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Heat treatment for disinfestation of empty grain storage bins ☆

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Abstract

An alternative to fumigants and insecticides for controlling stored-product insects in empty grain storage bins prior to filling is heat treatment, in which the temperature is quickly raised to a minimum of 50 °C and held there for 2–4 h. Effectiveness of heat treatment on empty grain storage bins was evaluated for five commercial propane and electric heat-treatment systems by measuring air temperature and associated mortality of *Tribolium castaneum* (Herbst), the red flour beetle, *Sitophilus oryzae* (L.), the rice weevil, and *Rhyzopertha dominica* (F.), the lesser grain borer, exposed for different time intervals. Eleven locations, six above and five below the drying floor, were monitored for air temperature and associated mortality of the three insect species, using arenas initially stocked with live adult insects. Data were analyzed separately for each heating system, with floor location and time interval as main effects for insect mortality. A high-output propane heater (29 kW) produced 100% mortality in 2 h for the three insect species at all test locations. An electric duct-heater system (18 kW) also produced 100% mortality at all test locations after 40 h when aided by a complicated interior heat-distribution system. The other three systems produced less than 100% mortality.
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Keywords: *Tribolium castaneum*; *Sitophilus oryzae* (L.); *Rhyzopertha dominica* (F.); Heat treatment

1. Introduction

On-farm grain storage bins are commonly inspected for insects prior to filling. Grain storage bins with perforated drying floors create an ideal harborage for insects (Raney, 1974) because the area below the drying floor is not normally accessible for cleaning unless the perforated floor is removed. Applying a registered insecticide to the walls and floors of empty bins supplements, but does not replace, sanitation and cleaning. Insecticide residues control insects that may have remained in hard-to-clean cracks and crevices or beneath the perforated floor, but maximum control of insects in the subfloor plenum requires fumigation or removal of the perforated floor and thorough cleanup. In recent years, there have been renewed efforts to investigate non-chemical insect control measures due to concerns for the environment, worker safety, or consumer preference. In addition, there is always the danger of insect resistance to chemicals in the target insect populations (Subramanyam and Hagstrum, 1995).

The challenge of controlling insect pests with a minimum of chemical insecticides has led to the development of integrated pest-management (IPM) strategies (Hagstrum et al., 1999). There are many definitions of IPM, but most have two important elements: monitoring-based decision making and multiple control strategies (Hagstrum et al., 1999). One of the central tenets of IPM is reduction in the use of chemical insecticides and use of more ecologically based control methods when possible (Campbell et al., 2004). A technique that has been used successfully for many years against stored-product pests is use of extreme temperatures (Fields, 1992). Use of elevated temperatures or heat treatments has long been recognized as an effective strategy for managing stored-product insects associated with food-processing facilities (Dean, 1911). In heat treatments of facilities, either gas, electric, or steam heaters are used to slowly heat the ambient air, with a long heat treatment period (24–36 h) necessary for the heat to

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penetrate wall voids and equipment (Mahroof et al., 2003a).

Target temperature for effective disinfestation of a facility during a heat treatment should be at least 50 °C (Imholte and Imholte-Tauscher, 1999; Wright et al., 2002; Roesli et al., 2003). Most stored-product beetles are killed within hours after being exposed to temperatures of 50 °C or more (Fields, 1992). However, during actual heat treatments, temperature profiles in the facility vary and the time insects are exposed to the lethal temperatures can differ depending on their location in the facility (Mahroof et al., 2003a).

Prior research had indicated that a minimum temperature of 50 °C in the subfloor plenum of a grain bin should eliminate insect infestations. However, this area below the drying floor is a maze of steel framing that hinders uniform heat distribution. The objective of this research was to evaluate different sources of heat and heater configurations for controlling stored-product insects in steel grain bins prior to filling.

2. Materials and methods

2.1. Grain bins

Two-grain bins were used to conduct heat treatments and a third bin used as a control. Test locations in each bin were monitored for temperature and insect mortality. Insect mortality was determined using arena cages containing live insects. Five heating systems were tested independently, with three different lengths of tests selected to be suitable for each system as described in Table 1.

