Appendix 1:

Comparative Evaluation of Heat Treatment Technologies as Alternatives to Methyl bromide Fumigation for Control of Stored-Product Pests in Canadian Grain Milling Facilities:

Efficacy Assessment Report[1]

Paul Fields
Research Scientist

Cereal Research Centre
Agriculture and Agri-Food Canada
pfields@agr.gc.ca

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[1]Appendix to *Comparative Evaluation of Heat Treatment Technologies as Alternatives to Methyl bromide Fumigation for Control of Stored-Product Pests in Canadian Grain Milling Facilities*, a report submitted by Canadian National Millers Association to Agriculture and Agri-Food Canada as part of the Canadian Adaptation and Rural Development Fund.

Summary

The efficacy of heat or methyl bromide to control pest insects in flour mills was evaluated. Two heat treatments, one using propane-fired heaters (Temp-Air), and another using portable low-pressure steam heaters (Roo-Can Manufacturing Inc.) were examined. Methyl bromide treatments were included so that the alternatives could be compared to the currently used control method. Insect populations within the mills were estimated by using traps and monitoring insect numbers from tailings from rebolt sifters. During the treatments, adults and larvae of the red flour beetle (*Tribolium castaneum* (Herbst)) were placed in cages throughout the mills to determine mortality.

The temperature highs ranged between 45 and 78^{o}C (113-172 ^{o}F) in the two mills treated with heat. Temperatures were generally higher in the mill that used propane-fired heaters and, all of the insects in the test cages were killed. In the steam-heated mill, there were 4 test cages out of 23 that had some survival at the end of the treatment. In the dome traps that monitored resident insect populations, the populations dropped to 5 to 27% of what they were before the propane-heat treatments. Both the methyl bromide treatments caused populations to drop to 0 to 6% of what they were before the treatments. The mill where steam heat was used could not be sampled using dome traps. Although populations were significantly reduced after the steam-heat treatment, inspections found live insects in the mill immediately after the heat treatment. The number of insects found in tailings was eventually reduced to zero after heat treatments in other parts of Mill 2.

The steam-heat treatment took 21 hours (3 hours shorter than the original schedule) of heating compared to 30 hours for the mill that used propane-fired heaters. The heat-treated mills were shut-down for 30 hours (steam heat) or 60 hours (propane heat), The mills that used methyl bromide were shut-down 52 or 94.5 hours.

The purpose of this study was to compare the control of insects in flour mills using heat treatments and methyl bromide. However, it is very difficult to make direct comparisons between the treatments because of differences between the mills; insect populations within the mills, equipment, age of the structure and sanitation practices before and after the treatments, For example, Mill 1 had not been treated with methyl bromide for over 10 years, whereas Mill 4 is treated with methyl bromide normally twice a year. In Mill 1, the entire mill except for grain storage, was heat treated, whereas in Mill 2, the mill was treated in sections over the autumn. Mill personal were satisfied by the level of insect control given by the heat treatments. There were no major equipment problems due to heat treatment. Both companies intend to use heat treatments to control insect infestations in the future.

Introduction

The Canadian National Millers Association (CNMA) was founded in 1919, and is Canada's national industry association representing primary processors of cereal grains in Canada. The majority of the 26 facilities operated by the 17 CNMA member firms are dedicated to the processing of various classes of wheat, of which approximately 3.1 million tonnes are milled into wheat flour, semolina, food-grade bran and millfeeds. Some CNMA member facilities also process oats into various flaked oat products, oat flour and oat bran and corn into corn grits, meal and flours.

In 2003, the CNMA received funding from Agriculture and Agri-Food Canada to assist some CNMA

member companies in testing alternatives to methyl bromide and compare these alternative treatments to standard methyl bromide treatments. Although the project scope originally foresaw the evaluation of alternative chemical fumigants and heat treatment technologies, only heat treatments were conducted as a consequence of the lack of availability of research permits and/or suitable facilities within the time frame of the funding agreement.

