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Extreme Temperatures

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Extreme temperatures, at or above 50°C and at or below 15°C, can be used to disinfest commodities and structures. Controlling stored-product insect populations with extreme temperatures offers a number of advantages. These techniques are environmentally benign, no registration or special licenses are required for application, and to our knowledge, insects do not develop resistance, as they do to chemical pesticides. A number of challenges prevent the widespread adoption of these techniques. They require extensive capital investment (grain chillers or heaters), treatments may be limited to certain times of year (winter for aeration, summer for heat treatments), and equipment or products may be damaged if techniques are used improperly (Fields 1992, Beckett et al. 2007).

The responses of stored-product insects to extreme temperatures are well documented (Fields 1992; Mason and Strait 1998; Burks et al. 2000; Beckett et al. 2007). Three temperature zones are significant for growth or death of stored-product insects. At optimal temperatures (25 to 32°C), insects have maximum rate of increase. At suboptimal temperatures (13 to 24°C and 33 to 35°C), development slows, and at lethal temperatures (below 13°C and above 36°C), insects stop feeding, develop slower, and eventually die. The more extreme the temperature, the more quickly they die (Table 1). These are general guidelines. Each insect species, stage, and physiological state will affect the particular response to temperature (Fields 1992). No stored-product insects can survive freezing. The target insect freezing point is the temperature that needs to be obtained to kill the insects instantly. The insect freezing point varies by species, stage, and physiological state between -4.0 and -22.0°C (Table 2). Insects die before they freeze. As temperature decreases, it takes less time to control insects (Fields 1992, Burks and Hagstrum 1999). Fields (1992) summarized times and temperatures required to control specific life stages of stored-product insects.

Low Temperatures

Commodities

Three methods to reduce temperature of bulk-stored grain are turning, ambient air aeration, and chilled aeration (Fields 1992; Mason and Strail 1998; Burks et al. 2000). Once cooled, grain will remain cool even with high outside air temperatures, because bulk grain is a good insulator. Turning bulk grain does little to reduce overall temperature because there is little opportunity for heat transfer, even in winter. “Hot spots,” or isolated pockets where grain heats up due to insect or microorganism activity, will be broken up. The disadvantages of turning grain include energy cost, empty bins needed to receive grain, and grain breakage, which is a problem particularly in maize.

Ambient air aeration is the most common method of cooling bulk grain. Aeration is discussed in depth in Chapter 11 of this book, Grain Aeration (Narrvarro et al. 2011). Aeration often is used to dry grain, but cooling requires smaller fans and weaker air flows. Automatic aeration systems simplify the operation,

Table 1. *Response of stored-product insect pests to temperature.*

Zone	Temperature range (˚C)	Effects
Lethal	above 62	death in < 1 min
	50 to 62	death in < 1 h
	45 to 50	death in < 1 day
	35 to 42	populations die out, mobile insects seek cooler environments
Suboptimal	35	maximum temperature for reproduction
	33 to 35	slower population increase
Optimal	25 to 32	maximum rate of population increase
Suboptimal	13 to 24	slower population increase
Lethal	5 to 13	slowly lethal
	3 to 5	movement ceases
	0 to -10	death in weeks, or months if acclimated
	-15 to -25	death in < 1 h

Adapted from Fields, 1992.

by starting the fans when ambient air is cooler than the grain. Overdrying grain to below the moisture content required by the grading authorities can be a commercial concern. Grain dries the greatest amount at the warmest temperatures.

Chilled aeration (Figure 1) is the most expensive method for cooling grain, but it allows chilling regardless of outside air temperature. It is used commercially in 50 countries around the world to cool about 80 million tonnes of grain annually (Maier and Navarro 2002). Grain is chilled to protect it from mold, insects, and to maintain germination. Chilled grain can be safely stored at higher moisture contents than warm grain. It takes six times more energy to reduce moisture content by 6% than to cool grain from 25 to 5°C. Air is dried and cooled before it is pushed through the grain bulk. Depending on the grain bulk and chilling unit, it takes 2 to 21 days to bring the grain temperature down to 15 to 20˚C, and a second chilling may be required after 2 to 6 months. It takes about 5 kilowatt hours per tonne (kwh/t) to cool grain from about 30 to 15˚C. The costs in the United States were estimated to be $1.50/t compared to $2.90/t for fumigation and aeration (Rulon et al. 1999).

Figure 1. *Grain chillers (From Burks et al. 2000).*

Insects in finished products also can be controlled with low temperatures. Packaged finished product often requires extremely low temperatures or extremely long durations to reach temperatures required to kill insects (Table 3) (Mullen and Arbogast 1979). For certain high value items, flash freezing with liquid nitrogen to obtain -18˚C is recommended. This method has been used for many years to disinfest herbs before processing (Adler 2010).

