.0003 mg (AI)/cm^2, and at half the label rate and double the label rate. The solutions were formulated to give the required amount of active ingredient when 1 ml of the solution was applied to the area of the Kraft paper. Untreated control papers were treated with 1 ml of water. The treatments were done by dispensing 1 ml from the appropriate solution, by using a pipette, onto the Kraft paper, and spreading the liquid over the paper using a glass rod. After the paper for an individual rate was treated, it was cut in circles to fit the 62-cm^2 area of the inner petri dish.

Adult female moths, <48 h old, were placed in a jar for oviposition and eggs were collected for a period of three hours. One-hundred of these *P. interpunctella* eggs were counted using an aspirator with a small glass collection jar and placed in the center of either treated or untreated papers cut to fit inside the inner petri dish. After eggs hatched they were allowed to exit the inner circle to the outer ring which contained the diet. A series of these treated and untreated arenas were constructed and eggs added as described above. The plates were sealed with Parafilm; placed into humidity boxes (separate boxes for treatments and controls); and held at 16, 20, 24, 28, and 32°C.

Preliminary observations indicated that 2–14 d was required for egg hatch, depending on temperature.

After sufficient time for hatching had elapsed, the plates were checked (by unsealing the dishes), and unhatched eggs were counted using a stereomicroscope. Treated and control papers were removed from the plates when at least 75% of the eggs were hatched in each plate, to prevent the larvae from coming into contact with the treated surface after their initial exposure. Days until 75% hatch, first date of adult emergence, the number of days to beginning and ending adult emergence, and total number of adults were recorded. Once adult emergence began, treatment arenas were monitored daily until adult emergence in each plate was complete. The experimental design was a split plot with temperature (growth chamber) representing the whole plot treatment and methoprene treatment serving as the subplot, organized in two randomized complete blocks with four replications each.

Experiment 2. Adult Emergence From Fifth Instars Exposed to Methoprene at Different Temperatures. Effects of temperature on toxicity of methoprene to wandering-phase fifth instars of *P. interpunctella* were evaluated by conducting a trial similar to that described above. Preliminary data showed that 16°C is near the minimum temperature needed for survival; therefore 20, 24, 28, and 32°C were used in this study. In addition, for this experiment methoprene was applied only at the label rate, along with untreated controls, because studies with the IGR hydroprene indicated that short exposure times of these late instars were sufficient to inhibit subsequent adult emergence (Mohandas et al. 2006b; 2006c). Kraft paper was cut and treated in the same manner as described previously; however, after the paper dried, it was not cut but instead folded into packets that allowed for movement of larvae inside the packets. Ten actively wandering larvae were collected with soft forceps and placed in individual treated packets. After the larvae were placed into the packets, the packets were then secured with painter's tape at the seams, and the larvae were held for 0, 0.5, 1, or 2 h. The 0-h exposure time was accomplished by immediately removing the larvae after the packet was sealed, to provide essentially a double control. Upon completion of the exposure period, packets were unsealed and remaining larvae (minus damaged and escaped) were transferred to 150-mm petri dishes, returned to the respective humidity boxes and temperature incubators, and held for adult emergence.

In the second portion of this experiment (we refer to the former as experiment A and to this portion as experiment B), four concentrations (0.5× the label rate, the label rate, 1.5× the label rate of methoprene, along with an untreated control) served as the treatments and an exposure interval of 4 h was added. Temperatures were 22, 27, and 32 ± 1°C, but all other procedures were the same, including the construction and use of the paper packets. Data collected for both temperature experiments included the number of days until first adult emergence and the overall number of emerging adults. The experimental design was a split-plot with the same treatment structure as the egg and temperature experiments. In the first experiment, temperature represented the whole plot treatment and length of exposure interval the subplot treatment. In the second experiment, concentration × exposure interval represented the subplot treatment. Treatments were organized into randomized complete blocks and three replications per experiment were completed.

Data for experiments 1 and 2 (both eggs and larvae) were analyzed using the MIXED Procedure of the Statistical Analysis System (SAS) (SAS Institute 2001). For percentage of survival to the adult stage for each life stage, means and SEs were calculated using the MEANS Procedure of SAS. Means for treatments were separated using the Ryan–Einot–Gabriel–Welsch multiple range test at a significance level of $P = 0.05$ for each treatment combination.

Experiment 3. Adult Emergence From Eggs Exposed to Methoprene on Different Surfaces. In this experiment, the exposure and holding temperature was 27°C, and the methoprene concentration was the label rate compared with controls treated with distilled water. Nine package and surface types were treated: uncoated brown Kraft paper, black paper with a laminated coating, cardboard, cardboard with a laminate coating, plastic pallet wrap, Kraft paper with a waxy coating, concrete, wood and tile. Brown Kraft paper was as described for experiments 1 and 2. Cardboard pet food cartons (for laminated and uncoated cardboard) and multiwalled pet food bags (for laminated paper and waxy paper) were obtained from Ashland Oil (formerly Northwest Coatings, Greensboro, NC). Package materials were chosen to represent the variety of materials that might be encountered in a typical grocery warehouse. These materials were cut to the same uniform size as used in experiments 1 and 2, but the 1 ml of methoprene was applied to the packaging materials using a Badger 100 artist's airbrush (Badger Air-Brush Corporation, Franklin Park, IL) to spray the materials directly onto the packaging materials. After treatment, circular pieces were cut to fit the inner petri dish ring as described previously.