The steel grain bins located at USDA, Grain Marketing and Production Research Center (GMPRC), Manhattan, KS, were each 6.7 m in diameter with a height of 4.1 m from the drying floor to the eave of the bin. Two of the experimental steel grain bins, bins 1 and 2, were located outside and the other, bin 3, was inside the GMPRC pilot plant. For tests of the outside heat-treated bin, bin 1, an adjacent outside bin, bin 2, was used as a control. The perforated floors of bins 1 and 3 were covered with tarps during the heat treatments to retain more heat below the drying floor, which was the slowest heating part of the bin. Bin 2 was not altered but was monitored at identical locations for temperature and insect mortality during heat treatments in bin 1. For tests in bin 3, there was no adjacent bin to use for a control, so arenas were placed around the outside of the bin as controls.

2.2. Insects and arenas

Tribolium castaneum (Herbst), the red flour beetle, was reared on 100% whole-wheat flour at 28 °C and 65% r.h. *Sitophilus oryzae* (L.), the rice weevil and *Rhyzopertha dominica* (F.), the lesser grain borer, were reared on 100% whole-wheat kernels at 28 °C and 65% r.h., respectively. Arenas for insect mortality studies were 0.5-L, clear polypropylene containers with recessed lids, each containing 8–10 g of cracked hard red winter wheat, a HOBO® data-logging unit (Onset Computer Corporation, Bourne, MA), and 15 insects—five each from the three different species. Unsexed, 3–5-week-old adults of the *T. castaneum, S. oryzae*, and *R. dominica* were added to the arenas. Each arena was modified with a 1.27-cm diameter breathing hole covered with 20-mill nylon wire mesh-screen. Three sets of insect arenas were positioned in each sampling location, described in Fig. 1 and Table 1, of each heating system. An insect arena was removed from each bin location at each of

Table 1
Steel grain bin and heat-treatment layout of each heating system

Heating system	Time intervals (h)	Energy use (kW h)	Test bin	Floor location	Treated bin arena locations	Control bin arena locations
Electric system 1 (18 kW)	12, 27, 40	216, 486, 720	3	Above Below	6[a] 5[c]	6[b]
Electric system 2 (18 kW)	12, 27, 40	216, 486, 720	3	Above Below	6[a] 5[c]	6[b]
Electric system 3 (15 kW)	12, 27, 40	180, 405, 600	1, 2	Above Below	6[a] 5[c]	6[a] 5[c]
Propane system 1 (29 kW)	2, 3, 4	58, 87, 117	1, 2	Above Below	6[a] 5[c]	6[a] 5[c]
Propane system 2 (19 kW)	4, 6, 8	76, 114, 152	1, 2	Above Below	6[a] 5[c]	6[a] 5[c]

Each heating system held three sets of insect arenas in each bin location. An insect arena was removed from each bin location at each of three specified time intervals. Three replications of each test were conducted with temperature and mortality results recorded.

[a]Arena sampling locations located above the bin drying floor of bins 1, 2, and 3 at the north, south, east, west, center, and top.

[b]Arena sampling locations of bin 3 located on the exterior perimeter at the north, south, east, and west.

[c]Arena sampling locations located below the bin drying floor of bins 1 and 2 at the north, south, east, west and center.