Structures

In Canada and the northern United States, winter temperatures are sufficiently cold to control insects in structures (Fields 1992). Typically this requires outside air temperatures of -17˚C for 3 days. As with heat treatments of structures described below,

Table 2. *Insect freezing temperatures, or the lowest temperature at which insects can survive. All stored-product insects die when frozen. Mortality will occur at higher temperatures.*

Insect scientific name	Insect common name	Stage	Insect freezing point (°C)
Alphitobius diaperinus[a]	lesser mealworm	adult	-9.4 to -12.3
Cryptolestes ferrugineus	rusty grain beetle	adult	-16.7 to -20.4
Cryptolestes pusillus	flat grain beetle	adult	-14.0
Ephestia kuehniella	Mediterranean flour moth	larval	-16.9 to – 21.7
Gibbium psylloides	hump beetle	adult	-10.7
Oryzaephilus surinamensis	sawtoothed grain beetle	adult	-13.7
Plodia interpunctella[b]	Indianmeal moth	larval	-7.4 to -16.0
		pupal	-5.0 to -22.0
		adult	-22.5
Rhyzopertha dominica	lesser grain borer	adult	-15.2
Sitophilus granarius	granary weevil		-15.0
Sitophilus oryzae[c]	rice weevil	adult	-22.0
Stegobium paniceum[d]	drugstore beetle	larval	-6.5 to -9.0
		pupal	-4.0
		adult	-15.2
Tenebrio molitior	yellow mealworm	larval	-7.7 to -14.9
		pupal	-13.3
		adult	-7.7 to -14.9
Tineola bisselliella[e]	webbing clothes moth	egg	-22.6
		larval	-13.0 to -16.2
		pupal	-16.9
		adult	-18.8
Tribolium castaneum[c]	red flour beetle	adult	-12.3 to -16.0

[a] Salin et al. 1998
[b] Fields and Timlick 2010; Carrillo et al. 2005
[c] Burks and Hagstrum 1999.
[d] Abdelghany et al. 2010
[e] Chavin and Vanier 1997.
Adapted from Fields, 1992.

Table 3. *Chilling times for selected commodities. Commodities were exposed in a 0.76-m^3 freezer filled to capacity.*

Commodity	Freezer setting (°C)	Time to 0°C (h)	Time to equilibrium (h)
Cornflakes (28 1.45-kg boxes)	-10	7	30
	-15	6	30
	-20	5	35
Flour (7 45-kg bags)	-10	55	160
	-15	29	130
	-20	25	145
Elbow macaroni and peas (15 11-kg cases of each)	-10	29	130
	-15	18	95
	-20	19	100

Adapted from Mullen and Arbogast, 1979.

to achieve control, product must be removed from equipment and equipment must be opened up. Good air circulation within the building is needed to insure that sufficiently low temperatures are achieved. Water must be drained from the facility to prevent pipes from freezing and cracking.

Such extreme cooling is not possible in most facilities during much of the year, but any cooling of structures, equipment, and finished product will reduce insect growth and population size in the long run. For example *S. oryzae* held at 29°C and given sufficient food will increase approximately 10,000-fold in 3 months. Insects held at 25.5°C will increase by 1,500-fold, and those held at 18.2°C by only 5-fold (Birch 1953). Food processing equipment can produce a considerable amount of heat and food, causing ideal conditions for insect development and population growth.

High Temperature

Commodities

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 et al., 2007). In heat treatments of fresh commodities, nuts, dried fruits, or grains, heating rates are from 1°C to 15°C/min, and high temperatures of 60°C to 85°C control infestations in a few minutes. It is important during heat treatments of products to ensure that end-use quality is not reduced.

A number of systems are used to heat commodities (Beckett et al. 2007). The Australians developed a 150 tonne per hour (t/h) continuous-flow fluidized bed process that heats grain to 70°C for 2 minutes before recooling the grain. A spouted-bed process with a capacity of 8 t/h is an option for farms. A few studies have shown that grain dryers greatly reduce insect populations. Not all grain reaches temperatures required to kill insects, as is the case in thermal disinfestations units built specifically to control insects. Some modifications to the dryers could increase the efficacy of control (Qaisrani and Beckett 2003; Bruce et al. 2004). Irradiation of commodities and finished products with non-ionizing radiation from microwaves, radio waves, and infrared has been studied extensively. Insects have higher water content (80%) than commodities (5 to 20%), causing insects to heat faster than the commodities they infest. Microwaves have greater power, but radio waves can penetrate deeper into products than infrared radiation. Currently, no commercial units exist to disinfest commodities using microwaves, radio waves, or infrared radiation.

