Susceptibility of Various Life Stages of *Rhyzopertha dominica* (Coleoptera: Bostrichidae) to Flameless Catalytic Infrared Radiation

MOSES KHAMIS, BHADRIRAJU SUBRAMANYAM, PAUL W. FLINN,[1] HULYA DOGAN,
ABIGAIL JAGER,[2] AND JEFFREY A. GWIRTZ

Department of Grain Science and Industry, Kansas State University, Manhattan, KS 66506

J. Econ. Entomol. 103(4): 1508–1516 (2010); DOI: 10.1603/EC10069

ABSTRACT In laboratory experiments, a flameless catalytic infrared emitter, fueled by propane, was used to disinfest hard red winter wheat, *Triticum aestivum* L., containing different life stages of the lesser grain borer, *Rhyzopertha dominica* (F.), an economically important insect species associated with stored wheat in Kansas. The emitter generates infrared radiation in the 3–7-μm range. The life stages of *R. dominica* exposed to infrared radiation included eggs, larvae in different stages of development, pupae, and 2-wk-old adults. A noncontact infrared thermometer measured grain temperatures continuously during exposures of infested wheat to infrared radiation. The grain temperatures attained were influenced by wheat quantity; distance from the emitter; and exposure time, which in turn influenced effectiveness against various life stages of *R. dominica*. In general, higher grain temperatures were attained in 113.5 g of wheat as opposed to 227.0 g, and at 8.0 cm from the emitter surface rather than at 12.7 cm, and during a 60-s exposure compared with a 45-s exposure. Logistic regression indicated the probability of death of various life stages of *R. dominica* was temperature dependent. The log odds ratios showed old larvae were less susceptible to infrared radiation than young larvae. Approximately ≥94% mortality of all *R. dominica* life stages occurred when using 113.5 g of wheat, exposed for 60 s at a distance of 8.0 cm from the emitter, resulting in mean ± SE wheat temperatures that ranged between 107.6 ± 1.4 and 113.5 ± 0.5°C. Our results with small grain quantities show flameless catalytic infrared technology to be a promising tool for disinfestation of stored wheat.

KEY WORDS *Rhyzopertha dominica*, infrared radiation, nonchemical method, efficacy assessment

Stored-grain insects have been historically managed by chemical methods (Martin et al. 1997). The prolonged use of chemicals has resulted in development of insecticide resistance in several species of stored-grain insects (Sinha and Watters 1985, Subramanyam and Hagstrum 1996). Therefore, newer and environmentally benign technologies need to be explored as alternatives to traditionally used insecticides for managing insects associated with stored grain. Some of these alternatives include heat treatment (Beckett and Morton 2003), modified atmospheres (McGaughey and Akins 1989), grain chilling (Rulon et al. 1999), spinosad (Flinn et al. 2004), and infrared radiation.

The use of infrared radiation for disinfestation of grain was explored between the 1960s and 1980s. Tilton et al. (1961, 1983), Tilton and Schroeder (1961, 1963), Cogburn (1967), Cogburn et al. (1971), Kirkpatrick and Tilton (1972), Kirkpatrick et al. (1972), Kirkpatrick (1975), and Kirkpatrick and Cagle (1978) evaluated the effectiveness of infrared radiation (3–7 μm range) against internal and external stored-grain insects in soft wheat and paddy rice. The infrared radiation used by these researchers was generated when propane gas was burnt over ceramic tiles producing >14.1 kW/h (≈48,000 BTU/h) of heat energy. With the gas-fired infrared emitters, temperatures as high as 930°C at the emitter surface were attained. Such high temperatures and flames are not safe in grain storage and handling facilities due to explosion hazards. In previous research, grain temperatures were not measured in "real-time," and temperatures were measured after infrared exposure, possibly resulting in underestimating the temperatures attained. Furthermore, life stages of insects, especially internal developers, exposed to infrared radiation were not accurately confirmed.

Flameless catalytic infrared radiation is a new technology developed by Catalytic Drying Technologies LLC in Independence, KS (www.catalyticdrying.com). The flameless catalytic infrared radiation is produced when propane or natural gas chemically reacts with oxygen in the presence of a platinum

---

This article presents research results only. Mention of a proprietary product name does not constitute an endorsement for its use by Kansas State University or USDA–ARS.

[1] USDA–ARS, Center for Grain and Animal Health Research, Manhattan, KS 66502.

[2] Visiting Professor, Department of Statistics, Kansas State University, Manhattan, KS 66506.

catalyst at temperatures below ignition (Gabel et al. 2006, Pan et al. 2008). This technology is best suited for drying various commodities, and one study examined the combined benefits of drying and disinfestation of rough rice (Pan et al. 2008). Infrared radiation can be used during baking, and for inactivating enzymes and microorganisms (Sandu 1986, Gabel et al. 2006). At the mid-infrared range (3–7 μm), water, protein, sugars and nucleic acids have maximum infrared absorption (Sandu 1986, Pan et al. 2008). The absorbed energy causes these chemicals to vibrate at a frequency of 8.8×10^7 to 1.7×10^8 MHz, resulting in an increase in temperature (Fasina et al. 1999). In infested grain, insects have greater moisture content than grain, and as a result the former may receive a lethal dose of infrared energy (Frost et al. 1944).

In the present investigation, the effectiveness of a benchtop flameless catalytic infrared emitter was evaluated against all life stages of the lesser grain borer, *Rhyzopertha dominica* (F.) (Coleoptera: Bostrichidae), a cosmopolitan pest of stored grains (Sinha and Watters 1985). Three factors that influence infrared intensity, as indicated by the measured temperature, were evaluated. These factors included grain quantity (113.5 and 227.0 g), distance from the emitter (8.0 and 12.7 cm), and exposure time (45 and 60 s).

