Heat treatment: A viable methyl bromide alternative for managing stored-product insects in food-processing facilities

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Abstract

Heat treatment involves raising and maintaining temperatures of grain storage structures, warehouses, and food-processing facilities between 50 to 60°C to manage stored-product insect species. The duration of heat treatment is application-specific and may vary from 6 h for an empty storage facility to 24 h for an entire food-processing facility. Laboratory and commercial trials with high temperatures during the last decade, especially with forced air gas heaters, have resulted in a wealth of information on (1) understanding responses of insect species and life stages to heat, (2) heat distribution within a treated area, and (3) techniques necessary for gauging effectiveness of commercial heat treatments. Insect responses vary with the temperature, among species, and within a species among life stages. Air movement and strategic placement of fans are important for eliminating cool spots (<50°C) and for uniformly heating a treated area. Insect bioassays and monitoring insect populations before and after a heat treatment are important to understand the degree and duration of insect suppression obtained in commercial facilities. Heat treatments are safe, effective, and a viable tool for the organic and non-organic sector. Research in both laboratory and food-processing facilities has shown heat treatments to be a viable alternative to methyl bromide fumigation.

Keywords: Heat, Forced air, Flour mills, Methyl bromide alternative

1. Introduction

Heat treatment, a 100-year old technique (Dean, 1911), involves raising the temperature of a room, equipment, or an entire facility to 50 to 60°C to kill insects, primarily stored-product insects (Heaps, 1994; Mahroof et al., 2003a,b; Roesli et al., 2003; Beckett et al., 2007). The duration of the heat treatment depends on the site being treated. Whole facility heat treatments typically last 24-36 h. There is renewed interest in exploring heat treatments as an alternative to methyl bromide, a structural fumigant that has been phased out in the United States, Canada and Europe, except for certain critical uses, because of its adverse effects on stratospheric ozone levels (Makhijani and Gurney, 1995).

Electric heaters, forced air gas heaters (Figure 1), or steam heaters (Figure 2) can be used to conduct a heat treatment. With the forced air gas heaters the building is placed under positive pressure during a heat treatment, and the entire air within the building is exchanged four to six times per hour. The number of air exchanges when using electric and steam heaters may be one or two per hour. The forced air also allows heat to reach gaps in the building and equipment much better than electric or steam heaters. The forced air gas heaters can use natural gas or propane as fuel. Since these heaters have an open flame they are placed outside a facility, and nylon ducts (Figure 1) are placed within the facility to introduce heated air. Hot air has a tendency to stratify horizontally and vertically within a facility. Therefore, several fans should be placed on different floors of a facility to redistribute heat and to uniformly heat a facility. Fan placement is an art, and during heat treatments, fans should be moved to eliminate cool spots-areas where the temperature is less than 50°C. In addition to food-processing facilities, heat treatment can also be used in empty storage structures (bins, silos), warehouses, feed mills, and bakeries. It is an environmentally benign method for managing insects.

Figure 1 Propane-fired heater (Temp-Air) heater (source of heat for studies in Figure 3 and 4). The door was sealed with plywood, and a flexible fabric duct delivered heated air through a hole cut in the plywood,

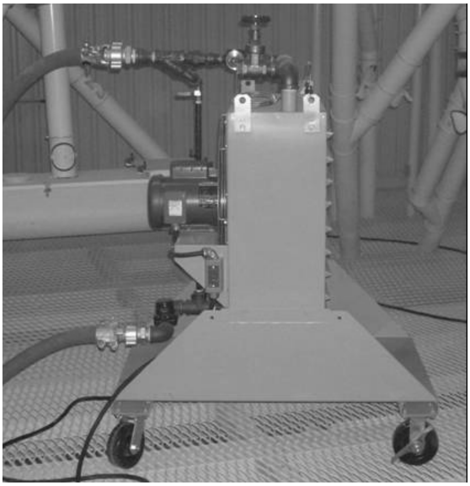

Figure 2 Portable steam heater (Armstrong International Inc.) used in heat treatment (Fields, 2007).

2. Heat treatment of commodities versus structures

Heat has also been used to disinfest perishable and dry, durable food products. High temperature treatments are used for disinfestations of dried fruits and nuts, perishable commodities (fruits) (Hansen and Sharp, 1998), and grains (Beckett and Morton, 2003). Facility heat treatments are distinctly different from heat treatment of fresh fruits, nuts, or grains. In facility heat treatments, heaters are used to slowly heat the ambient air. A long heat treatment period is necessary for the heat to penetrate wall voids and equipment to kill insects harbouring in them. A typical heat treatment may last 24-36 h (Mahroof et al., 2003a; Roesli et al., 2003). In heat treatments of fresh commodities, nuts, dried fruits, or grains, high temperatures of 60-85^{o}C are used for short time periods (in min). Typical heating rates during heat treatment of perishable commodities, nuts, dried fruits, and grains range from 1-15^{o}C per minute, whereas during facility heat treatments heating rates should generally be around 3-5^{o}C per hour for effective disinfestation. However, in both cases the products or the facility subjected to high temperatures are allowed to cool to ambient temperature, and this may take several hours. During heat treatments, it is important to remove all food products and packaging materials (bags) from the facility. Equipment should be opened and thoroughly cleaned of any food product where possible. It is important during heat treatments of products to ensure that the quality is not affected. Similarly, in the case of structural heat treatments, it is important to ensure that there is no damage to the equipment, uninfested materials stored within the facility, and the structure.