Heat Treatments

Structures

Heat treatment of grain-processing structures (flour mills) is a 100-year old technique (Dean 1911) that involves raising the temperature of a room, equipment, or an entire facility to 50°C to 60°C to control 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. Whole facility heat treatments typically last 24 hours. Depending on the facility, treatment times of 30 to 36 hours are not uncommon. Spot treatment of empty bins or equipment can be completed in as little as 4 to 6 hours (Tilley et al. 2007). There is renewed interest in exploring heat treatments as an alternative to methyl bromide. This structural fumigant 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).

At temperatures between 50°C and 60°C large differences exist between susceptibilities of the life stages (Table 4). Heat tolerance of a stage varies with the temperature. Tolerance to heat at temperatures of 50°C to 60°C is more important than at temperatures below 50°C (Mahroof et al. 2003b; Boina and Subramanyam 2004; Mahroof and Subramanyam 2006; Hulasare et al. 2010). These studies were based on laboratory experiments at fixed temperatures. Heat tolerance of life stages of a species has not been determined during commercial heat treatments. Experiments should be designed to confirm laboratory findings with field data. The heat tolerance of life stages confirmed under laboratory conditions at fixed temperatures could not be confirmed under field conditions (Mahroof et al. 2003a; Yu et al. 2011), perhaps due to heating rate influencing heat tolerance among life stages, an area for further research.

Table 4. *Time for 99% mortality of heat-tolerant stages of four stored-product insect species at constant temperatures between 50°C and 60°C.*

Species	Stage	Temperature (°C)	LT$_{99}$ (95% CL) (minutes)	Reference
Red flour beetle	young larvae	50	433 (365-572)	Mahroof et al. 2003b
		54	82 (60-208)	
		58	38 (29-76)	
		60	42 (34-66)	
Confused flour beetle	old larvae	50	90 (82-102)	Boina and Subramanyam 2004
		54	56 (49-67)	
		58	38 (30-71)	
		60	24 (20-33)	
Indianmeal moth	old larvae[a]	50	34 (29-43)	Mahroof and Subramanyam 2006
		52	34 (26-67)	Yu et al. 2008
Cigarette beetle	eggs[b]	50	190 (170-220)	
Drugstore beetle	young larvae	54	39 (36-43)	Abdelghany et al. 2010
		50	234 (176-387)[c]	
		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)

High temperatures that do not kill insects can adversely affect reproduction. Red flour beetle, *Tribolium castaneum* (Herbst) pupae exposed to 50°C for 39 minutes or adults exposed for 60 minutes resulted in surviving adults from these insects having significantly reduced oviposition, egg-to-adult survival rate, and progeny production (Mahroof et al. 2005).

In facility heat treatments, heaters are used to gradually heat the air in the structure. A long treatment period is necessary for the heat to penetrate wall voids and equipment to kill insects harboring in them. A typical heat treatment may last 24 to 36 hours (Mahroof et al. 2003b; Roesli et al. 2003; Beckett et al. 2007) with heating rates generally around 3°C to 5°C per hour (Figure 2). In effective heat treatments, the time to reach 50°C usually takes about 8 to 10 hours, depending on the time of year and the leakiness of a structure. 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 food product where possible. Unlike fumigants, heat does not penetrate deeply into flour, grain or grain products. It is important to ensure there is no damage to the equipment, uninfested materials stored within the facility, and the structure.

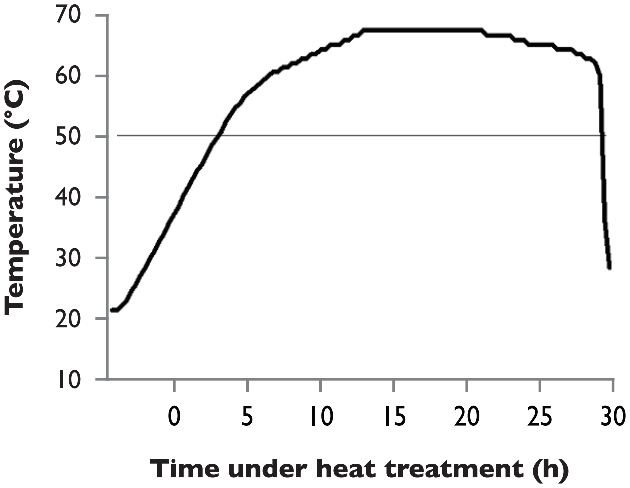

Figure 2. *Temperature during a heat treatment in a flour mill using propane-fired heaters.*

Electric heaters, forced-air gas (direct-fire) heaters (Figure 3), or steam heaters (Figure 4) are used to conduct a heat treatment. Two basic approaches to facility heat treatment are positive pressure or recirculation (Table 5). With 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. Forced-air gas heaters can use natural gas or propane as fuel. They have air intakes outside the heated envelop, and nylon ducts are placed within the facility to introduce heated air. Because hot air has a tendency to stratify horizontally and vertically within a facility, several fans should be placed on different floors to redistribute heat uniformly. Fans should be directed to areas that are difficult to treat such as corners, along walls, dead-end spaces, and areas away from the heat source. During heat treatments, fans should be moved to eliminate cool spots (less than 50°C). In addition to food-processing facilities, heat treatment can be used in empty storage structures (bins, silos), warehouses, feed mills, and bakeries.