Materials and Methods

Insect Rearing. Cultures of *R. dominica*, obtained from the USDA–ARS, Stored-Product Insect Research Unit, Manhattan, KS, were reared in a laboratory growth chamber (model I-36 VL; Percival Scientific, Perry, IA) in the Department of Grain Science and Industry, Kansas State University, Manhattan, KS, at 28°C, 65% RH, and a photoperiod of 14:10 (L:D) h on organic hard red winter wheat (variety Jagger) purchased from Heartland Mills in Marienthal, KS. These insects have been in rearing in the Department of Grain Science and Industry for 4 yr before use in this study.

Identifying Various Life Stages of *R. dominica*. Wheat ($\approx$250 g) was equilibrated to 12% moisture by placing it at 28°C and 65% RH for 1 wk in 0.45-liter glass jars with wire-mesh screened lids. Equilibrated wheat (5 g) was placed in each of five 24-ml plastic vials, and the wheat in vials was infested with 20 unsexed adult *R. dominica* and kept at the same environmental conditions. After 72 h, all adults were removed, and the grain contents, including eggs, were reintroduced back into the vials. The 5-g samples in the five vials were subjected to radiographic analysis (X-rays); 72 h after adult infestation (day 0); and on days 7, 14, 21, 24, and 28 after day 0. Adults that emerged daily from wheat in the vials were counted until cessation of adult emergence.

Kernels from each vial were spread into a single layer on a sample holder and subjected to X-rays from a Faxitron X-ray device (model MX-20, Faxitron X-Ray Corporation, Wheeling, IL). The voltage setting was 28 kV, and the time to acquire images using a digital camera (model MX-20-44, Bioptics Inc., Tucson, AZ) connected to the Faxitron, took 10 s. All images were saved in the tagged image file (TIF) format. The stage of development was characterized by measuring the width of tunnels inside kernels made by larvae. In total, 48 kernels on each of the observation days (0–28 d) were examined, and width within kernels was measured using Faxitron DR, version 3.2.3 software. The tunnel width within a kernel was not uniform throughout. Therefore, tunnel width was measured at three points—the upper portion of the tunnel, the middle portion of the tunnel, and the bottom portion of the tunnel. The average tunnel width was calculated from these three measurements.

The captured images were printed, coded, and given to six graduate students in the Department of Grain Science and Industry with varying levels of expertise in stored-product entomology. None of the students had experience with Faxitron or in determining the ages of *R. dominica* immatures inside kernels. The purpose of this exercise was to determine whether a naïve observer was able to accurately age-grade insects based on printed images alone. The scores of 0 (false identification) and one (correct identification) by students were tallied to determine accuracy in determining various ages of *R. dominica.*

Grain Infestation and Infrared Treatments. The 113.5 and 227.0 g of wheat at 12% moisture were placed in individual 0.45-liter glass jars with wire mesh and filter paper lids. One hundred unsexed adults of *R. dominica* from cultures were added to each jar. After 3 d of infestation, the infested wheat was sifted over two sets of sieves (Seedburo Equipment Company, Chicago, IL). The top sieve had 2,000-μm openings and the bottom sieve had 840-μm openings. The top sieve retained wheat and the bottom sieve retained *R. dominica* adults while allowing the eggs and grain dust to pass through to a bottom collecting pan. The eggs, grain dust, and wheat were returned to the jars. The 3-d-old jars with eggs represented age 0 of *R. dominica*, and jars that were held in the growth chamber at 28°C and 65% RH for 7, 14, 21, and 24 d represented larvae in different developmental stages within kernels, and jars held for 28 d represented pupal and teneral adults within kernels. For adult exposures, 100 unsexed 2-wk-old adults from cultures were introduced into jars containing 113.5 and 227.0 g of wheat.

A benchtop catalytic infrared emitter was used to treat wheat infested with various life stages of *R. dominica* with infrared radiation. The benchtop model, manufactured by Catalytic Drying Technologies LLC, has a circular heating surface of 613.4 cm^2, and is fueled by a 473-ml container of propane (Ozark Trail Propane Fuel, Bentonville, AR) at 28.0 cm of water column pressure. Infrared radiation (3–7 μm) is emitted when the propane reacts with oxygen in the presence of a platinum catalyst; the other coproducts of this catalytic reaction are carbon dioxide and water vapor. The total heat energy output of this unit is 1.5 kW/h ($\approx$5,000 BTU/h).

A steel pan (27.9 cm in diameter and 3.8 cm in depth) with a steel handle (43 cm in length) was used below the emitter to expose infested wheat in a single-kernel layer thickness to infrared radiation. Infested wheat (113.5 or 227.0 g) was exposed for 45 or 60 s to infrared radiation at 8.0 or 12.7 cm from the emitter. Temperature of exposed wheat was measured continuously at the center of the pan by using a noncontact infrared thermometer (Raynger MX4 model 4TP78, Raytek, Santa Cruz, CA). The infrared thermometer works in the 8–14-μm range and has a rapid response time of 250 ms. The thermometer was connected via a USB port to a laptop computer using a standard RS-232 cable to record "real-time" grain temperatures every second (LabVIEW; National Instruments Corporation, Austin, TX).

The infrared thermometer, with emissivity set at 0.95, was calibrated against a mercury thermometer (model 14-983–10E, ABgene House, Surrey, United Kingdom) using 12% moisture organic hard red winter wheat (1400 g in glass containers) as the substrate. Calibration was done at 13 different temperatures between 25 and 126.5°C, where it took ≈7.5–23 h for the wheat in glass containers to uniformly reach the set growth chamber temperatures (25–38°C) or forced air convection oven (Blue M, Blue Island, IL) temperatures (41.5–126.5°C). The mercury thermometer was placed on the surface of the wheat. Temperature with the infrared thermometer was measured at the same location as the mercury thermometer. Calibration experiments at each of the constant temperatures were replicated twice. The mean mercury temperatures were regressed against the mean infrared thermometer temperatures using linear regression, and the slope was tested for significant deviation from one using a t-test at $\alpha = 0.05$ (SAS Institute 2002).