The surface materials (concrete, wood and vinyl floor tile) were chosen as representative of three flooring types in most manufacturing plants and warehouses. Wood, which is a component of shelving and stackable pallets, also represents a surface that might be contacted by *P. interpunctella* (and other stored-product insect pests). Surface materials were constructed in a slightly different manner than what was described for the paper and packaging materials. Concrete treatment arenas were constructed by pouring a thin 10-mm layer of concrete patching material (Rockkite) in the bottom of a 100-mm petri dish. This slurry was water-based and prepared by mixing ≈2000 g of concrete mix with 1.0 liters of tap water. Construction grade plywood (1.25 cm in thickness) and self-adhesive vinyl flooring were cut to fit inside the bottom portion of a petri dish (62-cm^2 area) to make the individual treatments for those surfaces. These flooring surfaces were put in the inner ring of the petri

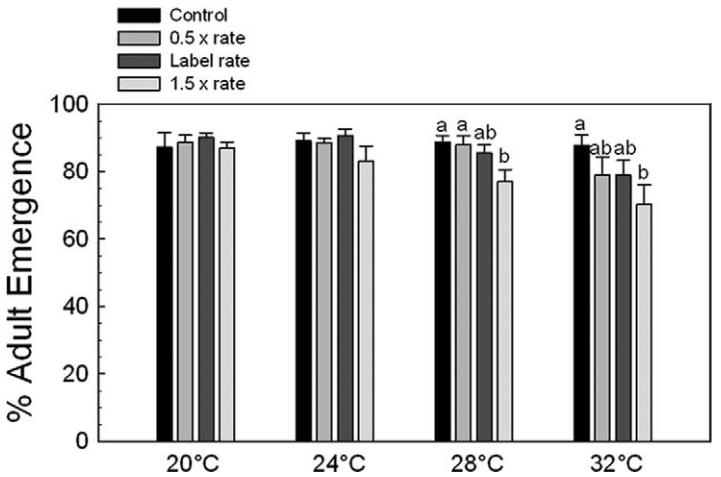

Fig. 1. Adult emergence from eggs of *P. interpunctella* exposed on untreated Kraft paper and paper treated with 0.00015, 0.0003 (label rate), and 0.00045 mg (AI) methoprene/cm^2 and held at 20, 24, 28, and 32°C. Means for treatments within temperature that are denoted by different lower-case letters are significantly different ($P < 0.05$; Ryan–Einot–Gabriel–Welsch multiple range test).

dish exposure arenas as described for experiments 1 and 2. Methoprene was sprayed onto surfaces using the same airbrush technique described above, and all of the experimental arenas were allowed to dry for 3–4 h before the eggs were exposed by placing 20 eggs, 3 h old or less, in the center of the treatment arenas. As described previously, after 75% hatch of eggs the treated materials were removed from the arenas to prevent further exposure. This experimental design was a randomized complete block design conducted in four blocks (replicates) over time. Treatment structure was a 2 by 6 by 3 factorial, with two concentrations (control and insecticide treatment), six packaging types, and three surface material types. The number of emerged adults, total number of days until beginning adult emergence in each treatment and number of days until adults were finished emerging from each treatment, was determined and data analyzed using the SAS Procedures described for experiments 1 and 2.

Experiment 4. Adult Emergence of Fifth Instars Exposed to Methoprene on Different Surfaces. For the evaluations of larval exposures to methoprene on different surfaces, the same packaging materials were used as described for experiment 3, but the concrete, tile, and wood arenas described in experiment 3 were not used. Larval exposure packets were made as described for experiment 2 for the packaging and paperboard surfaces. Temperature was again 27°C and the label rate of methoprene was compared with untreated controls. The various packaging materials were treated using the airbrush technique to spray the methoprene solution directly on the surface, and then the packets were constructed, larvae added, and packets sealed as described for experiment 2. The larvae were exposed for 2, 4, or 8 h and then removed as described for experiment 2 and held on the sealed containers containing food media until the completion of adult emergence. Two complete blocks with three treatment replicates and one control per block were run to reduce experimental variability. Data collection and analysis were conducted in the same way as described previously.

Construction of treatment arenas for testing surface materials for wandering larvae required a different approach to confine the larvae on the treated surfaces and minimize escape. Wooden boxes were constructed using plywood and fastened together with wood adhesive and had an inner surface area approximately equal to 4 by 3.3 by 2.4 cm. To obtain the concrete surface, the concrete material was mixed thick and poured into a box using a metal pan as a mold covered with plastic wrap. For the vinyl tile treatment, self-adhesive vinyl floor tile was cut to size and pressed into the cubes. The box joints of the boxes used for the wood and tile surfaces were smoothed and caulked to minimize larval escape from the boxes. Because of the differences in surface types and box construction, boxes had slightly different inner dimensions for which the insecticide treatment was adjusted accordingly. Lids for the wooden boxes were a 5- by 5-cm piece of plywood; for the concrete treatment, a 5.7- by 4.5 cm poured concrete slab was used; and for the tile, a 5- by 5-cm piece of the vinyl flooring. Boxes were treated and larvae added in the same manner as above. Lids were sealed to the boxes using window caulk which prevented escape but was easily removed after the exposure interval. This experiment was done as two complete blocks with three treatment replicates and one control per block to reduce variability. Because of the differences between the packaging types and the three flooring surfaces, analyses were run separately using the SAS Procedures as described above.

Partial Budget Analysis. Using chemical cost information calculated per 940 m^2 for surface application, a partial budget analysis was done to compare costs of methoprene as a surface treatment for eggs and larvae at several rates and exposure intervals. Economic risk