Figure 3. *Propane-fired heater (Temp-Air) heater (source of heat for studies in Figure 2).The door is sealed with plywood, and a flexible fabric duct delivers heated air through a hole cut in the plywood.*

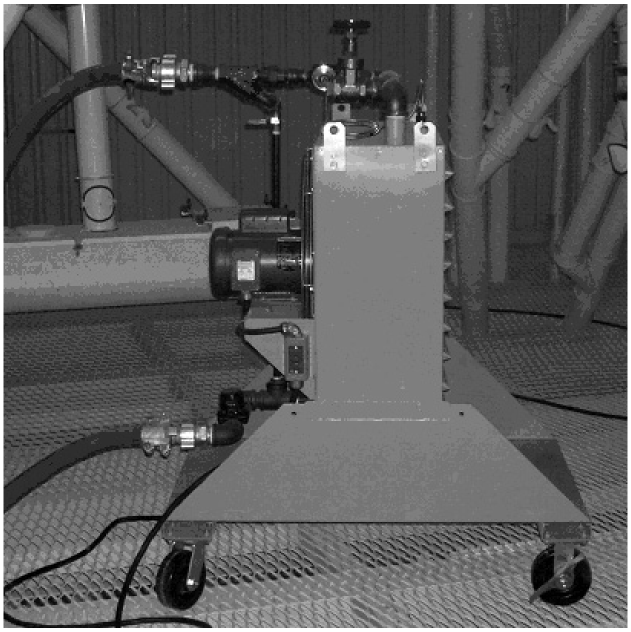

Figure 4. *Portable steam heater (Armstrong International, Inc.) used in heat treatment (Fields 2007).*

Dosland et al. (2006) gave step-by-step instructions for conducting and evaluating a facility heat treatment (see checklist, pages 8–10). Calculating how much heat energy is required after accounting for heat losses due to exposed surfaces, equipment, and infiltration is an important aspect of conducting an effective heat treatment. Research at Kansas State University and discussions with heat service providers shows that the amount of heat energy should range from 0.074 to 0.102 kilowatt per cubic meter (kwh/m^3) or 8.0 to 10.0 btu per cubic foot. During a 2009 heat treatment of a K-State flour mill the heat energy used was as high as 0.16 kwh/m^3. An indirect method of determining whether or not adequate

Table 5. *Differences between forced air heaters using positive pressure and recirculation.*

	Forced air heaters, positive pressure	Recirculation
Description	• Heaters external to building. • Building has positive air pressure, with 4 to 6 air exchanges per hour. • Patented process by TempAir.	• Heaters inside building. • Heaters permanently installed or portable. • Many are steam heaters. • Used by Quaker Oats for more than 50 years.
Advantages	• More even heating than recirculation. • Can be faster than recirculation.	• Takes less energy than forced air. • No moving or storage of heaters (fixed heaters only).
Limitations	• Open flame. • Takes more energy than recirculation.	• Some heaters are explosion proof. • Chimney effect that stratifies air in top of floors or upper part of building. • Infiltration of cold air from outside. • Needs more fans than forced air.

heat energy is being used is based on 50°C being attained within the structure in 6 to 10 hours.

To gauge heat treatment effectiveness, identify critical areas in the facility. These are places where insects can hide and breed or where temperatures cannot reach 50°C, which can be identified through inspections. Temperature sensors should be placed in these areas. During the heat treatment infrared guns and thermometers can be used to determine areas that have attained sufficient heat (50°C) or that are too hot (65°C). Monitoring temperatures during the heat treatment is needed to adjust equipment so all areas of the facility are heated sufficiently.

Insect bioassays are another method to determine the effectiveness of heat treatments. Commercial companies sell cards or vials with insects of different stages. Some bioassays have food in the container, which makes it more difficult to determine if insects are dead. This reduces the exposure temperatures, but it provides better quality insects and is more representative of the insects that are found in the mill. The use of live insects to gauge heat treatment effectiveness provides valuable information, but in some facilities bringing in live insects may be prohibited. Bioassay results are only available after the heat treatment is completed. Temperature monitoring provides immediate information needed to control an effective heat treatment.

Insect populations within a facility should be monitored before and after a heat treatment. Ideally, traps should be used throughout the year. Trapping for a minimum of 4 weeks before and 16 weeks post-treatment will show how effective the heat treatment was and potential centers of insect activity. At least 35 traps should be used inside the facility and five outside the facility. In some facilities such as flour mills, it is possible to sample rebolt sifter tailings to determine insect load. The rebolt sifter should be monitored daily, and the number of live and dead insects counted. Subsamples or a single rebolt sifter can be used as long as sample collection is consistent.