3. Issues to consider before a heat treatment

Dosland et al. (2006) gave detailed step by step procedures for conducting and evaluating a facility heat treatment. One important aspect of conducting an effective heat treatment involves calculating how much heat energy is required after accounting for heat losses due to exposed surfaces, equipment, and infiltration. Research at Kansas State University and discussions with heat service providers showed that the amount of heat energy should range from 0.074-0.102 kW per cubic meter of the facility per h, and during a 2009 heat treatment of a flour mill at Kansas State University, the heat energy used was as high as 0.16 kW per m^3 per h. An indirect method of determining whether or not adequate heat energy is being used is by observing how quickly ambient temperatures reached 50°C. In proper heat treatments, the time to reach 50°C should usually take about 8-10 h, and depending on the time of year and the leakiness of a structure, this time can take as long as 15 h.

4. Characterizing temperature profiles

A typical temperature profile during heat treatment is shown in Figure 3. From the temperature data, the following information should be extracted: the time taken to reach 50°C, the time temperatures were maintained above 50°C and the maximum temperature (Mahroof et al., 2003a; Roesli et al., 2003). The time to reach 50°C is important to determine the heating rate, which is calculated as the difference between 50°C and the ambient temperature at the start of the heat treatment divided by the time to 50°C. This rate should be between 3 and 5°C per hour in properly conducted heat treatments for effective disinfestation. Temperatures should be held at least for several hours above 50°C to kill insects. The maximum temperature should not exceed 60°C to prevent any structural damage or damage to equipment. Information broken down in this fashion can be related to insect mortality if live insects confined in cards or vials are used to gauge the effectiveness of a heat treatment.

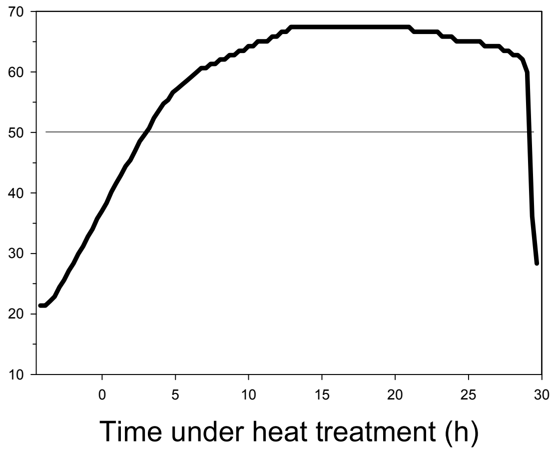

Figure 3 Temperature during a heat treatment (Fig. 4) in a flour mill using propane-fired heaters (Fig. 1).

5. Effects of heat on insects

Lethality in insects at high temperatures depends on both the temperature and time of exposure (Denlinger and Yocum, 1999; Evans and Dermott, 1981; Fields, 1992; Mahroof et al., 2003b). Temperature and exposure time to achieve a certain percentage of insect kill are inversely related. At high temperatures insect cuticular wax becomes compromised allowing loss of water. This affects water balance in insects, leading to death by desiccation as well (Hepburn, 1985). High temperature exposure denatures proteins, affects hemolymph ionic balance and pH, and adversely affects enzyme activity (Denlinger and Yocum, 1999; Neven, 2000).

High temperatures that do not kill insects can adversely affect the insect's reproduction. Recently, Mahroof et al. (2005a) have shown that when pupae and adults of the red flour beetle, *Tribolium castaneum* (Herbst) were exposed to 50°C for 39 and 60 min, respectively, the surviving adults from these insects showed significant reduction in oviposition, egg-to-adult survival rate, and progeny production.

6. Heat tolerance in insects

Insects when exposed to high temperatures may produce heat shock proteins (HSPs). Generally, these proteins protect the cells by preventing aggregation or improper folding of proteins (Currie and Tufts, 1997). There are several families of HSPs largely classified by molecular weight. HSP 70 is one of the most highly conserved heat shock proteins with the largest specific activity and thus may be easy to detect (Currie and Tufts, 1997). The heat tolerance in young larvae of *T. castaneum* was due to increased expression of HSP 70 (Mahroof et al., 2004; 2005b). Time, and temperature-dependent expression of HSP 70 showed that the increased heat tolerance in young larvae lasted only as long as 8 h at 40°C or 30 min at 46°C (Mahroof et al., 2004) The HSP 70 may not confer tolerance to *T. castaneum* at temperatures of 50-60°C typically used during heat treatments.