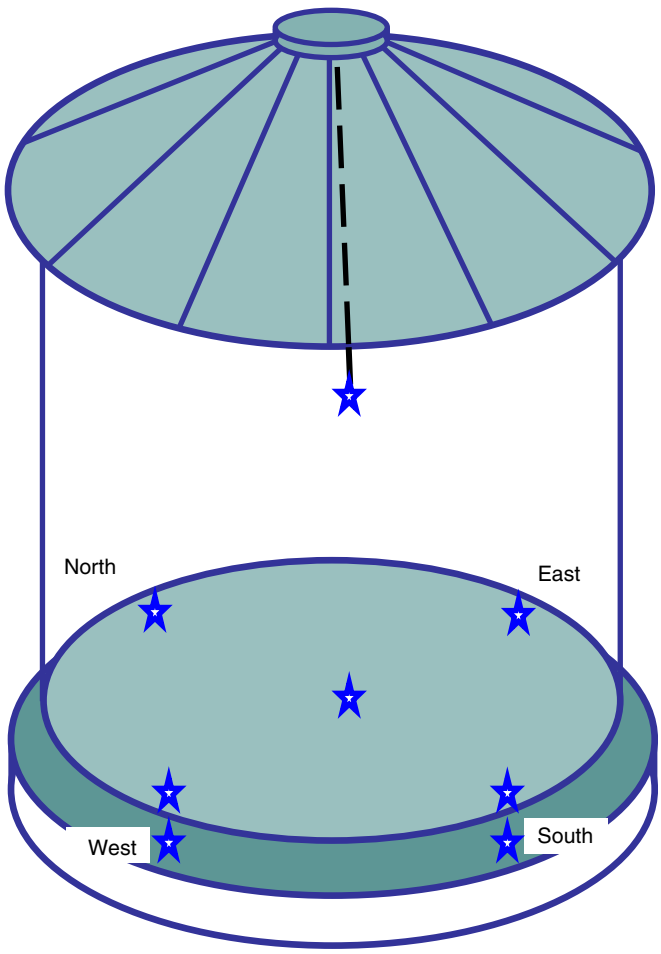

Fig. 1. Insect arena test locations in the grain bin fitted with a slotted drying floor. Eleven test locations (*) were determined, five above and five below the drying floor at the north, south, east, west, and center locations, and one suspended from the ceiling. Each test location contained three individual arenas. One arena was removed from each location at predetermined time intervals during a heat treatment and insect mortality determined.

three specified intervals. These time intervals were selected to be in the range where each system was expected to achieve temperatures of 50 °C. The times were also selected to be practical for field operations as far as possible, given the heat input of each system. Upon removal of each arena, mortality was assessed by examining each individual insect for movement. Beetles were probed repeatedly, and those that were on their backs and immobile were classified as dead. These insects displayed the typical form of dead insects; bodies were dried, legs were tucked under the abdomen, and there was no response from probing. A recovery period was not considered necessary because they were not "knocked-down," as is normally the case when stored-product beetles are exposed to residual insecticides. Methods for assessment of mortality were consistent with other studies in which stored-product beetles were exposed to lethal temperatures. Three replications of each test were conducted. After mortality was assessed and recorded, the insects were discarded.

2.3. Heating system selection

The five heating systems tested on the outdoor and inside grain bins were selected as follows:

- Electric system 1. An electric duct heater with an interior fan distributor. This system was selected to emulate a typical, low-temperature grain-drying system and was the largest heater, 18 kW, that could be found for the existing electrical system (480 V, 30 A).
- Electric system 2. Same as electric system 1 but with recirculation of the warm exhaust air and no interior distributor.
- Electric system 3. Portable electric heater (rated at 15 kW by the manufacturer: Chromalox, Inc., Pittsburgh, PA) with recirculation. Selected because it was the largest heater that could be found for the available electrical system (208 V, 50A).
- Propane system 1. Portable propane heater at high output, 29 kW. Selected because it was a standard-size, low-cost, and readily available forced-air heater (three-stage heater with manufacturer ratings of 19.0, 24.9, and 29.3 kW, Master Distributors, Grand Rapids, MI).
- Propane system 2. Portable propane heater at low output, 19 kW, was the low output setting of propane system 1 and selected to be comparable to the power of electric system 1.

A daytime high temperature of 26.7 °C or higher was required before starting a test so there would be consistent starting temperatures for all tests. The temperature of 26.7 °C was selected because it was consistent with the summer normal daytime high temperatures and the heater power ratings that had been selected to work at those temperatures.

2.4. Electric systems

Electric system 1 simulated a bin designed for low-temperature grain drying. These types of bins could likely be heat treated as part of an IPM approach, with only minor modifications. The heater was installed in the air-supply duct between the bin wall and fan of bin 3. The fan inlet was restricted to reduce airflow from this large drying fan (18.6 kW motor) to 0.33 m^3/s. The low airflow was required to limit heat loss in the exhaust air. An interior fan-distribution system was used to distribute heated air beneath the drying floor inside the bin. A 0.75 kW, tube-axial fan was placed inside the bin in the center on the drying floor with 12, 8.9-cm diameter metal flex tubes attached to an inlet manifold. Each of the individual metal flex tubes extended to the perimeter of the bin and below the drying floor, which was covered with a tarp to force the hottest air to flow beneath the drying floor. The flex tubes were spread around the perimeter with a greater concentration around the furthest point from where the heat entered the bin. Six of the tubes were placed in the

quadrant opposite that from where the heat entered the bin (north quadrant), three each in the east and west quadrants, and none in the south (heat entrance) quadrant.