Heat treatments can reduce insect populations, and the duration of insect suppression is related to sanitation and exclusion practices followed by the facility. The doors and windows should be tightly closed to prevent outside insects from coming into a facility. Insects can be brought into a facility on raw materials. 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.

Summary

Extreme temperatures, above 50°C and below 15°C, can be used to disinfest either commodities or structures. Using extreme temperatures has a number of advantages: no insecticide residues, no licenses needed for application, and no resistant populations. Among the challenges are that an extensive capital investment may be needed, treatments may be limited to certain times of the year, and extreme temperatures may damage equipment or products if used improperly. Heat treatment involves raising and maintaining temperatures of empty grain storage structures, warehouses, and food-processing facilities between 50°C to 60°C to kill stored-product insects. The duration of heat treatment is application-specific and may vary from 6 hours for an empty storage facility to up to 34 hours for an entire food-processing facility. Laboratory and commercial trials with high temperatures during the last decade have provided information about responses of insects at various life stages to heat, heat distribution within a treated area, and techniques necessary for gauging effectiveness of commercial heat treatments. Insect responses are species-specific, stage-specific, and temperature-specific. Air movement and strategic fan placement are important for eliminating cool spots (below 50°C) and uniformly heating a treated area. The use of heat and cold treatments for commodities and structures are described.

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Checklist for Heat Treatment

Before heat treatment

Appoint site heat-up planning team (including an engineer). Select a team leader to coordinate the heat treatment.

Identify specific areas to be heated and make a site plan. Determine local heat and air sources.

Identify heat sensitive structures and supports, including roofs. If protection or engineering assurances cannot be developed, then do not conduct a heat treatment because of possible damage to structures.

Identify and develop measures for protecting heat-sensitive equipment within the facility. Contact manufacturer if in doubt as to which equipment is heat-sensitive.

Identify sealing materials needed inside and outside the heat zone to exclude pest harborages.

Determine air movement plan, circulation equipment, fan placement, and type and number of fans needed. Identify energy sources, location of temporary electric panel to plug-in fans and extension cords to spread out the electrical load for air movement.

Establish a fire protection plan. Check the insurance carrier for coverage for any damage to structure or equipment.

Repair damaged doors, windows and other openings that would allow heat to escape. This would not be a major issue when using forced-air gas heaters. Wide open areas around forced-air gas heaters need to be closed with plywood or polyethylene to reduce or eliminate cold air infiltrating from outside. Eliminate major drafts from unheated areas

Notify corporate safety, engineering, and regional personnel of intent to conduct a heat treatment.

Notify local (city and county) fire and police departments.

Notify construction contractors or other persons who may be using the facility so equipment, materials and supplies may be removed.

Use 4 to 6 mm polyethylene sheet to seal off exhaust fans, dust collectors or air make-up systems that exhaust to the outside.

Remove heat-sensitive products or raw materials from the area to be heated. Examples are vitamins, shortenings, sugar, and some packaging materials. Many products are sensitive to the high temperatures used during heat treatments.

Empty storage structures (bins/silos). Grain or grain products (flour, etc.) are good insulators, so heat will not penetrate into the bulk and insects may survive if the stored product is infested. Alternatively, if the stored product is insect-free, bin entry and exit points must be sealed so that insects do not migrate into these storage structures. Make sure that high temperatures do not alter the quality or the end-use of the stored product.

Empty garbage cans and vacuum cleaners. Bagged, bulk raw, or processed products should be placed in a trailer and fumigated with phosphine to kill residual infestation.

Remove pressurized containers and cylinders from the heated area. Label fire extinguishers with proper location for emergency "near-by use" during heat treatments. Remove or empty beverage vending machine.

Where possible, remove electronic equipment. Unplug equipment that cannot be removed. Back up computer programs. An experiment run at the Kansas State University heat workshop in 1999 showed no adverse effects on computers after they were subjected to a 34-hour heat treatment.

Empty and remove all trash, waste, and product containers.

Check the sprinkler system and head sensitivity for 141°C. If heads activate at lower temperatures, replace them. One option is to drain the sprinkler systems and post a fireguard during the inactivation period. Check systems for tripped heads and refill slowly before activation.

Turn off older sodium or mercury vapor lights during heat treatment. Check with engineering staff or supplier regarding heat tolerance of these lights. Identify alternate lighting plans to minimize plant power usage.

Check bearing and belt types and loosen where necessary.

Check lubricant type and reservoirs, and provide for expansion during heating.

Identify plastic-type material, including PVC piping and Tygon tubes, and monitor these for possible damage during heat treatment. Check pneumatic line plastics connectors for any adverse heat-related effects.