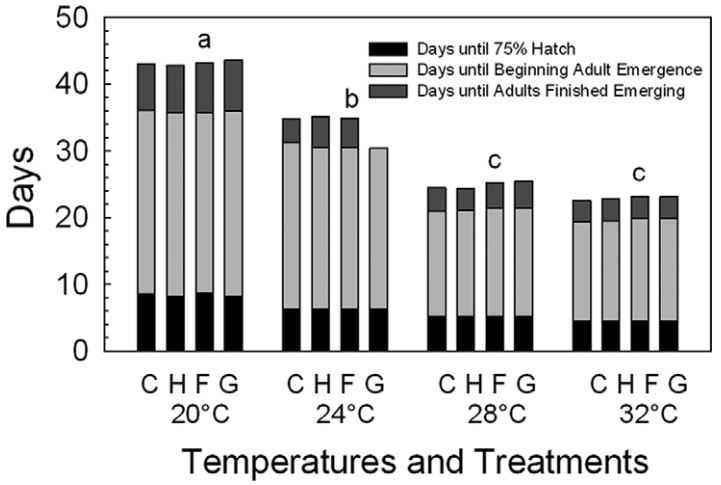

Fig. 2. Days until 75% hatch and beginning and ending adult emergence of eggs of *P. interpunctella* exposed on untreated Kraft paper (C), 0.00015 (H), 0.0003 (F, label rate), and 0.00045 (G) mg (AI) methoprene/cm^2 and held at 20, 24, 28, and 32°C. The C, H, F, and G designations on the x-axis are, respectively, for controls, half the label rate, the full label rate, and greater than the label rate. Means for temperature that are denoted by different lowercase letters are significantly different ($P < 0.05$; Ryan–Einot–Gabriel–Welsch multiple range test). There were no significant differences between treatments; therefore the single letter denotes differences between temperature for the entire group of treatments.

was calculated at 90, 95, and 99% deviations below the target goal, as described in detail in Tilley et al. (2007). Time and equipment cost were fixed and the only variable cost was the cost of the chemical. Risk in this case is the inverse of mortality up to the mortality target, at which it is set to zero. Therefore, the downside risk is mortality below the target level.

Results

Experiment 1. Adult Emergence From Eggs Exposed to Methoprene at Different Temperatures. The main effect, methoprene, was significant for emergence of adults from exposed eggs ($F = 7.0$; df = 3, 150; $P < 0.01$). However, neither temperature ($F = 1.4$; df = 3, 5; $P = 0.35$) nor the methoprene × temperature interaction was significant ($P = 0.45$). Although there was statistical significance, exposure of eggs to methoprene had little direct effect on subsequent adult emergence and there were very few significant pairwise differences in adult emergence across treatments or replications. At 32°C, adult emergence was reduced at the highest rate of methoprene exposure of eggs compared with emergence from eggs exposed on untreated controls (Fig. 1). Temperature had a significant effect on time to first adult emergence ($F = 4.9$;

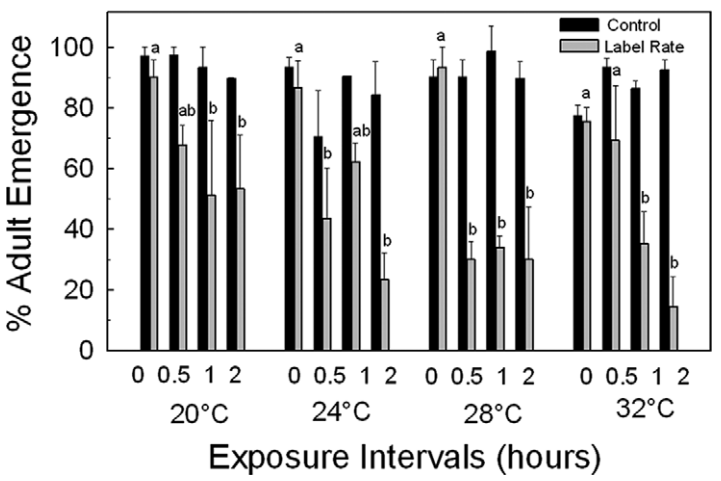

Fig. 3. Adult emergence from larvae of *P. interpunctella* exposed for 0 (untreated controls), 0.5, 1, and 2 h on Kraft paper treated with methoprene applied at the label rate of 0.0003 mg (AI) methoprene/cm^{2}and held at 20, 24, 28, and 32°C. Means for exposure intervals within temperature followed by different lowercase letters denote significant differences between those exposure intervals with respect to adult emergence ($P < 0.05$; Ryan—Einot–Gabriel–Welsch multiple range test). There were no statistical differences in survival of untreated controls at any temperature ($P \geq 0.05$).