Heat treatments have been used as early as the 16th century to control stored-product insects (Fields 1992). Heating flour mills and food processing facilities to control insects in the USA and Canada has been used since 1910 and continues to this day (Heaps 1994, Imholte and Imholte-Tauscher 1999, Fields and White 2002). Steam, propane and electric energy sources have been used to power the heaters.

Temp-Air uses the same heaters that are used for temporary heating of construction sites and sporting events. They have been doing heat treatments to control insect pests since 1999. Currently they heat treat approximately 25 locations a year, with most of these locations receiving two heat treatments a year. The size of the facilities range from 17,000 to 1,300,000 m^3 (600,000 to 4,500,000 ft^3) in size and include flour mills, pasta plants, food processing facilities and malting plants.

Roo-Can developed explosion-proof heaters from similar technology used in the oil and gas industry. Steam is an economical source of heat that is used in many facilities that use heat to produce finished foods, such as pasta, breakfast cereals or snack food. Some facilities use steam to maintain comfort heat within the building. There are mobile steam boilers that can be used to produce heat on a short term basis. Roo-Can heaters use low pressure steam, 13-15 psig, which may require some modifications of steam lines if high pressure steam is used in the facilities. However, the low pressure steam is safer to work with than high pressure steam.

In general, most stored-product insects die under the following time-temperature combinations: 24 hours at 40^{O}C (104^{O}F), 12 hours at 45^{O}C (113^{O}F), 5 minutes at 50^{O}C (122 ^{O}F), 1 minute at 55^{O}C (131^{O}F) and 30 seconds at 60^{O}C (140 ^{O}F) (Fields 1992). Mahroof et al. (2003a, b) have examined in detail the heat tolerance of the red flour beetle (*Tribolium castaneum*), and they have developed a model to predict the mortality of specific stages (egg, larva, pupa and adult) at different high temperatures. A common approach to heat treatments is to heat the structure to 50^{O}C air temperature for 24-36 hours, with a rate of heating or cooling of not more than 5^{O}C/hour (10 ^{O}F /hour) (Imholte and Imholte-Tauscher 1999, Fields and White 2002). Although, insects die in a few minutes at 50^{O}C (122^{O}F), at least 24 hours is needed to insure that all locations in the facility receive adequate heat. Good air circulation is important to distribute the heat within the structure, and additional fans are often used to distribute the heat.

Monitoring of the temperatures is often done by handheld electronic thermometers. This should be done at hourly intervals throughout the building to insure that heat is well distributed, heaters, fans are functioning and sprinklers are not activated. Some basic precautions should be taken to avoid heat stress of workers. (National Institute for Occupational Safety and Health. 1992).

Some modifications may be required before a structure is heat treated. Sprinkler heads should be rated for at least 85^{O}C (185 ^{O}F). Some electronic equipment may have to be removed or enclosed and provided with cool air. Some plastics (eg. brooms and water lines) may warp with the heat. Fire extinguishers should be removed before the heat treatment. Certain food additives are heat sensitive, and should be removed before the heat treatment. As with a methyl bromide fumigation, the structure and the equipment should be cleaned of food residues to allow good penetration of the heat.

This report provides an assessment of the efficacy, in terms of achieving insect mortality, of heat treatment and methyl bromide fumigation. Methyl bromide was included as a treatment so that the alternatives could be compared to the currently used control methods.

Methods

Treatments

There were two treatments that used heat, propane-fired heaters (Temp-Air) and steam heaters (Roo-Can Manufacturing Inc.) and two treatments that used methyl bromide (Table 1).

Mill 1 (Propane-fired heat treatment)