Double check temperature limitations on all solid-state equipments such as electronic controllers, small computers, or photoelectric sensors. The best information source is the equipment supplier. Protect sensitive equipment by placing it a cool zone during the heat treatment. Develop floor-by-floor and area-by-area checklists for preparation of sensitive equipment within heat treatment zones.

Take precautions about magnets that may be deactivated as a result of exposure to high temperatures (50 – 60°C). Contact the manufacturer for maximum temperatures.

Establish an employee safety plan that covers heat illness warning signs, use of the buddy system (people working in teams of two), tips on proper clothing, drinking, eating, heat stress first aid room outside heated area, first aid kit, emergency phone numbers, employee heat tolerances (based on physicals), and cool vests.

Identify and provide appropriate personal protective equipment (PPE) such as bump caps with cloth lining and cloth gloves. It is advisable to wear light, loose fitting clothing.

No metal or glass such as buttons and glasses, which are good heat conductors should be in direct contact with skin.

Establish temperature-monitoring plan, including key locations to be monitored manually or with remote temperature-measuring devices. Calibrate all monitoring tools with reference to a standard mercury thermometer.

Identify all areas adjacent to heated areas. Spray surfaces, especially floor-wall junctions and doorways, with a residual insecticide to prevent insect migration to unheated areas.

Determine numerous locations on the plant layout for placement of test insects. The cages should have an insect that is a problem within the facility, and temperatures should be measured near the test insects. It is important to use the most heat-tolerant stage of the insect. The best procedure is to expose all stages (eggs, young larvae, old larvae, pupae, and adults) of the insect species.

Thoroughly clean accessible equipment, leaving no more than 1 cm thickness of food products. Close equipment after cleaning. Proper cleaning is essential to an effective heat treatment because grain or stored product is a poor heat conductor.

Elevator and conveyor boots are good sources of insect populations. Areas under the elevator buckets are good harborage points for insects because broken, damaged grain becomes trapped or encrusted in these areas. Opening the boots of bucket elevators and conveyors and directing fans to these areas helps kill residual insect populations. Sometimes elevators may be run for a few hours before shutdown so that all areas of elevator (belts, cups, and screw conveyor) are exposed to lethal temperatures.

Identify the person responsible for turning off plant power, if necessary.

During heat treatment

Before heaters are turned on, walk through the facility with the heat treatment team to determine whether the facility is ready for the treatment. Determine whether the level of sanitation is adequate and ensure that all the critical items have been removed from the facility.

Measure the temperature from as many locations as possible within the facility to identify cool (less than 50°C) as well as overheated areas (greater than 60°C).

If the heat treatment is provided as a service by a private company, that company is responsible for the operation of the rental power, heating equipment, and assisting with temperature and humidity monitoring. Facility maintenance personnel should monitor specific structures and heat-sensitive equipment, in addition to providing oversight during heat treatment.

Numerous industrial strength fans, capable of withstanding 50 to 60°C, should be used to circulate the hot air within the facility. Circuit breakers on the temporary electrical panels for fans also need to be industrial strength so they do not trip. Tripping will cut-off power to the fans and reduce air flow necessary for uniform temperature distribution.

Record temperature and humidity at predetermined locations and intervals. This can range anywhere from a minute using microprocess-based temperature sensors to every hour if done manually using infrared thermometers.

Check areas near test insects regularly. Remember that insects exposed to sudden heat shock appear dead but may come back to life if they are removed from the heated areas. Insect test cages with adults removed during heat treatment should be kept at room conditions for 24 hours before insect mortality is assessed. All pre-adult stages should be reared to adulthood for mortality assessments.

Designate an office as a heat-treatment command center with phone, first aid kit, temperature log sheets, fluids (water or other hydrating beverages), and emergency phone numbers.

After heat treatment

Discontinue heating after the desired exposure time and temperature are achieved. Keep fans running after shutting down the heaters to facilitate cooling. In the case of forced-air heaters, the blowers may be left running after burner is shut down, forcing outside cool air into the facility for cooling.

Uncover roof and wall vents, air intakes, and other openings for exhaust air. Open screened windows. Turn on plant power when temperature cools to less than 43°C.

Recover test insects and temperature-sensing equipment or charts. Record insect mortality.

Treat areas where survival occurs in insect test cages with a residual insecticide.

Start the exhaust fans in heated areas. Monitor temperatures during the cool-down period.

Replace fire extinguishers at proper locations, and return plant to normal fire-protection standards. If sprinkler system was drained, check each sprinkler head before activation. Refill slowly.

Remove portable power or heater equipment and begin reassembly of plant equipment to prepare for normal operation.

Remove all sealing equipment and complete post-treatment cleanup. Flush the initial food material within the processing system for about 10 to 20 minutes and dispose of it as trash. A large number of insect fragments may exit processing equipment in the initial flush. Check flushed material and record information on the types and number of insects present.