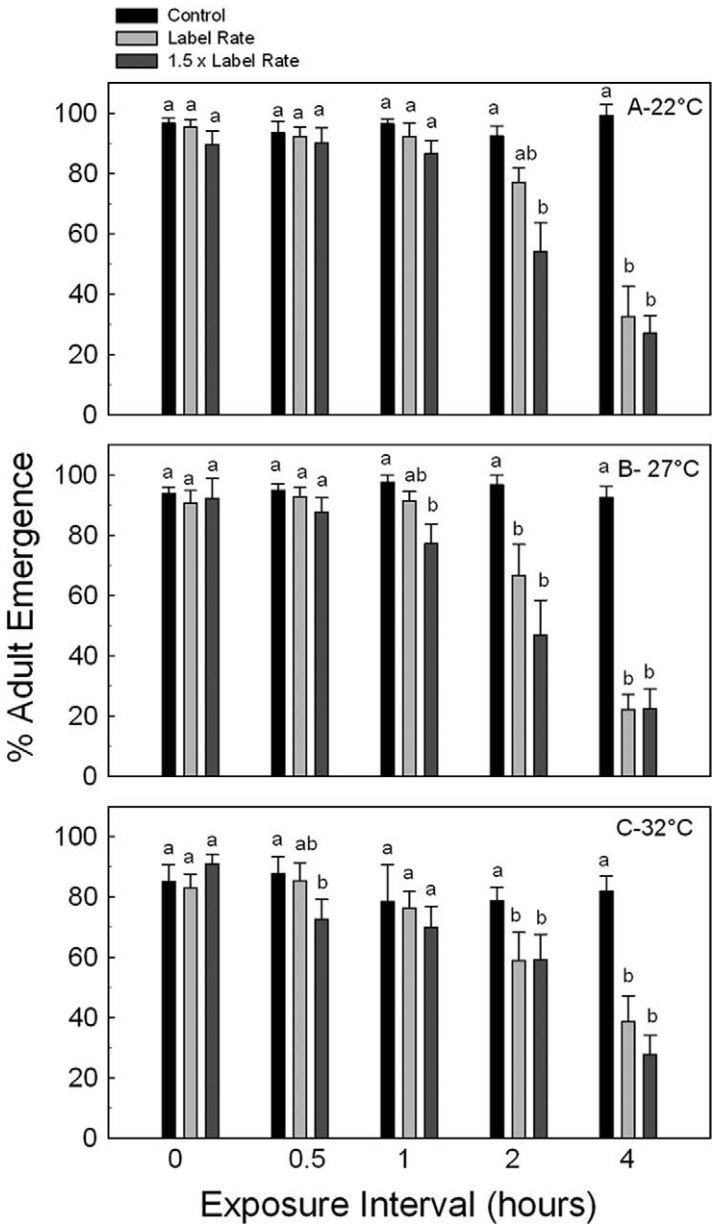

Fig. 4. Adult emergence of larvae of *P. interpunctella* exposed for 0 (untreated controls), 0.5, 1, 2, and 4 h on untreated Kraft paper (second control) and Kraft paper treated applied at the 0.0003 (label rate) and 0.0045 mg (AI) methoprene/cm^2 and held at 22°C (A), 27°C (B), or 32°C (C). Means within each exposure interval followed by different lowercase letters indicate significant differences among the three treatments ($P < 0.05$); Ryan–Einot–Gabriel–Welsch multiple range test).

df = 3, 6; $P = 0.047$), but adult emergence from exposed eggs in the methoprene treatments was not significant ($F = 0.4$; df = 3, 167; $P = 0.78$) nor was the temperature b× methoprene interaction ($P = 0.66$) (Fig. 2). However, both the temperature and the rate of methoprene at which the eggs were exposed were significant with respect to the time for final adult emergence ($F = 10.0$; df = 3, 6; $P < 0.01$ and $F = 4.4$; df = 3, 167; $P < 0.01$, respectively). Although the interaction was not significant ($P = 0.92$), it seemed that exposure of *P. interpunctella* eggs to methoprene delayed the normal time required for the completion of adult emergence (Fig. 2).

Experiment 2. Adult Emergence of Fifth Instars Exposed to Methoprene at Different Temperatures. Both treatment and exposure interval were significant ($P < 0.01$) with respect to emergence of adults from exposed larvae ($F = 107.0$; df = 1, 64 and $F = 11.6$; df = 3, 64); but temperature was not significant ($F = 0.0$; df = 3, 64; $P = 1.0$). The treatment by exposure in-

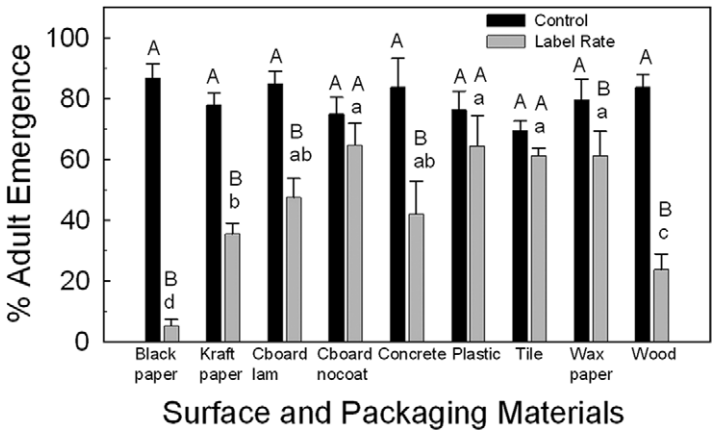

Fig. 5. Adult emergence from eggs exposed on nine different packaging and surface types treated with methoprene at the label rate of 0.0003 mg (AI) methoprene/cm^2 and held at 27°C. Means followed by different lowercase letters indicate differences between surface type treatment and means followed by different uppercase letters indicate differences between treatments and controls ($P < 0.05$; Ryan–Einot-Gabriel–Welsch multiple range test).

teraction was significant ($P < 0.01$), but there were no other significant interactions ($P \geq 0.05$). As exposure interval increased, adult emergence from those exposed larvae generally decreased (Fig. 3). In contrast to the egg stage, the larvae seemed to be susceptible to methoprene. Although temperature did not significantly affect survival, the greatest mortality occurred at the highest temperature (32°C).

For experiment B (which was run at 22, 27, and 32°C), temperature, treatment, and exposure interval all significantly affected adult emergence ($F = 9.1$, df = 2, 4, $P = 0.03$; $F = 72.2$, df = 2, 354, $P < 0.01$; and $F = 79.5$, df = 4, 354, $P < 0.01$, respectively). The treatment by exposure interaction was significant ($P < 0.01$), but no other interactions were significant ($P \geq 0.05$). At 22°C (Fig. 4A), adult emergence at the label rate was lower than in untreated controls only at the 4-h exposure, whereas at 27 and 32°C (Fig. 4B and C) adult emergence from larvae exposed for two and 4 h was significantly lower than the controls. The overall pattern seemed to indicate lower emergence at 32°C compared with 22 and 27°C. However, even at the 4-h exposure, adult emergence on both methoprene treatments was ≈20%, indicating a longer exposure interval would be necessary to give a complete reduction in adult emergence.

Experiment 3: Adult Emergence From Eggs Exposed on Different Surfaces Treated With Methoprene. Both main effects, surface type/packaging materials and level of methoprene treatment (either the label rate or distilled water control), were significant at $P < 0.01$ with respect to adult emergence ($F = 4.1$; df = 8, 51 and $F = 150.3$; df = 1, 51, respectively). There was also a significant interaction between these two factors ($P < 0.01$). Survival to adults was lowest when methoprene was applied to black paper with a laminate coating and second lowest to wood (5.2 ± 2.2 and 23.7 ± 5.2%, respectively) (Fig. 5). Differences in adult emergence on these treated surfaces also were greatest compared with their untreated controls. Adult emergence was greatest from eggs exposed to methoprene on plastic, tile, wax paper, and uncoated cardboard (60–63%). On most of these treated surfaces, adult emergence was not significantly different from that of the untreated controls ($P \geq 0.05$) (Fig. 5).