Mill 1 is a small mill (less than 10,000 metres ^{3} (350,000 ft^3)) that produces wheat flour. The mill was shut-down on 10 AM on Friday, August 29; the mill equipment (rollers, sifters, spouting equipment, screw conveyors) was partially dismantled and cleaned. Temp-Air (http://www.temp-air.com/remediation/remediation.htm) provided 7 propane-fired heaters (Figure 1) (Johnson and Danely 2000, Johnson and Danely 2003) that had a combined minimum capacity of 878,850 BTU/h and a combined maximum capacity of 19.7 million BTU/h (modulation system based on the outside temperature). There were: three THP-4500 heaters that provided between 202,500 to 4,500,00 BTU/h with blowers that provided 25,000 cfm; one THP-2000 heater that provided between 89,100 to 2,000,000 BTU/h with blowers that provided 11,000 cfm; and three THP-1400 heaters that provided between 60,750 to 1,400,000 BTU/h with blowers that provided 7,500 cfm. Given the size of the building there was approximately 10 air exchanges/hour. These heaters were placed in outside doors and loading docks. Heat was delivered to various sections of the mill by means of connectible fabric ducts. Some heaters were started at 8:00 AM Saturday, August 30, with all heaters in operation by noon. Approximately 30 36-inch-fans (115 Volt Schaeffer fans, 11,000 cfm each) were placed throughout the mill to insure the good air circulation within the building. Some of these fans did not function the entire heat treatment because of overheating. Some packaging material and ingredients were considered heat sensitive, and were placed in trucks and fumigated with methyl bromide. The heaters were shut-down at 2:00 PM on Sunday, August 31. The doors were opened to help cool the building and the mill was running 10 PM Sunday evening. Total shut-down of the mill was 60 hours. Approximately, 12,000 L of propane was used during the heat treatment, which cost a total of $ 6,000 CDN. Mill 1 had not been fumigated with methyl bromide for over 10 years.

Mill 2 (Low-pressure steam-heat treatment)

Mill 2 is a small mill (less than 10,000 metres ^{3} (350,000 ft^3)) that produces flour as well as specialty products. The mill was shut down at noon on Saturday, September 6. The mill was cleaned, although there was not a disassembly of the sifters as in other mills. Eighteen low-pressure steam heaters (Figure 2), manufactured by Roo-Can Manufacturing Inc. (www.roocan.com) were placed throughout the mill, the bulk of them on the lower floors. There were 17 heaters that produced 156,000 BTU/hr and 1,250 cfm; and 1 heater that produced 234,000 BTU/h and 1,650 cfm all operating on low-pressure steam at approximately 13 – 15 psig. All heaters together had the capacity to produce 2.8 million BTU/h. Heat was turned on at 4:30 PM on Saturday, September 6 and turned off at 1:30 PM on Sunday, September 7. Ten rental fans (12 inch diameter, 3200 cfm) and one Roo-Can fan (3600 cfm) were placed throughout the

building. Four of the rental fans overheated and stopped operating in the first 6-8 of hours the heat treatment. The mill was back in production at 6:00 PM later Sunday, September 7. Total shut-down of the mill was 30 hours. The approximate cost of the steam heat was approximately $ 300 CND. Only about half the facility was treated at this time, the other parts of the mill, were heat-treated at a later date.

Mill 3 (Methyl bromide)

Mill 3 is a medium size wheat mill (between 10,000 and 50,000 metres^3 (350,000 ft^3 and 1,800,000 ft^3)). The mill was shut down on 6:00 PM Friday, July 25. All equipment was opened and/or stripped down and vacuumed clean. The building structure and floor areas were also vacuumed clean. Methyl bromide was released on noon Saturday, July 26, and the aeration begun at noon on Sunday, July 27 and finished at 6:00 PM on that same day. The mill was back in operation by 10:00 PM July 27. The total shut-down of the mill was 52 hours.

Mill 4 (Methyl bromide)

Mill 4 is a medium size wheat mill (between 10,000 and 50,000 metres^3 (350,000 ft^3 and 1,800,000 ft^3)) that has milling facilities housed in two separate buildings located on the same site. Both mills were fumigated. The mills were shut down at 11:00 AM on Thursday, November 6. Clean-up involved disassembly of sifters and lasted until 7:00 PM Friday evening. The methyl bromide tanks were placed throughout the buildings, and the gas released at 8:00 PM on Friday, November 7. The aeration began at 5:30 AM on Sunday, November 10, and was complete 3:00 PM of that same day. The mill was back in production on 9:30 AM on November 11. The total shut-down of the mill was 94.5 hours.