For electric system 2, the interior fan/manifold distribution system was removed. A 25.4-cm diameter insulated flexible tube connected the heater's air inlet to a port entrance on the bin roof. Airflow was doubled to 0.66 m^3/s to provide better air distribution than the low airflow provided; the higher rate did not cause more heat loss in exhaust air because air was being recirculated with this system rather than being exhausted from the bin. Weights were placed on the tarp to keep it in place with this airflow. Fiberglass-insulated hard duct board was formed around the metal flange on the exterior, between the heater and bin wall, to limit heat loss.

For electric system 3, a similar method of recirculating heated air back to the heater inlet was used, as with electric system 2, using a 25.4-cm diameter insulated flexible tube. Airflow of 0.66 m^3/s was obtained by adding a 0.75 kW aeration fan to the inlet to supplement the portable electric heater fan. A weighted tarp was used again to force heated air below the drying floor.

2.5. Propane systems

The propane heater was modified with a pressure switch wired to turn off the propane supply and disable the unit if the fan blower malfunctioned. A thermal switch limited ambient air temperature entering the heater to 29.5 °C because, according to the manufacturer, temperatures above that could disable the unit. A small forced-air fan was attached to the heater's electrical component box to help cool the unit. An additional safety feature included in the system was a propane leak detector with shut-off valve. Two 45.4-kg propane tanks were connected to the unit. Propane tests were conducted on bin 1. The heater was connected to the plenum, with an insulated transition, through the existing drying-fan opening.

Data were analyzed separately for each heating system, with floor location and time interval as main effects for insect mortality. The General Linear Models procedure (SAS Institute, 2002) was used for data analysis and to separate means when main effects were significant. Mortality was compared when appropriate using the *t*-test procedure of SAS.

3. Results and discussion

All control arenas had 0% mortality for each heating system for *T. castaneum*, and *R. dominica*. Controls had 0% mortality for *S. oryzae*, except for propane systems 1 and 2, which had a maximum mortality of two rice weevils per arena for each of the three replications. Propane system 1 (29 kW) was the most effective resulting in 100% mortality, with standard error of 0.0, for all insects within 2 h and raising all test locations in the treated bin above 50 °C. However, this was accomplished at the expense of localized overheating, particularly below the drying floor near the heat source. Temperatures were significantly different above and below the floor and between time intervals for this heating system (Table 2). Temperatures in the bin below the drying floor reached a maximum of 112 °C. Bin temperatures crossed the 50 °C threshold, (Fig. 2A) in less than 1 h. Lower temperatures in

Table 2
Electric and propane heating systems mean temperature (mean ± SE) above 40 °C for each floor location and time interval

Heating system	Floor location	Time (h)		
		12	27	40
1. Electric system 1 (18 kW)	Above	52.2 ± 1.5 aA	52.4 ± 1.6 aA	52.9 ± 1.4 aA
	Below	54.4 ± 1.2 aA	55.4 ± 1.2 aA	56.3 ± 1.1 aA
2. Electric system 2 (18 kW)	Above	55.6 ± 1.2 aA	57.0 ± 0.6 aA	57.5 ± 0.7 aA
	Below	52.4 ± 1.4 aA	54.0 ± 1.1 aA	54.9 ± 1.2 aA
3. Electric system 3 (15 kW)	Above	45.1 ± 1.2 aA	48.2 ± 1.1 aA	47.3 ± 0.8 aA
	Below	48.8 ± 0.3 bB	51.7 ± 0.5 bA	51.7 ± 0.3 bA
		Time (h)		
		2	3	4
4. Propane system 1 (29 kW)	Above	59.4 ± 0.9 aA	61.9 ± 0.9 aA	60.1 ± 3.1 aA
	Below	67.3 ± 0.5 bA	70.1 ± 0.4 bB	71.9 ± 0.3 bC
		Time (h)		
		4	6	8
5. Propane system 2 (19 kW)	Above	49.5 ± 3.1 aA	51.3 ± 2.9 aA	52.2 ± 2.6 aA
	Below	53.1 ± 0.7 aA	55.0 ± 0.9 aA	56.4 ± 1.0 aA

For each of the five heating systems, means for above and below the floor followed by the same lower-case letter are not significantly different; means between time intervals followed by the same upper-case letter are not significantly different ($P \geqslant 0.05$, Waller–Duncan *k*-ratio *t*-test).

the other test applications resulted in less than 100% mortality, except in electric system 1 (18 kW) at the 40-h test (Tables 3 and 4).