Data recorded by the infrared thermometer were saved in an Excel file (Microsoft, Redmond, WA) for further analysis. The thermometer was mounted on a tripod away from the infrared emitter and was directed in such a way to record only the wheat sample being heated below the infrared emitter. Each life stage, grain quantity, distance, and time combination were replicated three times, and all replicates were tested on the same day. Wheat (113.5 and 227.0 g), infested similarly, but unexposed to infrared treatment, served as the control treatments; there were four replicates for each grain quantity, distance from emitter, and exposure time.

Assessment of Insect Mortality. Wheat exposed to infrared radiation was placed back in jars and the mortality of *R. dominica* adults was determined after infested wheat in jars was held for 24 h at 28°C and 65% RH. After infrared exposure, the wheat with immature stages was placed back in the jars and incubated at 28°C and 65% RH until emergence of adults. Adult emergence was checked after 42 d from day 0. Untreated wheat replicates (controls) were handled similarly. Larvae and pupae of *R. dominica* complete development within kernels, and therefore, it would be difficult to determine survival of these stages in infrared-exposed and control wheat samples (Wadley's problem) (Finney 1971). Hence, these stages were reared to adulthood to confirm mortality, and the number of adults that emerged from eggs, larvae, and pupae in untreated wheat indicated both the validity and robustness of our experimental approach and the degree of control obtained due to infrared exposure.

Experimental Design and Data Analysis. The experiment was run as a completely randomized design. The mean temperature attained every second was plotted as a function of time for 113.5 and 227.0 g of wheat exposed for 45 and 60 s at 8.0 and 12.7 cm from the infrared emitter. There were eight temperature profiles for each insect age.

The temperature profile for each replicate was averaged over time. The mean wheat temperature attained for any given insect age, wheat quantity, and exposure time combination between 8.0- and 12.7-cm distance from the emitter was compared using two-sample t-tests for equal variance (SAS Institute 2002). Two-sample t-tests also were used to compare mean temperatures attained after a 45- and 60-s exposure or in 113.5 and 227.0 g of wheat when all other factors were fixed.

To determine whether the mean wheat temperature attained for a given quantity of grain, distance from emitter, and exposure time combination across the various ages tested (eggs [day 0], 7, 14, 21, 24, 28, and 42 d [adults]) was similar, a linear regression of mean temperature versus insect age was performed, and the slope was tested for deviation from zero at $\alpha = 0.05$ (SAS Institute 2002).

The number of adults that emerged from untreated wheat and those exposed to infrared in the various treatment combinations was recorded. The main effect of insect age, wheat quantity, distance from emitter, and exposure time, and their two-way interactions on the probability of death were determined using logistic regression at $\alpha = 0.05$ (SAS Institute 2002). Odds ratios from logistic regression were used to show differences in susceptibility (odds of dying) of various life stages exposed to infrared. The odds ratio for adults (1) was used as a reference, and a ratio >1 showed that a life stage was more susceptible than adults to infrared radiation, whereas a ratio <1 showed that a stage was less susceptible than adults. Differences in susceptibility of various life stages also was determined by plotting probability of death as a function of mean temperature averaged over wheat quantity, distance from the emitter, and exposure time.

Results

Identifying *R. dominica* Life Stages. Wheat infested with adults for 3 d represented the egg stage (day 0). Larvae eclosing from eggs enter kernels to continue development (Arbogast 1991), and these larvae within kernels were first evident from radiographs taken 8–9 d after day 0 or 11–12 d after adult infestation of wheat (Fig. 1B). Larvae in various stages of development were evident in the radiographs at 14 and 21 d (Fig. 1C and D). A majority of kernels had pupae at 24 d (Fig. 1E), and both pupae and teneral adults were observed within kernels at 28 d (Fig. 1F).

As larvae developed, the tunnel width within kernels showed a corresponding increase. For example,