The stage that is heat tolerant varies with the species (Table 1), especially at temperatures between 50 and 60°C. Mahroof et al. (2003b) and Boina and Subramanyam (2004) have shown that the heat tolerance of a stage varies with the temperature, and tolerance to heat at temperatures of 50-60°C is therefore more important than at temperatures below 50°C. All of these studies were based on laboratory studies at fixed temperatures. Heat tolerance of life stages of a species has not been determined during commercial heat treatments, and experiments should be designed to confirm laboratory findings with field data.

Table 1 Time for 99% mortality of heat tolerant stages of four stored-product insect species at constant temperatures between 50 and 60°C.

Species	Stage	Temp. (°C)	LT_{99} (95% CL) (min)	Reference
T. castaneum	Young larvae	50	433 (365-572)	Mahroof et al. (2003a)
		54	82 (60-208)	
		58	38 (29-76)	
		60	24 (20-33)	
T. confusum	Old larvae	50	90 (82-102)	Boina & Subramanyam(2004)
		54	56 (49-67)	
		58	38 (30-71)	
		60	24 (20-33)	
P. interpunctella	Old larvaea	50	34 (29-43)	Mahroof & Subramanyam (2006)
		52	34 (26-67)	
L. serricorne	Eggsb	50	190 (170-220)	Chun Yu (2008)
		54	39 (36-43)	
S. paniceum	Young larvae	50	234 (176-387)[c]	Abdelghany et al. (2010)d
		55	10.8 (6.6-13.8)	
		60	4.8 (4.2-4.8)	

[a]Fifth instars; [b]Time-mortality relationships were based on egg hatchability data; [c]These values are LT_{90s} (95% CL);
[d]Abdelghany A.Y., Awadalla, S.S., Abdel-Baky, N.F., EL-Syrafi, H.A., Fields, P.G., 2010 (unpublished data).

6.1. Flour mill treatment with six insects; methods

The following insects were used in tests of efficacy of heat treatments in flour mill: *Stegobium paniceum* (L.), *Lasioderma serricorne* (F.), *Cryptolestes ferrugineus* (Stephens), *T. castaneum*, *Tribolium confusum* Jacquelin du Val and *Tenebrio molitor* (L.). All insects were adults, except for *T. molitor* which was exposed as late instar larvae and *S. paniceum* which exposed as young larvae (5-d old) and as adults. Insects were reared at 30°C, 60% r.h., except *T. molitor* which was reared at room temperature.

Field data was collected in Western Canada at a medium-sized mill on 23-24 October, 2008. The various species were prepared at the Cereal Research Center, Agriculture & Agri-Food Canada, Winnipeg, Canada. Ten grams of wheat flour mixed with brewers yeast (95:5 by weight) was placed into a vial (29 mm diameter with 50 mm high) and 50 insects of a given species were placed into the vial with sealed with a screened lid. There were three days between placing the insects in the vials and the exposure to heat in the mill. During shipment, the insects experienced the temperatures between 20 to 30^{0}C. Seven vials, one for each species, were grouped tightly around a HOBO data logger and twelve sets of seven vials were placed on the floor of the mill in a ring with about 20 cm diameter at two locations in the mill. At the middle of the ring, there was one set of vials for measuring flour temperatures, with the same amount flour and yeast, but without insects. The temperatures inside these vials were measured by introducing T-type thermocouples which were connected with HOBO data logger (Onset Computer Corporation, Bourne, MA). The tip of a thermocouple was located at the flour center inside the vial.

The mill was heat treated from 9:15 am 23 October 2008 until 10:00 am 24 October 2008. During that period, groups of the vials were taken out of the mill, one set at a time when the flour temperatures reached approximately; 32, 35, 37, 40, 42, 45, 47, 50, 52, 55 and 60°C. The vials were shipped back to the laboratory and held at 30°C, 70% r.h. until the emergence of adults for *S. paniceum* and *T. molitor* larvae. The survival of adults was assessed upon arrival at the laboratory.

6.2. Flour mill treatment with six insects; results

Lasioderma serricorne in location 1A and *L. serricorne* and *S. paniceum* larvae in location 1B all had greater than 20% mortality at temperatures below 35^{o}C, therefore the mortality was adjusted by using Abbott's equation (Abbott, 1925). Although there were large differences in response of insects to heat, there was significant deviation from the probit model making it impossible to calculate the lethal time for 50% of the population (LT_{50}) using probit analysis. We estimated LT_{50} graphically (Figure 4). In general, *C. ferrugineus* was the most heat tolerant, *T. molitor* larvae was the least heat tolerant with the other species falling between these two extremes.