Efficacy Assessment

Dome traps

In Mills 1, 3 and 4, dome traps that are specific for flour mill insects were placed on the roller stand floor and the sifter floor, 8 to 10 traps/floor and the insects removed and counted each week. These traps were purchased from Trece Inc (http://www.trece.com/). The traps were set out 3 to 9 weeks before the control treatments and for at least 6 weeks post-treatment. The traps were baited with pheromones for the confused and red flour beetles (*Tribolium confusum* and *Tribolium castaneum*) and the insects caught were identified as flour beetles, flat grain beetles (*Cryptolestes* spp, and *Oryzaephilus spp*) or weevils (*Sitophilus* spp.). The vast majority of insects were flour beetles, and those data are reported here. The insect numbers were expressed as a percentage of the pre-treatment populations. The mean number of insects/trap/day in the pre-treatment periods was calculated and the means and standard error of the means (SEM) divided by pre-treatment mean and multiplied by 100 to give a standardized measure of the effect of the heat and methyl bromide treatments between mills.

Rebolt sifter tailings

In all mills, the number of live and dead insects from tailings from the rebolt sifters was recorded. In Mills 1, 2, and 3 all of the tailings were sifted each day. In Mill 4, 1 kg (2.2 lbs) samples were taken each day from Monday to Friday. Insect counts were divided by the number of days of sampling and the daily average calculated for the pre-treatment period, and all numbers divided by this to express the insect count data as a percentage.

Caged test insects

The red flour beetle insect *Tribolium castaneum* (Steinbach strain) was used as a test insect. They were reared on white wheat flour with 5% brewer's yeast at 30°C, 60% relative humidity. Twenty unaged, unknown sex were placed in 16 g of culture medium in plastic vials, 7-8 days before the heat treatment, and held at 30°C, (86°F) 60% relative humidity. For adults, a total of 80 vials were used, 10 for the controls, 20 for placement throughout the mills (Figure 3) and held for the entire treatment, and 50 for placement in one spot (Figure 4) with 2 vials being removed every 1-2 hours during the heat treatments. Mini data loggers (Hobo Dataloggers, Onset Computers Inc.) were placed with each set of vials (Mills 1, 2 and 4), and the temperature recorded every 15 minutes (Figure 3). For the methyl bromide treatment in Mill 3, 15 samples with 10 confused flour beetles adults and 5 larvae were placed throughout the mill. The test insects for Mill 4 reached a minimum of -8 °C (18°F) during transport. However, for Mill 4 approximately 60 samples with 4 adult red flour beetles and 1 larva were placed throughout the mills. These insects were collected from the mill.

Results

Heat and methyl bromide levels

The temperature highs were between 55 and 78°C (131-172°F)(Tables 1, 2) in Mill 1 with the propane-fired heaters. See Figure 5 for a typical temperature curve at one of the locations. The temperature highs were between 45 and 74°C (113-165 °F)(Tables 1, 3, 4) in Mill 2 with the low-pressure steam heaters. See Figure 6 for a typical temperature curve at one of the locations.

In Mill 3, the methyl bromide concentrations were measured using 7 sample lines. The initial concentrations at 1:00 PM July 26 were between 32 and 36 g/m^3. The concentration-time products for the 7 locations were: 296, 321, 352, 327, 314, 440, and 294 g h/m^3. The half-loss time, the time to lose half the methyl bromide, was 10 hours. The temperatures were between 22 and 30°C (72 and 86 °F) inside the mill.

In Mill 4, there were 8 sample lines for methyl bromide. The initial concentrations at 9:00 PM on Friday, November 7 were: 50, 38, 39, 45, 42 g/m^3 in mill 4A and 18, 13 and 22 g/m^3 in Mill 4B. The concentration-time products for the 8 locations were: Mill 4A; 350, 309, 292, 360 and 376 g h/m^3; and Mill 4B; 93, 88 and 106 g h/m^3. The half-loss times were 6 hours for Mill 4A and 4 hours for Mill 4B. The average temperatures were between 15 and 26°C (59 and 79 °F) inside the mill.