All test applications, except electric system 3, produced localized overheating causing the mean temperature profiles to be above 50 °C for most of the tests. Even though most means were above 50 °C, many tests had localized cool spots that did not reach 50 °C. Test locations farthest from the heat source under the floor increased in temperature slowly. Because the heat entered on one side under the floor, the greatest overheating occurred under the floor. Because the under-floor supports impeded airflow, the greatest under heating also occurred under the floor. Above the floor, there was less temperature variation, less overheating, and rarely any under heating. The net result below the floor produced higher mean temperatures than above the floor, but also produced lower overall mortality in many cases because of the under heated locations below the floor. The mortality results below 100% (Tables 3 and 4) corresponded to cases where some under heated locations did not reach the 50 °C target.

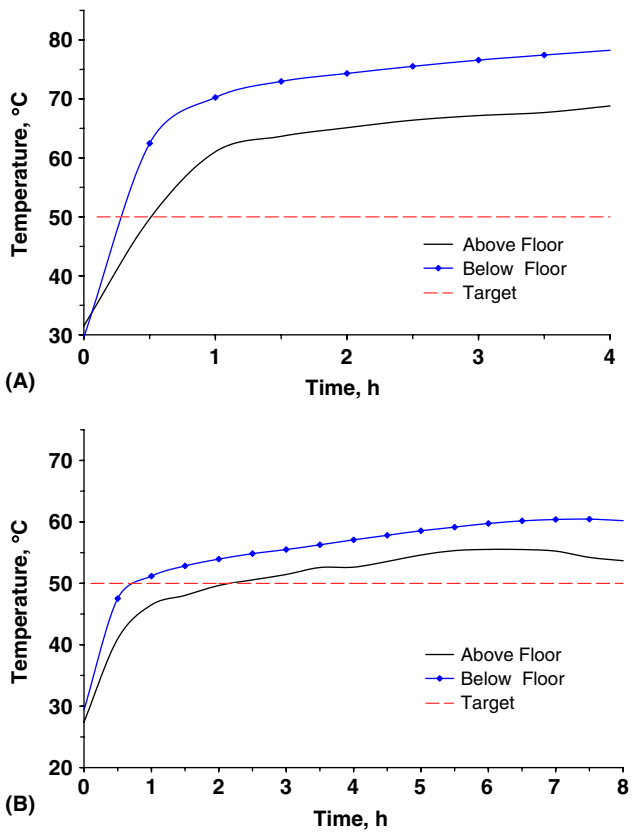

Fig. 2. Propane system 1 (A, 29 kW) and 2 (B, 19 kW), respectively; mean-temperature profile above and below the drying floor of a steel grain bin from three independent replications. A horizontal dashed line indicates the 50 °C target temperature.

Under heated locations could possibly occur in grain debris both above and below the flooring. Grain debris above the flooring should be removed prior to the heat treatment; material below the flooring is likely to be of minimal thickness, which would allow heat penetration. Insects would likely penetrate debris, attempting to survive, but it is unlikely decreased mortality would occur in locations that have minimal quantities of debris. Additional research would be required to determine the rate of heat penetration in larger piles and if treatment times would need to be extended to achieve adequate mortality in any such piles.

Decreased mortality in under heated locations was similar to that reported by Dowdy and Fields (2002) when heat treating a flour mill, where the slower rate of temperature increase was suspected as allowing time for insects to produce heat-shock proteins (HSP) that offered protection at higher temperatures (Denlinger et al., 1991). Quickly raising the bin temperature above 50 °C with the 29 kW propane system 1 resulted in 100% mortality and likely prevented insects from establishing HSP. Increasing the bin temperature quickly may also help prevent insects from fleeing the heat; but during a slow temperature increase, insects have more time to migrate to cooler areas attempting to survive.

Table 3
Propane system 2 (19 kW), insect mortality rate (% mean ± SE) of *Sitophilus oryzae* (L.), *Tribolium castaneum* (Herbst), and *Rhyzopertha dominica* (F.)