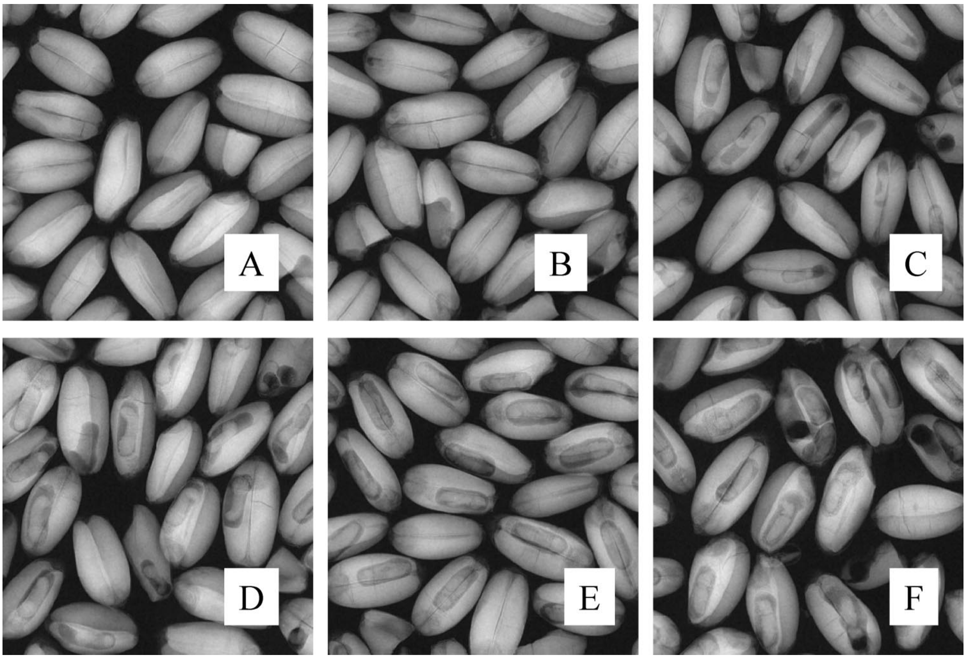

Fig. 1. Radiographic images of *R. dominica* life stages within kernels. Control (A), 8–9 d (B), 14 d (C), 21 d (D), 24 d (E), and 28 d (F).

the mean ± SE tunnel widths measured on days 8, 14, 21, 24, and 28 were 0.24 ± 0.03, 0.34 ± 0.01, 0.40 ± 0.02, 0.53 ± 0.01, and 0.61 ± 0.02 mm, respectively. All six students (100.0%) accurately scored *R. dominica* life stages that were 21, 24, and 28 d old. However, only four of the six students (66.7%) were able to accurately score *R. dominica* stages that were 7 and 14 d old.

Calibration of Infrared Thermometer. The actual wheat temperature, as measured by the mercury thermometer (y), relative to the infrared thermometer (x) was best described by the following linear regression equation: $y = 0.86\ (0.28) + 0.99\ (0.004)x$ ($n = 13; r^2 = 0.999$). The slope was not significantly different from one ($t = 2.5$; df = 11; $P = 0.985$); therefore, no corrections were necessary when using infrared thermometer for measuring wheat temperature during infrared exposures.

Temperature Profiles During Infrared Exposure. Thirteen measurements, taken at different points of the emitter surface with the infrared thermometer, showed temperatures ranging from 335 to 474°C, and the lower temperatures were at the edges of the emitter. Because lower temperatures were observed near the edges of the emitter surface, temperature of wheat was measured in the center of the pan during infrared exposures.

The temperatures attained were generally greater when wheat was exposed for longer time periods at fixed grain quantity and distance from the emitter. A representative temperature profile obtained for wheat infested with eggs exposed to infrared in 113.5 and 227.0 g of wheat at distances of 8.0 and 12.7 cm from the emitter for 45 and 60 s is illustrated in Fig. 2. The temperature profiles for other ages for a given wheat

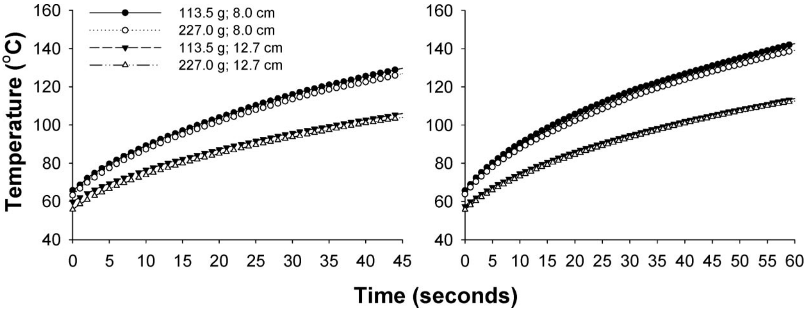

Fig. 2. Generalized time-dependent temperature profile attained with different quantities of wheat exposed to infrared radiation at 8.0 and 12.7 cm from the emitter surface for 45 and 60 s.

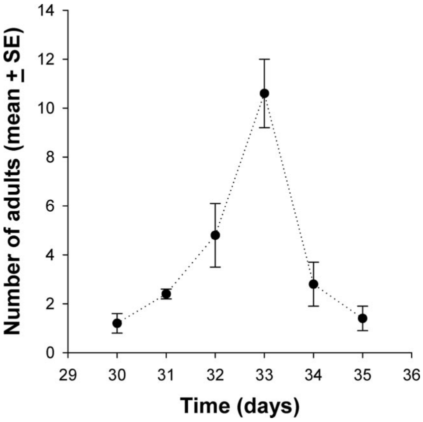

Fig. 3. Adult emergence curve for *R. dominica* in 5 g wheat samples ($n = 5$).

quantity, emitter distance, and exposure time followed a similar trend. In general, temperatures attained by wheat were greater in 113.5 g of wheat, at 8.0 cm from the emitter, after a 60-s exposure. The time-dependent temperature profile was highest for 113.5 g of wheat exposed for 45 or 60 s at a distance of 8.0 cm from the emitter followed by 113.5 g of wheat exposed at 12.7 cm. In 227.0-g samples of wheat exposed to infrared radiation, recorded grain temperatures were consistently lower than in 113.5 g of wheat, regardless of emitter distance or exposure time.

Adults of *R. dominica* Observed in Unexposed Wheat Samples. In 5 g wheat samples, adults of *R. dominica* started to emerge at 30 d, and the peak emergence occurred at 33 d. No adults emerged after 35 d (Fig. 3). A mean ± SE of 211.5 ± 8.7–581.0 ± 14.3 *R. dominica* adults emerged from infested wheat that was not exposed to infrared radiation (Table 1). Consistently more adults emerged in 227.0 g of wheat compared with 113.5 g of wheat, irrespective of insect age.