Insects

For the caged insects in the propane-fired heat treatment in Mill 1, all insects in all 23 locations were dead (Table 2). At the one location, where insects were removed every 2 hours, all insects were dead 10 hours after the heat treatment was begun (Table 3). In Mill 2, where low-pressure steam heat was used, there were 19 of 23 locations where all insects were dead (Table 7). At the one location where insects were pulled every hour, all insects were dead 13 h after the beginning of the heat treatment. For the methyl bromide treatments, all insects in all locations in Mill 3 were dead. In Mill 4A, there was no survival in any of the 43 cages, in Mill 4B, there were 2 cages out of a total of 30 cages that had survival (100%).

Resident insect populations in the propane-fired heat treatment dropped to 5 to 27% of what they were before the heat treatments (Table 6). Both the methyl bromide treatments (Table 7, 8) caused populations to drop to 0 to 6% of what they were before the treatments. Mill 2 did not use the dome traps before and after the treatment. Although populations were significantly reduced after the heat treatment in Mill 2, inspections found live insects in the mill immediately after the heat treatment and the weeks that followed.

In Mills 1 and 3 no insects were found in the tailings. In Mill 2 there were no insects in the tailings, but population gradually built up over the year. A similar pattern was seen in Mill 4.

Discussion

It required 2-3 hours at 50^{o}C (122^{o}F) to obtain 100% mortality in the test cages. The set-up of the test cages, grouping several cages together with the datalogger on the outside, did buffer the insects from the rising temperatures somewhat. Also insects were free to move within the vial. Hence, the temperature recorded on the datalogger, was not exactly the temperature of the insects in the test cages. Similar values were seen in laboratory experiments with red flour beetles (Mahroof et al. 2003b). To kill 99% of all adults, one hour was required at 50^{o}C (122^{o}F), whereas almost seven hours at 50^{o}C (122^{o}F) were required to get similar mortality with young larvae.

Mill 2 needed to continue the heat treatment for longer than just 21 hours, to insure that all areas with in the targeted area received sufficient heat. Paradoxically, the insect numbers in the tailings in Mill 2 increased after initial the heat treatment. This certainly is not due to an increase in the population, as a few days is not enough for the red flour beetle to lay eggs and complete its life cycle. This requires 25 days under ideal conditions. Also, although not all insects were killed, 98% of the insects in the test cages were killed and dead insects were seen in the mill after the heat treatment. The combination of cleaning and heating probably flushed insects from their hiding spots, some of these survived the heat treatment, fell into the mill stream and were sifted out at the rebolt sifter. With additional heat treatments in other sections of the mill and redoing the heat treatment a second time in the main mill, no insects were found in the tailings after November 16, 2003.

All mills had some insects in the facilities. In Mills 2 and 4, insects were found in the tailings from the rebolt sifters. In Mills 1 and 3, no insects were detected in the tailings from the rebolt sifters, although insects were found in the dome traps. These differences may be due to differences in how the mills sampled the tailings from the rebolt sifters, or due to differences in the set-up of the milling equipment.

Conclusions

The purpose of this study was to compare the control of insects in flour mills using heat treatments and methyl bromide. However, it is very difficult to make direct comparisons between the treatments because of differences between the mills; insect populations within the mills, equipment, age of the structure and sanitation practices before and after the treatments, For example, Mill 1 had not been treated with methyl bromide for over 10 years, whereas Mill 4 is treated with methyl bromide normally twice a year. In Mill 1, the entire mill except for grain storage, was heat treated, whereas in Mill 2, the mill was treated in sections over the autumn. Mill personal were satisfied by the level of insect control given by the heat treatments. There were no major equipment problems due to heat treatment. Both companies intend to use heat treatments to control insect infestations in the future.

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Table 1. Summary of treatments.

Mill	Size	Treatment	Temperature (^{o}C)	Temperature (^{o}F)	Methyl bromide C-T (g h/m^{3})	Mill shut-down time (h)
1	small	propane heat	53-78	131-172	-	60
2	small	steam heat	45-74	113-165	-	30
3	medium	methyl bromide	22-30	72-86	294 - 440	52
4	medium	methyl bromide	5-28	41-82	93 - 376	94.5

Table 2. The temperatures at the various locations in Mill 1, heated with propane-fired heaters on August 30-31. Initial temperatures were between 23 and 25 ^{o}C, (73 and 77^{o}F).