Experiment 4: Adult Emergence From Fifth Instars Exposed to Methoprene on Different Surfaces. In the first set of studies involving different treated surfaces, including packaging types, both methoprene and surface significantly affected survival to adult emergence ($F = 137.9$; df = 1, 177; $P < 0.01$ and $F = 5.2$; df = 5, 111; $P < 0.01$, respectively), but exposure interval did not ($F = 0.2$; df = 2, 177; $P = 0.85$). There was a significant interaction between methoprene and packaging type ($P < 0.01$). For all surfaces, differences between treatments and controls became larger as the exposure interval increased from 2 h (Fig. 2A), to 4 h (Fig. 6B), and then to 8 h (Fig. 6C).

Adult emergence was consistently the lowest on laminated cardboard compared with its control across all exposure intervals (Fig. 6). When larvae were exposed on concrete, wood, and tile, adult emergence was significantly reduced both by methoprene treatment and the length of exposure at $P < 0.01$ ($F = 76.2$; df = 1, 53 and $F = 5.7$; df = 2, 53, respectively). However, emergence did not differ among the three surfaces ($F = 1.6$; df = 1, 53; $P = 0.20$) (Fig. 7).

Partial Budget Analysis. Results show that for control of the egg stage of *P. interpunctella,* by using the no action (untreated control) strategy is virtually as effective as either half the label rate or the label rate (Table 1). Risk decreases with increased mortality but decreases with an increase in the risk threshold. For example, reading across the line for the untreated control, at the 90% risk level there is a 78.3% chance of getting the mortality level of 12.7% if nothing is done, i.e., no treatment. If the risk levels increase to 95 and 99%, then the probability levels of achieving 12.7% control increase to 83.3 and 87.3%, respectively. As mortality or

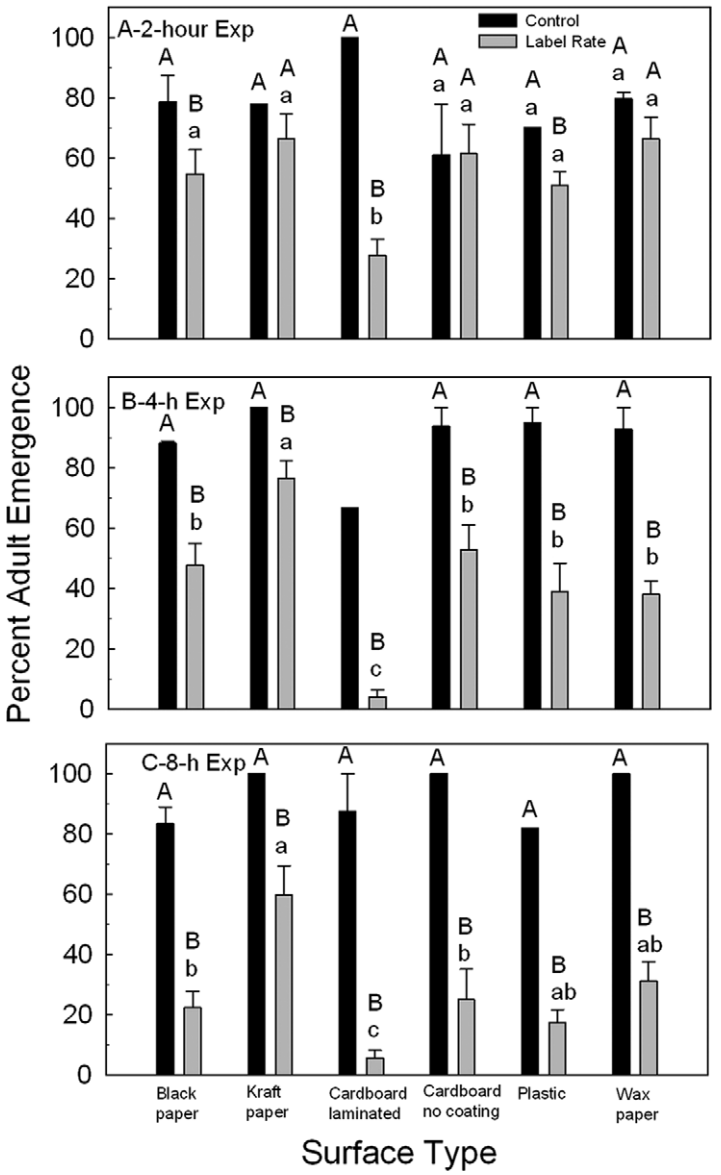

Fig. 6. Adult emergence from larvae exposed on six different packaging materials treated with methoprene at the label rate of 0.0003 mg (AI) methoprene/cm^2 for 2 h (A), 4 h (B), or 8 h (C) and then removed from the surfaces and held at 27°C until adult emergence. Within each exposure interval, means followed by different lowercase letters indicate differences between surface type treatment and means followed by different uppercase letters indicate differences between treatments and controls ($P < 0.05$; Ryan–Einot–Gabriel–Welsch multiple range test).

control increases downward in the table under each of the three risk levels, risk decreases with this increase mortality. The same pattern can be followed for each of the listed treatments, and the economic analysis shows that methoprene provides very little appreciable benefit for control of eggs of *P. interpunctella.*

However, for control of wandering-phase larvae, methoprene is much more effective and with increasing exposure interval, risk decreases through the increased level of control, but total chemical cost remains the same (Table 2). The decrease in risk levels is seen by an increase in mortality, or a decrease in the emergence of adults from exposed larvae, as the exposure interval increased. Again, reading across the table, using the highest mortality value of 69.7%, at 90, 95, and 99% risk, the probability of achieving the specified mortality is 20.2, 25.3, and 29.3%, respectively.