Mean Temperatures Attained and *R. dominica* Responses in Infrared-Exposed Wheat Samples. Mean grain temperatures attained in various infrared treatment combinations is shown in Table 2. Two sample *t*-tests for each life stage or *R. dominica* age group (0, 7, 14, 21, 24, 28, and 42 d) indicated that the mean temperature attained by 113.5 or 227.0 g of wheat during a 45- or 60-s exposure was significantly greater at 8.0 cm from the emitter when compared with mean temperature attained by wheat at 12.7 cm from the emitter (t, range among ages, grain quantities, and exposure times = 7.48–61.12; df = 4; $P < 0.002$). The mean temperature attained by wheat after a 60-s exposure was significantly and consistently higher than those attained after a 45-s exposure at a given insect age, grain quantity, and distance from the emitter (t, range = −3.89 to −16.80; df = 4; $P \leq 0.0176$). In general, grain quantity did not consistently influence the mean grain temperatures attained for any given insect age, distance from emitter, and exposure time. In 21 of the 28 comparisons, the difference in mean temperature attained by 113.5 and 227.0 g of wheat was not significant (t, range = −2.75 to 2.51; df = 4; $P > 0.5130$). In the remaining seven comparisons, mean temperatures attained by wheat were higher in 113.5 g than in 227.0 g of wheat.

Table 1. Emergence of adults from infested wheat samples containing various ages of *R. dominica* that were not exposed to infrared radiation[a]

Insect age (d)	Mean ± SE (n = 4) no. adults in	
	113.5 g	227.0 g
0 (eggs)	437.3 ± 5.4	581.0 ± 14.3
7	300.0 ± 20.8	570.0 ± 29.0
14	228.3 ± 53.3	517.5 ± 68.2
21	211.5 ± 8.7	384.5 ± 39.9
24	241.5 ± 31.2	530.3 ± 29.0
28	284.8 ± 34.8	415.0 ± 42.1

[a] Ages correspond to when *R. dominica* stages were exposed to infrared treatments.

The slope of the linear regression between mean temperature attained by 113.5 or 227.0 g of wheat at 8.0 or 12.7 cm from the emitter after a 45- or 60-s exposure and the insect age was not significantly different from zero (t, range among grain quantities, distance from emitter, and exposure times = −1.62 to 0.19; $n = 7$; $P \geq 0.1656$).

In general, the number of adults that emerged, or the probability of death, estimated by the logistic regression seemed to be influenced by grain quantity, distance from the emitter, and exposure time, all of which directly influenced temperatures attained by the wheat (Table 2). Increasing the grain quantity or increasing the emitter distance resulted in lowering the probability of insect death. Logistic regression analysis showed that the probability of death of *R. dominica* was influenced significantly ($P < 0.0001$) by insect age ($\chi^2 = 642.65$; df = 6), wheat quantity ($\chi^2 = 323.10$; df = 1), distance from the emitter ($\chi^2 = 342.67$; df = 1), and exposure time ($\chi^2 = 223.79$; df = 1). All two-way interactions (insect age x wheat quantity, insect age × distance from the emitter, insect age x exposure time [df = 6]; wheat quantity × distance from the emitter, wheat quantity x exposure time, and distance from the emitter × exposure time [df = 1]), were highly significant (χ^2, range = 47.11–565.57; $P < 0.0001$).

Based on the probability of death, 7-d-old insects (young larvae) were the most susceptible whereas 21-d-old insects (old larvae) were least susceptible. The odds ratios also provided similar information. For example, the odds ratio for 21-d-old insects was 0.93 compared with the adults (odds ratio, 1.00), which were the next least susceptible stage to infrared radiation. Odds ratios for the other stages in increasing order were pupae (28 d old; 1.13), eggs (1.45), 24-d-old insects (2.35), 14-d-old insects (2.41), and 7-d-old insects (3.80). Irrespective of insect age, the best treatment seemed to be 113.5 g of wheat exposed for 60 s at a distance of 8.0 cm from the emitter, because in these treatments the mean temperatures attained ranged from 107.6 ± 1.4–113.5 ± 0.5°C, and the probability of death was ≥94%.

Table 2. Emergence of *R. dominica* adults from infested wheat in various infrared-exposed treatments, mean temperatures attained by wheat, and probability of death of various insect ages