Data Logger	Location	Time to 45^{o}C / 113 ^{o}F (h)	Time above 45^{o}C /113 ^{o}F (h)	Time to 50^{o}C / 122 ^{o}F (h)	Time above 50^{o}C / 122 ^{o}F (h)	Max. Temp. (^{o}C)	Max. Temp. (^{o}F)	Adult Mortality (%)	Larvae Mortality (%)**
T8	basement	4.25	27.25	6.75	24.0	62.0	143.6	100	100
T9	basement	4.75	27.0	6.5	24.75	62.7	144.9	100	100
T1	1st floor *	5.5	27.25	6.0	25.5	65.0	149.0	100	100
T22	1st floor *	5.5	27.25	6.25	26.25	65.0	149.0	100	100
T23	1st floor *	5.75	27.0	7.0	25.5	65.0	149.0	100	100
T3	1st floor, bin	4.75	6.75	6.0	4.25	54.7	130.5	100	100
T4	1st floor	0.25	32.5	0.5	30.0	77.8	172.0	100	100
T5	1st floor	4.5	27.25	5.5	25.75	65.0	149.0	100	100
T7	1st floor, tempering	6.25	25.5	7.25	24.0	59.2	138.6	100	100
T21	1st floor, stairwell	4.0	28.75	4.25	28.25	72.7	162.9	100	100
T6	2nd floor roll stand	4.25	28.75	4.75	27.0	66.6	151.9	100	100
T10	2nd floor	4.0	29.0	4.75	27.5	65.0	149.0	100	100
T11a	2nd floor, roll stands	5.0	28.0	5.75	27.25	65.0	149.0	100	100
T11c	2nd floor, near bins	5.0	26.75	5.75	25.75	62.0	143.6	100	100
T12	2nd floor, stairwell	5.0	27.75	5.5	27.25	69.1	156.4	100	100
T13	3rd floor, sifters	6.0	27.25	7.5	24.75	62.7	144.9	100	100
T14	3rd floor, bran finisher	4.25	29	5.0	28.0	63.5	146.3	100	100
T15	4th floor, sifter	6.5	26.75	7.0	26.0	64.2	147.6	100	100
T16	4th floor, sifter	8.5	24.75	10.5	22.25	61.3	142.3	100	100
T17	4th floor, outside door	7.0	26.25	8.5	24.5	62.0	143.6	100	100
T18	4th floor	5.5	27.5	7.0	25.25	62.7	144.9	100	100
T19	4th floor, bins	9.25	23.5	9.75	22.75	62.7	144.9	100	100
T20		5.75	26.75	7.0	25.5	62.7	144.9	100	100

* location of timed sequence (Table 8), vials removed approximately every 2 hours.
** 20 late instar larvae, held in heat and then incubated for 3 weeks, survival was assessed as emergence to adults, control dead, 13.0$\pm$ 2.5% (mean $\pm$ SEM, n=10)

Table 3. The temperatures at the various locations in Mill 1, heated with propane-fired heaters on August 30-31.

Time of day	Time since heat on (h)	Time above 45°C / 113 °F T1 (h)	Time above 50°C / 122 °F T1 (h)	Time above 45°C / 113 °F T23 (h)	Time above 50°C / 122 °F T23 (h)	Temp. T1 (°C)	Temp. T23 (°C)	Temp. T1 (°F)	Temp. T23 (°F)	Adult Mortality (%)	Larvae Mortality (%)*
12:00	4	0	0	0	0	45.4	44.4	113.7	111.9	3	5
14:00	6	2	1.5	2	0.5	53.5	51.2	128.3	124.2	0	25
16:00	8	4	3.5	4	2.5	59.2	56.0	138.6	132.8	100	85
18:00	10	6	5.5	6	4.5	60.6	58.6	141.1	137.5	100	100
20:00	12	8	7.5	8	6.5	62.0	60.6	143.6	141.1	100	100
21:30	13.5	9.5	9.0	9.5	8.0	62.7	62.0	144.9	143.6	100	100
9:45	25.75	21.75	21.25	21.75	20.25	65.0	65.0	149.0	149.0	100	100
12:00	28.0	24.0	23.5	24.0	22.5	65.0	65.0	149.0	149.0	100	100
16:00	32.0	27.0	24.0	27.0	25.5	31.9	34.0	89.4	93.2	100	100