Discussion

Overall, temperature does not affect the efficacy of methoprene as a surface treatment for control of *P.*

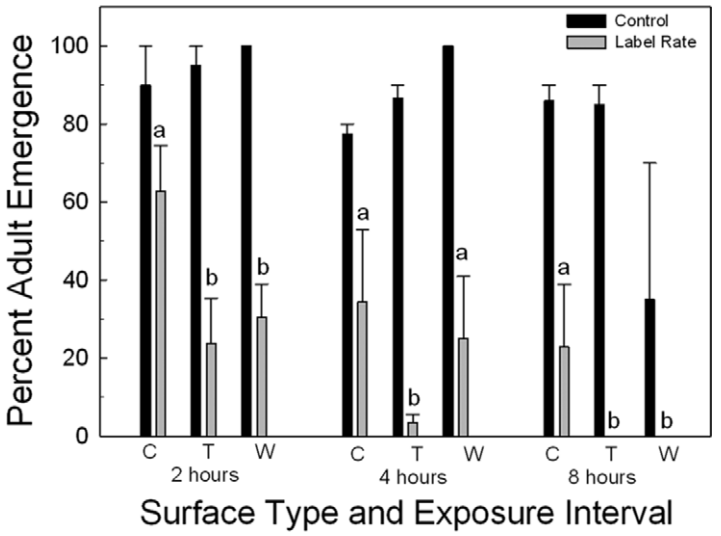

Fig. 7. Adult emergence from larvae exposed on concrete (C), tile (T), and wood (W) treated with methoprene at the label rate of 0.0003 mg (AI) methoprene/cm^2; exposed for 2, 4, and 8 h; and held at 27°C until adult emergence. Treatments were different from controls in all cases, and means within each exposure interval followed by different lowercase letters indicate differences between surface type ($P < 0.05$; Ryan–Einot–Gabriel–Welsch multiple range test).

interpunctella. These results are similar to those for the IGR hydroprene (Mohandass et al. 2006b). However, the relatively low control of eggs and wandering-phase larvae exposed to surface applications of methoprene contrasts with results reported by Arthur (2004) and Chanbang et al. (2007) with eggs and early instars of the lesser grain borer, *Rhyzopertha dominica* (F.), exposed on wheat, *Triticum aestivum* L., and rice, *Oryza sativa* L., treated with methoprene. Our results also differ from those of Mohandass et al. (2006b,c) which established efficacy of hydroprene as a surface treatment for eggs and wandering-phase larvae of *P. interpunctella.* Hydroprene is also effective against larvae of the red flour beetle, *Tribolium castaneum* (Herbst), exposed on different treated surfaces (Toews et al. 2005). The lack of control of eggs exposed on a surface treated with methoprene is surprising because, like hydroprene, it is an IGR with a similar mode of action.

Based on our findings, surface treatment with methoprene may not provide a reliable strategy for controlling eggs of *P. interpunctella,* because overall adult emergence from these exposed eggs was ≈78–88% in all treatments compared with 88% adult emergence from eggs in the control treatments. Fifth instars were more susceptible than eggs. However, survival to the adult stage was still high (≈54%) compared with the untreated controls (≈90%). In fact, given the low tolerance for *P. interpunctella* in packaged food products, this level of adult survival would probably be considered unacceptable by practical standards. Adult emergence was reduced when larvae were exposed for 2 h or more at temperatures ranging from 22 to 32°C; but survival was still ≈51%. Our results suggest that mortality of wandering-phase larvae may be increased with repeated or prolonged exposure, but more data are needed to verify this assumption.

Although processed food manufacturers may not be directly responsible for the damage done to packaging

Table 1. Summary of costs and risk levels for methoprene surface treatment compared with the untreated controls in experiment 1 (eggs, temperature, and rate of methoprene)

Treatment	% mortality	90% risk	95% risk	99% risk	Cost ($)
Control	12.7a	78.3	83.3	87.3	0.00
0.5× label	12.2a	77.8	82.7	86.8	0.78
Label rate	15.6a	74.4	79.3	83.4	1.56
1.5× label	21.8b	68.1	73.1	77.1	2.34

The label rate is 0.0003 mg (AI)/cm^2. Letters denote statistical difference at $P = 0.05$; means for percentage of mortality of eggs (the inverse of emergence to the adult stage) are separated using statistical procedures described for the individual experiment. Risk is presented as three thresholds: 90, 95, and 99% mortality above which risk is set equal to zero. Costs are based in U.S. dollars per 940 m^2.

Table 2. Costs and risk levels for methoprene surface treatment compared with the untreated controls in experiment 2A (larvae, label rate for methoprene of 0.0003 mg [AI]/cm^2; exposure intervals of 0, 0.5, 1, and 2 h)

Treatment (h)	% mortality	90% risk	95% risk	99% risk	Cost ($)
Control	10.4a	79.6	84.5	88.5	0.00
0	13.6a	76.4	81.4	85.3	1.56
0.5	47.4b	42.5	47.5	51.5	1.56
1.0	54.4b	35.6	40.6	44.6	1.56
2.0	69.7b	20.2	25.3	29.3	1.56

Letters denote statistical difference at $P = 0.05$; means for percentage of mortality of larvae (the inverse of emergence to the adult stage) are separated using statistical procedures described for experiment 2A. Risk is presented as three thresholds: 90, 95, and 99% mortality above which risk is set equal to zero. The cost is calculated as 1.56 U.S. dollars per 940 m^2, by using the cost for treatment with the label rate of methoprene.

in shipment, they may absorb some of the costs of insect infestations (Highland 1978). Although it is difficult to quantify the economic losses caused by stored-product insects, there also may be an accompanying quality loss that cannot be easily quantified as a dollar value. There are several options for limiting the incidence of insects entering finished product packages; these include the use of repellents, odor barriers, insecticides and insect-resistant packaging (Highland 1978, Mullen 2000, Mullen and Mowery 2003). Surface and package material treatment with methoprene or similar IGRs may be an effective control strategy for other stored product insects, such as flour beetles (Arthur 2001). However, these surface treatments may not give complete protection against *P. interpunctella.* Although the use of methoprene on finished product packaging materials may not prevent entry into packages, it could partially suppress infestations by preventing subsequent generations from infesting other packages during the shipment or in the warehouse.