Insect age (d)	Grain quantity (g)	Distance from the emitter (cm)	Exposure time (s)	Mean ± SE temp (°C)	Mean ± SE no. adults	Probability of death
0	113.5	8.0	45	102.3 ± 1.0	6.0 ± 0.8	0.97
			60	113.5 ± 0.5	0.7 ± 0.2	0.99
		12.7	45	87.6 ± 0.8	52.7 ± 5.4	0.88
			60	91.9 ± 0.8	14.7 ± 2.0	0.97
	227.0	8.0	45	102.1 ± 1.0	119.3 ± 8.7	0.83
			60	110.5 ± 1.4	18.3 ± 0.6	0.96
		12.7	45	85.4 ± 0.3	214.0 ± 12.3	0.57
			60	90.7 ± 0.8	190.0 ± 6.4	0.83
7	113.5	8.0	45	99.9 ± 0.3	0.3 ± 0.3	0.99
			60	111.5 ± 0.2	0.3 ± 0.3	1.00
		12.7	45	83.8 ± 0.3	10.7 ± 0.7	0.95
			60	91.4 ± 0.9	0.7 ± 0.3	0.99
	227.0	8.0	45	101.8 ± 0.6	28.3 ± 6.2	0.94
			60	109.3 ± 1.0	1.0 ± 0.6	0.99
		12.7	45	84.1 ± 0.3	187.0 ± 22.5	0.78
			60	87.9 ± 0.7	51.7 ± 13.2	0.92
14	113.5	8.0	45	102.4 ± 1.0	0	1.00
			60	107.9 ± 0.7	0	1.00
		12.7	45	86.3 ± 0.3	14.7 ± 6.1	0.94
			60	90.8 ± 0.2	0	1.00
	227.0	8.0	45	100.6 ± 1.4	49.3 ± 6.3	0.90
			60	108.4 ± 0.7	5.0 ± 2.3	0.98
		12.7	45	82.9 ± 0.3	220.7 ± 15.6	0.68
			60	87.8 ± 0.3	65.7 ± 8.1	0.88
21	113.5	8.0	45	99.9 ± 0.5	3.0 ± 0.4	0.95
			60	108.5 ± 0.5	0	1.00
		12.7	45	84.6 ± 0.1	27.7 ± 6.9	0.85
			60	89.4 ± 0.5	20.3 ± 4.1	0.95
	227.0	8.0	45	100.3 ± 0.0	118.7 ± 5.2	0.77
			60	108.1 ± 0.6	22.7 ± 3.0	0.94
		12.7	45	83.9 ± 0.5	288.3 ± 9.2	0.47
			60	88.8 ± 0.1	117.7 ± 11.6	0.76
24	113.5	8.0	45	102.9 ± 0.6	0.7 ± 0.2	0.98
			60	109.4 ± 0.3	0	1.00
		12.7	45	85.7 ± 0.3	28.3 ± 10.5	0.93
			60	90.4 ± 1.0	0.7 ± 0.2	0.98
	227.0	8.0	45	101.7 ± 0.4	49.7 ± 10.1	0.90
			60	109.0 ± 0.3	15.7 ± 2.1	0.97
		12.7	45	83.9 ± 0.3	173.3 ± 19.1	0.68
			60	89.2 ± 0.7	73.0 ± 3.6	0.88
28	113.5	8.0	45	76.2 ± 24.1	5.7 ± 1.0	0.95
			60	110.2 ± 0.4	0.3 ± 0.2	0.99
		12.7	45	84.9 ± 0.3	53.0 ± 10.6	0.87
			60	91.4 ± 0.7	2.7 ± 0.9	0.97
	227.0	8.0	45	100.7 ± 0.8	10.3 ± 1.8	0.81
			60	107.6 ± 1.4	37.7 ± 9.0	0.94
		12.7	45	82.6 ± 0.3	194.7 ± 11.3	0.50
			60	88.4 ± 0.3	125.0 ± 13.7	0.79
42 (adults)	113.5	8.0	45	102.3 ± 1.0	0.3 ± 0.2	0.96
			60	109.7 ± 0.9	0	1.00
		12.7	45	85.9 ± 0.3	7.7 ± 1.0	0.86
			60	91.6 ± 0.9	0.7 ± 0.2	0.96
	227.0	8.0	45	100.8 ± 0.9	8.3 ± 0.6	0.81
			60	110.2 ± 0.2	0	1.00
		12.7	45	84.0 ± 0.4	91.0 ± 1.1	0.45
			60	90.1 ± 0.2	21.3 ± 1.4	0.77

The probability of death as a function of mean temperature averaged over wheat quantity, distance from emitter, and exposure time showed variation in how the various ages of insects responded to infrared radiation, especially at temperatures <105°C (Fig. 4). The 7-d-old insects were consistently more susceptible than the other ages at a range of temperatures. At the highest mean temperature of 113.5°C, the probability of death of all ages was 0.99–1.00 (99–100% mortality).

Discussion

The fact that 211.5 ± 8.7–581.0 ± 14.3 adults emerged from untreated (control) infested wheat suggested that the experimental protocol used in this study was robust and suitable for gauging the effectiveness of infrared radiation against various *R. dominica* ages. The eggs of *R. dominica,* which are laid outside the kernels (Arbogast 1991), take ≈7 d to hatch at the experimental conditions used in the study

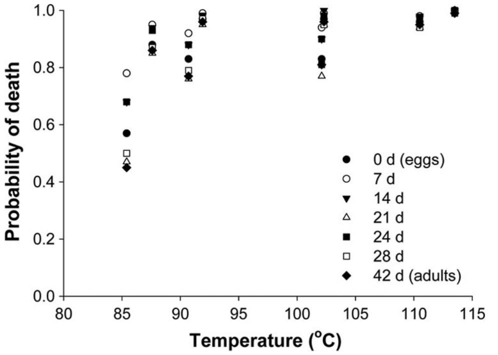

Fig. 4. Probability of death of different life stages of *R. dominica* as a function of wheat temperature averaged across grain quantities, distances from emitter, and exposure times.

(Hagstrum and Milliken 1988), and the first instars enter kernels to continue their development. This explains why we were unable to identify any first instars in the radiographs taken at 7 d. However, larvae inside kernels were visible from 8 d onward. Potter (1935) opened wheat kernels and extricated larvae in different developmental stages and measured their head capsule widths. We did not use this destructive method, but instead used a nondestructive method, which involved measuring tunnel widths in kernels created by developing larvae. Tunnel widths were also used to characterize the four instars of three stored-grain insects that develop within kernels of wheat: the granary weevil, *Sitophilus granarius* (L.) (Kirkpatrick and Wilbur 1965); maize weevil, *Sitophilus zeamais* Motschulsky (Sharifi and Mills 1971a); and rice weevil, *Sitophilus oryzae* (L.) (Sharifi and Mills 1971b). These authors showed four periods of tunnel widening indicative of four instars. In our study, the five periods of tunnel widening suggested *R. dominica* to have five instars. In our study, tunnel width at 28 d was greater than that observed at 24 d, although at 24 d many of the observed kernels had pupae. Even though 48 kernels from the same set of five vials were observed over time, the same 48 kernels were not measured on different observation days. Therefore, variations in development of larvae among kernels may have contributed to the differences observed between 24 and 28 d. Both Potter (1935) and Elek (1994) have reported *R. dominica* to go through four to five instars. The fact that we observed several adults within kernels in scans during the 28-d observation period supports the view that *R. dominica* may only have four instars. Schatzki and Fine (1988) also noted that some adults remained inside kernels after completing development to adulthood. Stemley (1962) reported that preemergent adults spend up to 6 d within kernels. Nevertheless, the radiographs and our experimental protocol used provided a valid basis to gauge the impact of infrared treatments on various life stages (ages) of *R. dominica.*