* 20 late instar larvae, held in heat and then incubated for 3 weeks, survival was assessed as emergence to adults, control dead, 13.0$\pm$ 2.5% (mean $\pm$ SEM, n=10)

Table 4. The temperatures at the various locations in Mill 2, heated with steam heaters on September 6. Initial temperatures were between 30 and 34 ^{o}C, (86-93^{o}F).

Data Logger	Location	Time to 45^{o}C / 113 ^{o}F (h)	Time above 45^{o}C /113 ^{o}F (h)	Time to 50^{o}C / 122 ^{o}F (h)	Time above 50^{o}C / 122 ^{o}F (h)	Max. Temp. (^{o}C)	Max. Temp. (^{o}F)	Adult Mortality (%)	Larvae Mortality (%)**
T1	basement *	8.5	13.25	9.25	5.5	56.0	132.8	100	100
T3	basement *	6.75	14.75	11.5	9.75	59.2	138.6	100	100
T4	basement, blower room	19.75	1.0	--	--	45.4	113.7	5	100
T5	basement, old blower room	12.5	8.75	12.5	8.25	60.6	141.1	100	100
T6	basement	5.5	15.75	5.5	14.25	64.2	147.6	100	100
T7	basement, bins	13.25	8.0	15.75	5.0	52.4	126.3	100	100
T8	1st floor, roll stands	5.0	16.5	9.5	11.5	54.1	129.4	100	100
T9	1st floor, outside door	5.75	14.5	8.25	3.75	53.0	127.4	100	100
T10	1st floor, electrical room	8.25	14.25	8.25	7.25	73.7	164.7	100	100
T11	2nd floor, stone mill	5.5	16.5	11.0	10.25	55.4	131.7	100	100
T12	2nd floor	4.75	16.75	12.75	8.25	52.4	126.3	100	100
T13	2nd floor, outside wall	3.75	17.75	8.0	10.0	54.7	130.5	100	100
T14	2nd floor, conveyer	5.25	16.75	10.0	11.25	56	132.8	100	100
T15	3rd floor, stairwell	13.5	9.0	19.25	1.75	50.1	122.2	78	45
T16	3rd floor, outside wall	16.0	5.25	21.0	0.25	50.1	122.2	10	25
T17	3rd floor, outside door	8.5	10.25	15.75	5.25	53.0	127.4	100	100
T18	3rd floor, in sifter	10.25	11.5	19.25	2.0	50.1	122.2	100	100
T19	3rd floor, electrical	20.5	0.75	--	--	45.4	113.7	0	15
T20	3rd floor, sieve storage	8.25	13.0	9.0	12.0	54.1	129.4	100	100
T21	4th floor, stairwell	6.75	15.75	15.5	6.25	53.5	128.3	100	100
T22	4th floor, bin	6.0	16.25	16.0	5.5	53.0	127.4	100	100
T23	4th floor	8.5	13.25	19.0	2.0	50.1	122.2	100	70
T24	4th floor	3.75	18.25	9.5	12.0	56.6	133.9	100	100

* location of timed sequence (Table 10), vials removed every hour.

** 20 late instar larvae, held in heat and then incubated for 3 weeks, survival was assessed as emergence to adults, control dead, 12.5$\pm$ 2.5% (mean $\pm$ SEM, n=15)

Table 5. The temperatures at the various locations in Mill 2, heated with steam heaters on September 6-7.