Although there are a number of literature references describing tests in which adult stored-product beetles have been exposed on surfaces treated with different contact insecticides (Arthur 2008), there are fewer studies with evaluating the effect of surface on toxicity of insecticides to *P. interpunctella.* In our test, we generally had greater emergence of larvae exposed on concrete treated with methoprene compared with tile and wood. In addition, there are no comparable studies in which methoprene has been applied to packaging materials and assessed for efficacy against larvae of *P. interpunctella* exposed on packaging surfaces. Although direct application of methoprene on package surfaces through contact insecticides may not be a labeled use at present, it is possible that incorporation of methoprene into packaging materials could be tested in the future, as well as further research on direct application of methoprene on packaging surfaces to control other stored-product insects.

Methoprene is considered to be relatively stable over a long period in grain bins and over a wide range of temperatures (Arthur et al. 1990, Daglish et al. 1995, Daglish and Wallbank 2005); so, the relatively high adult emergence observed in our study is probably not related to degradation. However, there may be other reasons for the high survival of *P. interpuctella* eggs and larvae on treated package materials. For example, differences in surface materials may be an important factor because absorption of methoprene into the package material may not leave enough active ingredient on the surface to produce an effect on neonates and larvae. This may correspond to the reduced adult emergence from larvae of *P. interpunctella* on nonporous materials such as vinyl flooring tile and laminated paper, and hence greater efficacy, compared with porous materials. The low adult emergence from eggs exposed on the sprayed surfaces also may be attributed to the application method (airbrush versus dispersing with a glass rod), because the airbrush could have provided a more even distribution. Other options to control *P. interpunctella* include aerosol applications of insecticides. These treatments are effective in the control of flour beetles and also give some indication of suppression of *P. interpunctella* (Arthur 2008). Although methoprene as a surface treatment is not likely to replace aerosol insecticides or fumigants for control of this pest, it could be a useful part of an overall integrated pest management program. The partial budget analysis showed that the cost of methoprene treatment is relatively small compared with the risks of insect infestation and would provide a direct economic benefit through reduction of the populations through treatments directed at the wandering phase of *P. interpunctella* larvae.

Acknowledgments

We thank B. D. Barnett and C. Smith for technical assistance and J. W. Whitworth for reviewing the manuscript before journal submission. This paper is contribution 09-229-J of the Kansas Agricultural Experiment Station, Kansas State University, Manhattan, KS.

References Cited

Armstrong, J. W., and L. C. Whitehand. 2005. Effects of methyl bromide concentration, fumigation time, and fumigation temperature on Mediterranean and oriental fruit fly (Diptera: Tephritidae) egg and larval survival. J. Econ. Entomol. 98: 1116–1125.

Arthur, F. H. 1989. Pests of stored peanuts: toxicity and persistence of chlorpyrifos-methyl. J. Econ. Entomol. 82: 660–664.

Arthur, F. H. 1995. Susceptibility of fifth-instar Indianmeal moth and almond moth (Lepidoptera: Pyralidae) to cyfluthrin residues on peanuts. J. Entomol. Sci. 30: 319–323.

Arthur, F. H. 1997. Residual susceptibility of *Plodia interpunctella* to deltamethrin dust: effects of concentration and time of exposure. J. Stored Prod. Res. 33: 313–319.

Arthur, F. H. 2000. Toxicity of diatomaceous earth to red flour beetles and confused flour beetles (Coleoptera: Tenebrionidae): effects of temperature and relative humidity. J. Econ. Entomol. 93: 526–532.

Arthur, F. H. 2001. Susceptibility of last instar red flour beetles and confused flour beetles (Coleoptera: Tenebrionidae) to hydroprene. J. Econ. Entomol. 94: 772–779.

Arthur, F. H. 2004. Evaluation of methoprene alone and in combination with diatomaceous earth to control *Rhyzopertha dominica* (Coleoptera: Bostrichidae) on stored wheat. J. Stored Prod. Res. 40: 485–498.

Arthur, F. H. 2008. Aerosol distribution and efficacy in a commercial food warehouse. Insect Sci. 15: 133–140.

Arthur, F. H., J. E. Throne, and R. A. Simonaitis. 1990. Chlorpyrifos-methyl degradation and biological efficacy toward maize weevils (Coleoptera: Curculionidae) on corn stored at four temperatures and three moisture contents. J. Econ. Entomol. 84: 1926–1932.

Arthur, F. H., B. Yue, and G. W. Wilde. 2004. Susceptibility of stored-product beetles on wheat maize treated with thiamethoxam: effects of concentration, exposure interval, and temperature J. Stored Prod. Res 40: 527–546.

Bell, C. H. 1975. Effects of temperature and humidity on development of four pyralid moth pests of stored products. J. Stored Prod. Res. 11: 167–175.

Campbell, J. F., F. H. Arthur, and M. A. Mullen. 2004. Insect management in food processing facilities, pp. 240–295. *In*

Advances in Food and Nutrition Research, vol. 48. Elsevier, New York.

Chanbang, Y., F. H. Arthur, G. W. Wilde, and J. E. Throne. 2007. Efficacy of diatomaceous earth and methoprene, alone and in combination, against *Rhyzopertha dominica* (F.) (Coleoptera: Bostrichidae) in rough rice. J. Stored Prod. Res. 43: 396–401.

Cline, L. D. 1970. Indian-meal moth egg hatch and subsequent larval survival after short exposures to low temperatures. J. Econ. Entomol. 63: 1081–1083.

Daglish, G. J., and B. E. Wallbank. 2005. Efficacy of diflubenzuron plus methoprene against *Sitophilus oryzae* and *Rhyzopertha dominica* in stored sorghum. J. Stored Prod. Res. 41: 353–360.