Insect species	Floor location	Time (h)		
		4	6	8
1. *S. oryzae*	Above	100 ± 0.0 aA	100 ± 0.0 aA	100 ± 0.0 aA
	Below	80.0 ± 10.0 aA	98.7 ± 1.3 aA	93.3 ± 6.6 aA
2. *T. castaneum*	Above	82.0 ± 10.6 aA	99.0 ± 1.0 aA	100 ± 0.0 aA
	Below	46.6 ± 6.6 bB	76.0 ± 0.0 bA	78.6 ± 7.4 bA
3. *R. dominica*	Above	77.6 ± 14.6 aA	94.6 ± 3.9 aA	100 ± 0.0 aA
	Below	52.0 ± 6.1 aB	74.6 ± 3.5 bA	82.6 ± 1.3 bA

Each of three replications had insect arenas positioned at independent locations with six above and five below the steel grain bin drying floor. Each arena contained five insects of each of three species, with insect mortality determined for three time intervals.
For each of the three species, means for above and below the floor location followed by the same lower-case level are not significantly different; means between time intervals followed by the same upper-case letter are not significantly different ($P \geqslant 0.05$, Waller–Duncan k-ratio t-test).

Table 4
Electric heating system insect mortality rate (% mean ± SE) of *Sitophilus oryzae* (L.), *Tribolium castaneum* (Herbst), and *Rhyzopertha dominica* (F.)

Heating system	Insect species	Floor location	Time (h)		
			12	27	40
Electric system 1 (18 kW)	*S. oryzae*	Above	100 ± 0.0 aA	95.3 ± 4.6 aA	100 ± 0.0 aA
		Below	81.3 ± 14.8 aA	100 ± 0.0 aA	100 ± 0.0 aA
	T. castaneum	Above	88.6 ± 11.3 aA	86.6 ± 13.3 aA	100 ± 0.0 aA
		Below	44.0 ± 2.3 bB	50.6 ± 5.8 aB	100 ± 0.0 aA
	R. dominica	Above	87.6 ± 12.3 aA	86.6 ± 13.3 aA	100 ± 0.0 aA
		Below	49.3 ± 1.3 bB	54.6 ± 2.6 aB	100 ± 0.0 aA
Electric system 2 (18 kW)	*S. oryzae*	Above	100 ± 0.0 aA	100 ± 0.0 aA	100 ± 0.0 aA
		Below	98.6 ± 1.3 aA	100 ± 0.0 aA	100 ± 0.0 aA
	T. castaneum	Above	100 ± 0.0 aA	100 ± 0.0 aA	100 ± 0.0 aA
		Below	56.0 ± 14.0 bA	74.6 ± 5.3 bA	81.3 ± 1.3 bA
	R. dominica	Above	100 ± 0.0 aA	100 ± 0.0 aA	100 ± 0.0 aA
		Below	53.3 ± 13.3 bA	73.3 ± 6.6 bA	81.3 ± 1.3 bA
Electric system 3 (15 kW)	*S. oryzae*	Above	100 ± 0.0 aA	100 ± 0.0 aA	100 ± 0.0 aA
		Below	77.3 ± 2.6 bB	100 ± 0.0 aA	100 ± 0.0 aA
	T. castaneum	Above	100 ± 0.0 aA	100 ± 0.0 aA	100 ± 0.0 aA
		Below	49.3 ± 5.8 bB	84.0 ± 8.3 aA	89.3 ± 3.5 bA
	R. dominica	Above	89.6 ± 5.2 aA	100 ± 0.0 aA	100 ± 0.0 aA
		Below	49.3 ± 5.8 bB	76.0 ± 4.0 bA	85.3 ± 2.6 bA

Each of three replications had insect arenas positioned at independent locations of six above and five below the steel grain bin drying floor. Each arena contained five insects of each of three species, with insect mortality determined for three time intervals. Every control arena had 0% mortality for all insects.

For each of the nine combinations of heating system and insect species, means for above and below the floor location followed by the same lower-case letter are not significantly different; means between time intervals followed by the same upper-case letter are not significantly different ($P \geqslant 0.05$, Waller–Duncan k-ratio t-test).