In our study, consistently more adult progeny emerged from 227.0 g than 113.5 g of untreated wheat that was infested with 100 unsexed adults for only 3 d, and further studies are warranted to understand this phenomenon. Toews et al. (2000) reported on progeny production when 100 g of each of eight U.S. wheat cultivars were infested with 50 unsexed *R. dominica* adults for 7 d. In their study, they carried out three separate experiments and progeny production was determined at 27 and 34°C and 70% RH. They found large differences in progeny production, which varied from a low of 123 to a high of 940 adults. These differences were attributed to differences in kernel size which may vary with the cultivar and the environmental conditions tested.

Of the factors examined, distance from the emitter surface and exposure time mostly influenced mean temperatures attained. The quantity of grain used had minimal impact on mean temperatures attained. Fewer adults of *R. dominica* emerged in infrared treatments where the temperatures ranged from 107.6 ± 1.4 to 113.5 ± 0.5°C compared with treatments where the temperatures were <105°C. The temperatures we observed were twice as high as those reported by previous researchers (Tilton and Schroeder 1963, Kirkpatrick and Tilton 1972, Kirkpatrick et al. 1972, Kirkpatrick 1975, Kirkpatrick and Cagle 1978, Tilton et al. 1983, Pan et al. 2008). Our results cannot be directly compared with work done by these authors for several reasons. In all of the previous work, except for Pan et al. (2008), the stage of development of insects within kernels that were exposed to infrared radiation was unknown. Furthermore, the infested samples were subdivided (pseudoreplicates) for infrared exposure, and the type of infrared unit used was gas-fired and not a flameless catalytic emitter. All authors, including Pan et al. (2008), measured grain temperatures immediately after infrared exposure; hence, their temperatures were lower than those reported in this article. Pan et al. (2008) used a flameless catalytic emitter on rough rice of 20.6 and 25.0% moisture, infested for 4 d with 100 adult *R. dominica.* They exposed rough rice in a single layer (250 g) for 25, 40, 60, and 90 s. Temperatures were measured using a Type T thermocouple (Omega Engineering Inc., Stamford, CT) immediately after heated rice was placed in a container. In 20.6 and 25.0% moisture rice, the temperatures attained ranged from 49.0 to 69.4°C. A 90-s exposure was necessary for 99.5–100.0% mortality of adults and/or eggs present in infested samples.

The purpose of testing various ages of insects to infrared radiation was to identify the most heat tolerant stage, because controlling the most heat tolerant stage may control all other stages. In our study, susceptibility differences among the various ages of *R. dominica* were noted. The 21-d-old insects (old larvae) were more tolerant to infrared radiation relative to the other stages, and the 7-d-old insects (young larvae) were most susceptible. The variation in susceptibility among *R. dominica* stages, especially those developing within kernels, may be related to the adverse effects of infrared radiation on the insect's physiological processes. Except for the egg and adult stages, all other stages of *R. dominica* are spent within kernels. In the 113.5 and 227.0 g of infested wheat, it was difficult to know how the infestation was distributed among kernels relative to the portion of grain being heated. This could have had an effect on insect responses. The location of the insect within the kernel also may influence its susceptibility to heat (Beckett and Morton 2003). For adults, their ability to move away from areas that are hotter to seek cooler areas may make them less susceptible to heat. Similarly, some of the eggs could have escaped infrared treatment, perhaps by being shielded by kernels.

In conclusion, of all the infrared treatments, 113.5 g of wheat exposed for 60 s at a distance of 8.0 cm from the emitter, was the most effective treatment in disinfesting wheat containing eggs, larvae, pupae, and adults of *R. dominica.* Our laboratory results using small grain quantities showed that flameless catalytic infrared technology is a promising tool for managing *R. dominica* life stages in stored wheat, provided a short duration of exposure to such high temperatures does not adversely affect the physical, chemical, rheological, and end-use qualities of wheat.

Acknowledgments

We thank Virgil Macaluso (Catalytic Drying Technologies LLC) for donating the bench top infrared emitter. Russell Taylor (Electronics Design Laboratory, Kansas State University, Manhattan, KS) developed the LabView program for real-time temperature data acquisition. This work was supported by a grant from USDA–CSREES NC-IPM funds. This article is contribution 10-265-J of the Kansas State University Agricultural Experiment Station.

References Cited

Arbogast, R. T. 1991. Beetles: Coleoptera, pp. 131–176. *In* R. J. Gorham [ed.], Ecology and management of food industry pests. Association of Official Analytical Chemists, Arlington, VA.

Beckett, S. J., and R. Morton. 2003. Mortality of *Rhyzopertha dominica* (F.) (Coleoptera: Bostrychidae) at grain temperatures ranging from 50°C to 60°C obtained at different rates of heating in a spouted bed. J. Stored Prod. Res. 39: 313–332.

Cogburn, R. R. 1967. Infrared radiation effect on reproduction by three species of stored-product insects. J. Econ. Entomol. 60: 548–550.

Cogburn, R. R., J. H. Brower, and E. W. Tilton. 1971. Combination of gamma and infrared radiation for control of the Angoumois grain moth in wheat. J. Econ. Entomol. 64: 923–925.