Daglish, G. J., M. Eelkema, and L. M. Harrison. 1995. Chlorpyrifos-methyl plus either methoprene or synergized phenothrin for control of Coleoptera in maize in Queensland, Australia. J. Stored Prod. Res. 31: 235–241.

Doud, C. W., and T. W. Phillips. 2000. Activity of *Plodia interpunctella* (Lepidoptera: Pyralidae) in and around flour mills. J. Econ. Entomol. 93: 1842–1847.

Firstenberg, D. E., and D. L. Silhacek. 1976. Food consumption by *Plodia interpunctella* feeding on diets containing insect growth regulars. J. Entomol. Sci. 11: 78–82.

Greenspan, L. 1977. Humidity fixed points of binary saturated aqueous solutions. J. Res. Natl. Bur. Stds. 81A: 89–96.

Henrick, C. A. 2007. Methoprene. J. Am. Mosq. Control Assc. 23: 225–239.

Highland, H. A. 1978. Insect resistance of food packages: a review. J. Food Process. Preserv. 2: 123–130.

Johnson, J. A. 2007. Survival of Indianmeal moth and navel orangeworm (Lepidoptera: Pyralidae) at low temperatures. J. Econ. Entomol. 100: 1482–1488.

Johnson, J. A., P. L. Wofford, and L. C. Whitehand. 1992. Effect of diet and temperature on development rates, survival, and reproduction of the Indianmeal moth (Lepidoptera: Pyralidae). J. Econ. Entomol. 85: 561–566.

Johnson, J. A., S. Wang, and J. Tang. 2003. Thermal death kinetics of fifth-instar *Plodia interpunctella* (Lepidoptera: Pyralidae). J. Econ. Entomol. 96: 519–524.

Loschiavo, S. R. 1976. Effects of the synthetic insect growth regulators methoprene and hydroprene on survival, development or reproduction of six species of stored-products insects. J. Econ. Entomol. 69: 395–399.

Mahroof, R., and Bh. Subramanyam. 2006. Susceptibility of *Plodia interpunctella* (Lepidoptera: Pyralidae) developmental stages to high temperatures used during structural heat treatments. Bull. Entomol. Res. 96: 539–545.

Manzelli, M. A. 1982. Management of stored-tobacco pests, the cigarette beetle (Coleoptera: Anobiidae) and tobacco moth (Lepidoptera: Pyralidae), with methoprene. J. Econ. Entomol. 75: 721–723.

McGregor, H. E., and K. J. Kramer. 1975. Activity of insect growth regulators, hydroprene and methoprene, on wheat and corn against several stored-grain insects. J. Econ. Entomol. 68: 668–670.

Mian, L. S., and M. S. Mulla. 1982. Biological activity of IGRs against four stored-product coleopterans. J. Econ. Entomol. 75: 80–85.

Mohandass, S., F. H. Arthur, K. Y. Zhu, and J. E. Throne. 2006a. Hydroprene: mode of action, current status in stored-product pest management, insect resistance, and future prospects. Crop Prot. 25: 902–909.

Mohandass, S., F. H. Arthur, K. Y. Zhu, and J. E. Throne. 2006b. Hydroprene prolongs developmental time and increases mortality of Indianmeal moth (Lepidoptera: Pyralidae) eggs. J. Econ. Entomol. 99: 1007–1016.

Mohandass, S., F. H. Arthur, K. Y. Zhu, and J. E. Throne. 2006c. Hydroprene prolongs developmental time and increases mortality in wandering-phase Indianmeal moth (Lepidoptera: Pyralidae) larvae. J. Econ. Entomol. 99: 1509–1519.

Mohandass, S., F. H. Arthur, K. Y. Zhu, and J. E. Throne. 2007. Biology and management of *Plodia interpunctella* (Lepidoptera: Pyralidae) in stored products. J. Stored Prod. Res. 43: 302–311.

Mondal, K.A.M.S.H., and S. Parween. 2000. Insect growth regulators and their potential in the management of stored-product insect pests. Integr. Pest Manage. Rev. 5: 255–295.

Mullen, M. A. 2000. Insect-resistant packaging. Int. Food Hyg. 11: 13–14.

Mullen, M. A., and S. V. Mowery. 2003. Packaging, pp. 423–433. *In* Y. H. Hui, B. L. Bruinsma, J. R. Gorham, W. K. Nip, P. S. Tong, and P. Ventresca [eds.], Food plant sanitation. Marcel Dekker, New York.

Oberlander, H., D. L. Silhacek, E. Shaaya, and I. Ishaaya. 1997. Current status and future perspectives of the use of insect growth regulators for the control of stored product insects. J. Stored Prod. Res. 33: 1–6.

SAS Institute. 2001. The SAS system for Windows, release 8.0 SAS Institute, Cary, NC.

Strong, R. G., and J. Diekman. 1973. Comparative effectiveness of fifteen insect growth regulators against several pests of stored products. J. Econ. Entomol. 66: 1167–1173.

Tilley, D. R., M. R. Langemeir, M. Casada, and F. H. Arthur. 2007. Cost and risk analysis of heat and chemical treatments. J. Econ. Entomol. 100: 604–612.

Toews, M. D., J. F. Campbell, F. H. Arthur, and M. West. 2005. Monitoring *Tribolium castaneum* (Coleoptera: Tenebrionidae) in pilot-scale warehouses treated with residual applications of (*S*)-hydroprene and cyfluthrin. J. Econ. Entomol. 98: 1391–1398.

Tzanakakis, M. E. 1959. An ecological study of the Indianmeal moth *Plodia interpunctella* (Hübner) with emphasis on diapause. Hilgardia 29: 205–246.

Weller, G. L., and R. Morton. 2001. Fumigation with carbonyl sulfide: a model for the interaction of concentration, time and temperature J. Stored Prod. Res 37: 383–398.

Received 3 February 2009; accepted 23 May 2009.