Temperature-related mortality is often linked to duration of insect heat exposure (Dowdy, 1999; Dowdy and Fields, 2002; Mahroof et al., 2003b). Arthur (2006) reported that complete mortality of all life stages at temperatures of 51 and 54 °C should occur in a matter of hours; therefore, even the most heat-tolerant insect stages should be killed during a normal heat treatment. The adult life stage was tested in all heat treatment applications. However, complete mortality of all life stages in the grain bin would likely occur in a matter of hours when temperatures exceed 50 °C.

With the propane heater output reduced to 19 kW, temperatures decreased by a maximum of 30 °C below the drying floor when compared to the 29 kW results. The lower bin temperature produced lower mortality rates, particularly below the drying floor. The *T. castaneum* and *R. dominica* had significantly different mortality rates below the floor between 4 and 6 h and both above and below the floor for each time period, except the 4-h period for the *R. dominica*. The efficacy of the treated bin was mainly a function of the heater's power rating and ambient temperature for the tested systems, although use of an interior distribution system or recirculation of exhaust air increased test temperatures for the systems with marginal power output.

Electric system 1 (18 kW) reached the critical 50 °C threshold mean temperature in 2.3 h at all test locations above the drying floor. Below the floor, the mean temperature reached 50 °C in 2 h (Fig. 3A), but locations farthest from the heat source increased much slower. The *T. castaneum* and *R. dominica* had significantly different mortality rates between 12 and 27 h. The differences in mortality rates are likely due to localized overheating and underheating below the floor. After 40 h, electric system 1 resulted in 100% mortality at all test locations. However, the energy requirement for electric system 1 was much greater than for the other heating systems (Table 1), which would increase the total cost of this system.

All of the test-location temperatures were affected by outside temperatures, decreasing slightly as the ambient air-cooled and increasing as the air temperature increased. This effect was particularly noticeable during tests with electric system 3 (Fig. 3C). Electric system 3 tests were conducted on bin 1, located outside; and electric system 2 was conducted with bin 3, located inside. The high mid-day ambient air temperature, combined with solar radiation on the steel bin, raised the temperatures between 16 and 24 h as shown in Fig. 3C. The electric system 3 mortality below the floor increased significantly between 12 and 27 h (Table 4) for each insect species. This indicates that