The heat treatment team should review treatment activity and effectiveness and list suggestions to improve a future application. Generally, subsequent heat treatments are more effective than first ones. Modifications often are needed due to the uniqueness of the structure and training of personnel.

Prepare a detailed post-heat-treatment report. This report should serve as a baseline for future heat treatments.

Adverse effects observed should be investigated and a plan developed to prevent such occurrences in the future.

References

Abdelghany, A. Y., S. S. Awadalla, N. F. Abdel-Baky, H. A. El-Syrafi, P. G. Fields. 2010. The effect of high and low temperatures on the drugstore beetle, *Stegobium paniceum* (L.) (Coleoptera: Anobiidae). J. Econ. Entomol. 103: 1909-1914.

Adler, C. 2010. Physical control of stored product insects. In: Reichmuth, C., M. Schoeller, (eds), International European Symposium on Stored Product Protection "Stress on chemical products", Julius-Kühn-Archive, Berlin, Germany, pp. 33-35.

Beckett, S. J., P. G. Fields, Bh. Subramanyam. 2007. Disinfestation of stored products and associated structures using heat. In: Tang, J., E. Mitcham, S. Wang, S. Lurie (Eds), Heat Treatments for Post Harvest Pest Control: Theory and Practice. CABI, Wallingford, Oxfordshire, UK, pp. 182-237.

Birch, L.C. 1953. Experimental background to the study of the distribution and abundance of insects. Ecology 34: 698-711.

Boina, D., Bh. Subramanyam. 2004. Relative susceptibility of *Tribolium confusum* (Jacquelin du Val) life stages to elevated temperatures. J. Econ. Entomol. 97: 2168–2173.

Bruce, D. M., P. J. C. Hamer, D. Wilkinson, R. P. White, S. Conyers, and D. M. Armitage. 2004. Disinfestation of Grain using Hot-Air Dryers: Killing Hidden Infestations of Grain Weevils without Damaging Germination. Project Report No. 345, Home-Grown Cereals Authority, UK. http://www.hgca.com/cms_publications.output/2/2/Publications/Final%20project%20reports/Disinfestation%20of%20grain%20using%20hot-air%20dryers%e2%80%93%20Killing%20hidden%20infestations%20of%20grain%20weevils%20without%20damaging%20germination.mspx?fn=show&pubcon=1477 .

Burks, C. S., D. W. Hagstrum. 1999. Rapid cold hardening capacity in five species of coleopteran pests of stored grain. J. Stored Prod. Res. 35: 65-75.

Burks, C. S., J. A. Johnson, D. E. Maier, J. W. Heaps. 2000. Temperature. In: Subramanyam, B., Hagstrum, D.W. (Eds.), Alternatives to pesticides in stored-product IPM. Kluwer Academic Publishers, Boston, pp. 73-104.

Carrillo, M. A., C. A. Cannon, W. F. Wilcke, R. V. Morey, N. Kaliyan, W. D. Hutchison. 2005. Relationship between supercooling point and mortality at low temperatures in Indianmeal moth (Lepidoptera: Pyralidae). J. of Econ. Entomol. 98, 618-625.

Chauvin, G., G. Vannier. 1997. Supercooling capacity of *Tineola bsselliella* (Hummel) (Lepidoptera : Tineidae): Its implication for disinfestation. J. Stored Prod. Res. 33: 283-287.

Dean, D. A. 1911. Heat as a means of controlling mill insects. J. of Econ. Entomol. 4, 142–158.

Dosland, O., Bh. Subramanyam, G. Sheppard, R. Mahroof. 2006. Temperature modification for insect control. In: Heaps, J. (Ed), Insect Management for Food Storage and Processing, Second Edition, American Association of Cereal Chemists International, St. Paul, MN, pp. 89-103.

Fields, P., B. Timlick. 2010. The effect of diapause, cold acclimation and ice-nucleating bacteria on the cold-hardiness of *Plodia interpunctella*. In: Carvalho, O. M., Fields, P. G., Adler, C. S., Arthur, F. H., Athanassiou, C. G., Campbell, J. F., Fleurat-Lessard, F., Flinn, P.W., Hodges, R. J., Isikber, A. A., Navarro, S., Noyes, R. T., Riudavets, J., Sinha, K. K., Thorpe, G. R., Timlick, B. H., Trematerra, P., White, N.D.G. (eds.), Proceedings of the10th International Working Conference on Stored Product Protection, 27 June - 2 July, 2010, Estoril, Protugal, Julius-Kühn-Archiv, Berlin, Germany, pp. 650-656.