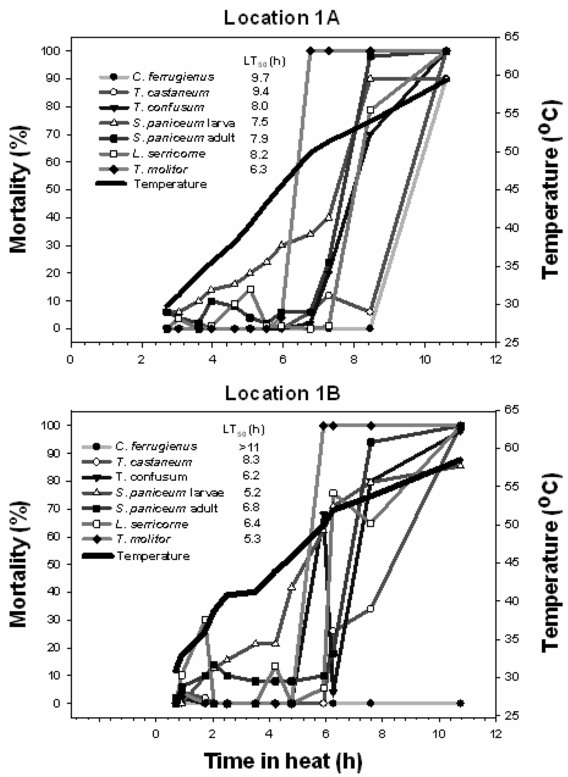

Figure 4 The lethal time to kill 50% of the population (LT_{50} estimated graphically), mortality of stored-product beetles and temperature during a heat treatment in a flour mill at two different locations in a flour mill.

7. *Gauging heat treatment effectiveness*

To gauge heat treatment effectiveness, it is important to identify critical areas in the facility. These areas are usually places where insects can hide and breed or places where temperatures can not penetrate or reach at least 50°C. Such places are usually identified through inspections. Temperature sensors should be placed in these areas to measure temperatures. Cards with insects such as those marketed by Alteca (www.alteca.com) or insects in vials with food should be placed in critical areas and examined during or after a heat treatment to determine effectiveness against insects. Insects in the cards are usually without food and therefore these stressed or starved insects tend to succumb quickly to a heat treatment, and may falsely indicate that the treatment was effective, when in fact it was not. For example, in a pet food facility, the mortality of adults of *T. castaneum* in cards and in bioassay vials with flour (3 g) were compared. These results showed that during the 23-h-heat treatment, all insects in the cards died at 15 h, whereas in the vials at the end of the heat treatment, the mortality of adults was below 20%. The use of live insects to gauge heat treatment effectiveness provides valuable information, but in some facilities bringing live insects may be prohibited. Resident insect populations within a facility should be monitored before and after a heat treatment. At least thirty-five traps should be used inside the facility and five outside the facility. In some facilities such as flour mills, it is possible to sample tailings to determine insect load. These observations should occur every week and should be resumed soon after a heat treatment. The trapping or visual observations of products/tailings following a heat treatment should be done at least on a daily basis for the first week and should continue weekly for at least 8-16 wk. These data provide valuable information on the degree and duration of control obtained after a heat treatment intervention. Table 2 shows mean trap captures of *T. castaneum* adults before and after a heat treatment of a pasta facility. These data show that a single treatment's effectiveness lasted close to two months, because the facility managers use sanitation and exclusion tactics. Similar heat treatments in Canada has shown that heat treatments can be effective for over 5 mon (Fields, 2007) The doors and windows should be tightly closed to prevent insects from outside coming into a facility. Insects can be brought into a facility on raw materials, and care must be taken to inspect all materials to ensure that they are insect-free. Inspection, sanitation and exclusion practices can help extend the degree and duration of insect suppression obtained with a heat treatment.

Table 2 Captures of *T. castaneum* adults in pitfall traps before and after a heat treatment of a pasta facility in 2006.

Date	**Mean number of adults/trap/week**[a]		
	Press room	**Flour room**	**Outside**
May 30	0.46	0.40	0.50
June 14	0.20	0.42	0.65
June 28	0.32	0.65	0
July 4	**Heat treatment**[b]		
July 11	0 (100%)c	0.09 (86%)c	0
July 25	0.03	0.10	0.38
August 8	0	0.05	0.50
August 23	0.01	0.05	0.20

Source: Bh. Subramanyam (unpublished data); [a]The number of traps in the press room, flour room, and outside was 35, 10, and 5, respectively; [b]Traps were replaced immediately after the heat treatment was done; [c]Percentage reduction in trap catch, based on catch just prior to the heat treatment.

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