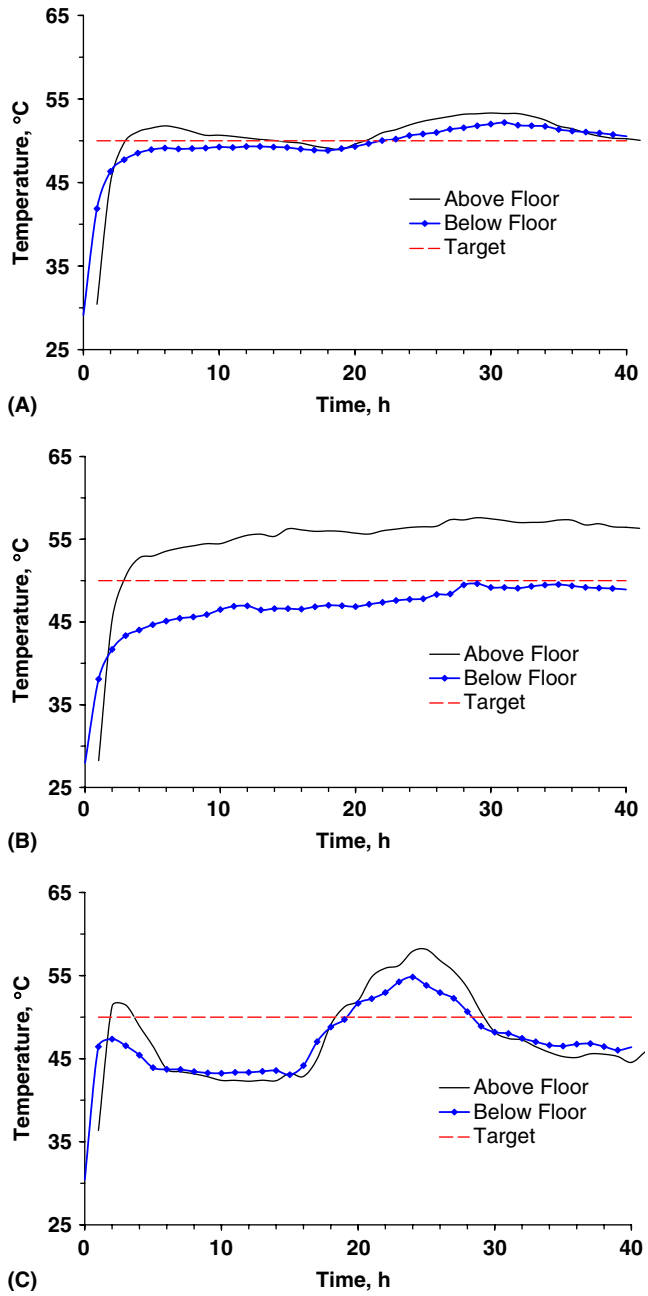

Fig. 3. Mean-temperature profile above and below the grain bin drying floor from three independent replications for electric systems 1, 2, and 3 in A, B, and C, respectively; electric system 1 is an 18 kW duct heater with a distributor; electric system 2 is an 18 kW duct heater with recirculation; electric system 3 is a portable 15 kW heater with recirculation. A horizontal dashed line indicates the 50 °C target temperature.

distribution of air below the flooring approached a minimum of 50 °C or higher, between 12 and 27 h. Although the below-floor mean temperature profile for this system was greater than 50 °C between 2 and 4 h (Fig. 3C), localized overheating and under heating occurred as indicated by low mortality at 12 h. The system had significantly different mortality rates above and below the flooring for the *R. dominica* at 12, 27, and 40 h; for the *T. castaneum* at 12 and 40 h; and for the *S. oryzae* at 12 h. Also, the above- and below-flooring temperatures were significantly different for each time interval (Table 2), likely due to the distribution of air. *S. oryzae* mortality occurred at lower temperatures and much earlier in each test application compared to the *T. castaneum* and *R. dominica*, which showed that this species was much more susceptible to control by heat treatment than the other two.

Electric system 2 resulted in 100% mortality above the flooring for each insect species. Below-floor mortality was excellent for the *S. oryzae* and was significantly different at each time interval for the *T. castaneum* and *R. dominica* (Table 4). However, electric system 1 had 100% mortality after 40 h of operation. The high efficacy of this system was likely due to the interior distribution system that helped reduce the cool spots, combined with high ambient air temperatures. The interior distribution system pulled hot air across the bin below the drying floor, providing more heat to locations farthest from the heat source. When the interior distribution system was replaced by recirculation (electric system 2), mean temperatures were higher while mortalities were lower. All three electric systems had borderline power available to heat treat the steel grain bin. Electric system 2 produced temperatures above the drying floor greater than 50 °C for 37 h and a minimum of 6.6 h during electric system 3 tests. But as the ambient temperature began to decrease late in the day with electric system 3, test temperatures decreased and fell below 50 °C for all locations above the drying floor (Fig. 3C).

Disinfestation of empty steel grain bins prior to storage was successful with some of these readily available systems tested for heat treatment. However, if heat treatments are to receive widespread usage, development of heat tolerance should be closely monitored. Thermotolerance, or the ability to withstand elevated temperatures in organisms, including insects, is attained by genetic adaptation, long-term thermal acclimation, and rapid heat hardening (Hallman and Denlinger, 1998). One of the physiological changes an organism undergoes during the process of developing thermotolerance is the expression of HSP (Currie and Tufts, 1997). These proteins can be monitored to detect development of increased thermotolerance in insect populations that experience continued heat treatments (Mahroof et al., 2006).

4. Conclusions

The best-performing heat-treatment systems tested provided an effective method for pre-binning sanitation as part of an integrated pest management program. Specific conclusions based on the results of these tests were as follows:

- The 29 kW propane system was the most effective, producing 100% mortality for all three insect species in 2 h.
- The 18 kW electric system with duct heater and interior fan/manifold distribution was effective after 40 h of

operation, but required a complicated setup to achieve adequate heat distribution.

- Ambient temperatures and heater power rating were the biggest factors in determining the success of a heat treatment; however, coordinating with times of high ambient temperature enhanced the efficacy of heat treatments.
- Effective heat treatments were obtained when heater power rating was adequate. Effective heat treatments were also possible in some cases with marginal heater power ratings, but these systems required extra effort to recirculate exhaust air or distribute the heat to maximize the limited available power.

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