Elek, J. A. 1994. Methods for collecting eggs and monitoring egg-hatch and immature development of *Rhyzopertha dominica* (F.) (Coleoptera, Bostrichidae). J. Stored Prod. Res. 30: 261–265.

Fasina, O. O., R. T. Tyler, M. D. Pickard, and G. H. Zheng. 1999. Infrared heating of hulless and pearled barley. J. Food Proc. Preserv. 23: 135–151.

Finney, D. J. 1971. Probit Analysis. Cambridge University Press, London, United Kingdom.

Flinn, P. W., Bh. Subramanyam, and F. H. Arthur. 2004. Comparison of aeration and spinosad for suppressing insects in stored wheat. J. Econ. Entomol. 97: 1465–1473.

Frost, S. W., L. E. Dillis, and J. E. Nicholas. 1944. The effects of infrared radiation on certain insects. J. Econ. Entomol. 37: 287–290.

Gabel, M. M., Z. Pan, K.S.P. Amaratunga, L. J. Harris, and J. F. Thompson. 2006. Catalytic infrared dehydration of onions. J. Food Sci. 71: 351–357.

Hagstrum, D. W., and G. A. Milliken. 1988. Quantitative-analysis of temperature, moisture, and diet factors affecting insect development. Ann. Entomol. Soc. Am. 81: 539–546.

Kirkpatrick, R. L. 1975. Infrared radiation for control of lesser grain borers and rice weevils in bulk wheat. J. Kans. Entomol. Soc. 48: 100–104.

Kirkpatrick, R. L., and D. A. Wilbur. 1965. The development and habits of the granary weevil, *Sitophilus granarius,* within the kernel of wheat. J. Econ. Entomol. 58: 979–985.

Kirkpatrick, R. L., and E. W. Tilton. 1972. Infrared radiation to control adult stored-product Coleoptera. J. Ga. Entomol. Soc. 7: 73–75.

Kirkpatrick, R. L., J. H. Brower, and E. W. Tilton. 1972. A comparison of microwave and infrared radiation to control rice weevils (Coleoptera: Curculionidae) in wheat. J. Kans. Entomol. Soc. 45: 434–438.

Kirkpatrick, R. L., and A. Cagle. 1978. Controlling insects in bulk wheat with irradiation. J. Kans. Entomol. Soc. 51: 386–393.

McGaughey, W. H., and R. G. Akins. 1989. Application of modified atmospheres in farm grain storage bins. J. Stored Prod. Res. 25: 201–210.

Martin, M. A., C. R. Edwards, L. J. Mason, and D. E. Maier. 1997. Stored wheat IPM practices and pesticide use in key regions of the United States and Canada: 1996. Agricultural Research Program, B-752, Purdue University, West Lafayette, IN.

Pan, Z., R. Khir, L. D. Godfrey, R. Lewis, J. F. Thompson, and A. Salim. 2008. Feasibility of simultaneous rough rice drying and disinfestations by infrared radiation heating and rice milling quality. J. Food. Eng. 84: 469–479.

Potter, C. 1935. The biology and distribution of *Rhizopertha dominica* (Fab.). Trans. R. Entomol. Soc. Lond. 83: 449–482.

Rulon, R. A., D. E. Maier, and M. D. Boehje. 1999. A post harvest economic model to evaluate grain chilling as IPM technology. J. Stored Prod. Res. 35: 369–383.

Sandu, C. 1986. Infrared radiative drying in food engineering—a process analysis. Biotechnol. Prog. 2: 109–119.

SAS Institute. 2002. SAS/STAT user's guide, version 9.1. SAS Institute, Cary, NC.

Sharifi, S., and R. B. Mills. 1971a. Developmental activities and behavior of *Sitophilus oryzae* (L.), within the kernels of wheat. J. Econ. Entomol. 64: 1114–1118.

Sharifi, S., and R. B. Mills. 1971b. Radiographic studies of *Sitophilus zeamais* Mots. in wheat kernels. J. Stored Prod. Res. 7: 195–206.

Schatzki, T. F., and T.A.B. Fine. 1988. Analysis of radiograms of wheat kernels for quality control. Cereal Chem. 65: 233–239.

Sinha, R. N., and F. L. Watters. 1985. Insect pests of flour mills, grain elevators, and feed mills and their control. Agriculture Canada Publication 1776, Canadian Government Publishing Centre, Ottawa, ON, Canada.

Stemley, P. G. 1962. The life history and behavior of an internal feeding stored grain insect, *Rhyzopertha dominica* (Fab.), by use of x-ray. Ph.D. dissertation, Kansas State University, Manhattan.

Subramanyam, B. H., and D. W. Hagstrum. 1996. Resistance measurement and management, pp. 331–397. *In* Bh. Subramanyam and D. W. Hagstrum [ed.], Integrated management of insects in stored products. Marcel Dekker, New York.

Tilton, E. W., and H. W. Schroeder. 1961. The effect of infrared radiation on immature insects in kernels of rough rice. Rice J. 64: 23–25.

Tilton, E. W., and H. W. Schroeder. 1963. Some effects of infrared irradiation on the mortality of immature insects in kernels of rough rice. J. Econ. Entomol. 56: 727–730.

Tilton, E. W., H. H. Vardell, and R. D. Jones. 1983. Infrared heating with vacuum for control of the lesser grain borer, (*Rhyzopertha dominica* (F.)) and rice weevil (*Sitophilus oryzae* (L.)) infesting wheat. J. Ga. Entomol. Soc. 18: 61–64.

Toews, M. D., G. W. Cuperus, and T. W. Phillips. 2000. Susceptibility of eight US wheat cultivars to infestation by *Rhyzopertha dominica* (Coleoptera: Bostrichidae). Environ. Entomol. 29: 250–255.

Received 23 February 2010; accepted 30 April 2010.