Fields, P.G. 2007. Comparative Evaluation of Intensive Pest Management, Heat Treatments and Fumigants As Alternatives to Methyl Bromide for Control of Stored Product Pests In Canadian Flour Mills. Canadian National Millers Association. http://www.canadianmillers.ca/english/pdf/issues/ComparativeEvaluation_March2007.pdf

Fields, P. G. 1992. The control of stored product insects and mites with extreme temperatures. J. Stored Prod. Res. 28: 89-118.

Hansen, J. D. and J. L. Sharp. 1998. Thermal death studies of third-instar Caribbean fruit fly (Diptera:Tephritidae). J. Econ. Entomol. 90: 968–973.

Heaps, J. W. 1994. Temperature Control for Insect Elimination. Methyl Bromide Conference 56, 1-3.

Hulasare, R., Bh. Subramanyam, P. G. Fields, and A. Y. Abdelghany. 2010. Heat treatment: a viable methyl bromide alternative for managing stored-product insects in food-processing facilities. In: O. M. Carvalho, P. G. Fields, C. S. Adler, F. H. Arthur, C. G. Athanassiou, J. F. Campbell, F. Fleurat-Lessard, P. W. Flinn, R. J. Hodges, A. A. Isikber, S. Navarro, R. T. Noyes, J. Riudavets, K. K. Sinha, G. R. Thorpe, B. H. Timlick, P. Trematerra, N. D. G. White (Eds.), Proceedings of the10th International Working Conference on Stored Product Protection, 27 June - 2 July, 2010, Estoril, Protugal, Julius-Kühn-Archiv, Berlin, Germany, pp. 661-667.

Mahroof, R., 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.

Mahroof, R., Bh. Subramanyam, P. Flinn. 2005. Reproductive performance of *Tribolium castaneum* (Coleoptera : Tenebrionidae) exposed to the minimum heat treatment temperature as pupae and adults. J. Econ. Entomol. 98: 626-633.

Mahroof, R., Bh. Subramanyam, and D. Eustace. 2003a. Temperature and relative humidity profiles during heat treatment of mills and its efficacy against *Tribolium castaneum* (Herbst) life stages. J Stored Prod. Res. 39: 555-569.

Mahroof, R., Bh. Subramanyam, J. E. Throne, A. Menon. 2003b. Time-mortality relationships for *Tribolium castaneum* (Coleoptera: Tenebrionidae) life stages exposed to elevated temperatures. J. Econ. Entomol. 96: 1345-1351.

Maier, D., and S. Navarro. 2002. Chilling of Grain by refrigerated air. pp 489-560. In: S. Navarro, and R.T. Noyes (Eds.) The Mechanics and Physics of Modern Grain Aeration Management. CRC Press, Boca Raton.

Makhijani, A. and K. Gurney. 1995. Mending the Ozone Hole: Science, Technology, and Policy. MIT Press, Boston.

Mason, L. J. and C. A. Strait. 1998. Stored product integrated pest management with extreme temperatures. pp. 141-177. In G.J. Hallman, and D.L. Denlinger (Eds.), Temperature sensitivity in insects and application in integrated pest management. Westview Press.

Mullen, M. A., R. T. Arbogast. 1979. Time-temperature-mortality relationship for various stored-product insect eggs and chilling times for selected commodities. J. Econ. Entomol. 72: 476-478.

Navarro, S., B. Timlick, C. J. Demianyk and N. D. G. White. 2011. Controlled and Modified Atmospheres. In D. W. Hagstrum, T. W. Phillips, and G. Cuperus (Eds.) Stored Product Protection. Kansas State University. Manhattan, Kansas (in press).

Neven, L.G., 2000. Physiological responses of insects to heat. Postharvest Biol. Techn. 21: 103-111.

Qaisrani, R. and S. Beckett. 2003. Possible use of cross-flow dryers for heat disinfestations of grain. In: Wright, E. J., M. C. Webb, and E. Highley (Eds) Stored Grain in Australia 2003. Proceedings of the Australian Postharvest Technical Conference, Canberra, 25–27 June. CSIRO, Canberra, Australia, pp. 30–35.

Roesli, R., Bh. Subramanyam, F. J. Fairchild and K. C. Behnke. 2003. Trap catches of stored-product insects before and after heat treatment in a pilot feed mill. J. Stored Prod. Res. 39: 521-540.

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

Salin,C., P. Vernon, G. Vannier. 1998. The supercooling and high temperature stupor points of the adult lesser mealworm *Alphitobius diaperinus* (Coleoptera: Tenebrionidae J. Stored Prod. Res. 34: 385-394.

Tilley, D. R., M. Casada, F. H. Arthur. 2007. Heat treatment for disinfestation of empty grain storage bins. J. Stored Prod. Res. 43: 221-228.

Yu, C., Bh. Subramanyam, P.W. Flinn, and J. A. Gwirtz. 2011. Susceptibility of *Lasioderma serricorne* (F.) life stages to elevated temperatures used during structural heat treatments. J. Econ. Entomol. 104: 317-324.

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