Time of day	Time since heat on (h)	Time above 45°C / 113 °F T1 (h)	Time above 50°C / 122 °F T1 (h)	Time above 45°C / 113 °F T3 (h)	Time above 50°C / 122 °F T3 (h)	Temp. T1 (°C)	Temp. T3 (°C)	Temp. T1 (°F)	Temp. T3 (°F)	Adult Mortality (%)	Larvae Mortality (%)*
18:30	2	0	0	0	0	36.1	32.8	97.0	91.0	3	25
19:30	3	0	0	0	0	37.9	34.9	100.2	94.8	3	15
20:30	4	0	0	0	0	39.2	36.1	102.6	97.0	4	70
21:30	5	0	0	0	0	39.2	42.5	102.6	108.5	1	10
22:30	6	0	0	0	0	40.1	43.9	104.2	111.0	0	15
23:30	7	0	0	0.25	0	41.0	44.9	105.8	112.8	1	20
00:30	8	0	0	1.25	0	41.5	45.4	106.7	113.7	1	50
1:30	9	0.5	0	2.25	0	48.0	46.9	118.4	116.4	35	85
2:30	10	1.5	0	3.25	0	50.1	47.4	122.2	117.3	40	60
3:30	11	2.5	0	4.25	0	45.4	48.5	113.7	119.3	4	75
4:30	12	3.5	0	5.25	0.5	45.9	58.6	114.6	137.5	75	10
5:30	13	4.5	0.25	6.25	1.5	56.0	51.8	132.8	125.2	100	100
6:30	14	5.5	1.25	7.25	2.5	49.6	53.0	121.3	127.4	100	100
7:30	15	6.5	1.25	8.25	3.5	47.4	53.0	117.3	127.4	100	100
8:30	16	7.5	2.0	9.25	4.5	50.1	54.7	122.2	130.5	100	100
9:30	17	8.5	3.0	10.25	5.5	53.0	56.6	121.3	133.9	100	100
10:30	18	9.5	4.0	11.25	6.5	49.0	55.4	120.2	131.7	100	100
11:30	19	10.5	4.0	12.25	7.5	49.0	56.0	120.2	132.8	100	100
12:30	20	11.5	4.0	13.25	8.5	49.0	57.2	120.2	135.0	100	100
15:30	23	15.0	4.0	15.0	9.5	40.1	39.2	104.2	102.6	100	100

* 20 late instar larvae, held in heat and then incubated for 3 weeks, survival was assessed as emergence to adults, control dead, 12.5$\pm$ 2.5% (mean $\pm$ SEM, n=15).

Table 6. Flour beetles (red flour beetle and confused flour beetles, mean ± standard error of the mean, SEM) as a percent of pre-treatment populations caught in baited dome traps. A heat treatment with propane-fired heaters took place on Aug 29-31, 2003 in Mill 1. There were 10 traps in each location.

Location	Flour beetles as percent of pre-treatment (%± SEM)											
	Pre-Treatment						Post Treatment					
	25 July	1 Aug.	8 Aug.	18 Aug.	25 Aug.	29 Aug.	8 Sept.	15 Sept.	22 Sept.	29 Sept.	6 Oct.	17 Oct.
Roller Floor	67 ± 11	74 ± 8	105 ± 10	71 ± 6	110 ± 5	201 ± 50	13 ± 5	9 ± 3	17 ± 4	15 ± 5	27 ± 5	17 ± 2
Sifter Floor	37 ± 8	65 ± 9	77 ± 7	68 ± 6	140 ± 41	245 ± 72	4.5 ± 1.4	5.7 ± 1.5	7.4 ± 1.9	5.7 ± 1.7	6.2 ± 1.6	7.6 ± 1.1

Table 7. Flour beetles (red flour beetle and confused flour beetles, mean ± SEM) as a percent of pre-treatment populations caught in baited dome traps. A methyl bromide fumigation took place on July 26-27, 2003 in Mill 3. There were 10 traps in each location.

Location	Flour beetles as percent of pre-treatment (%± SEM)											
	Pre-Treatment				Post Treatment							
	15 July	22 July	25 July	29 July	5 Aug.	8 Aug.	18 Aug.	25 Aug.	2 Sept.	9 Sept.	16 Sept.	23 Sept.
Roller Floor	136 ± 54	104 ± 32	60 ± 14	20 ± 4	1.1 ± 0.6	4.3 ± 2.3	2.1 ± 0.9	1.5 ± 0.8	0.7 ± 0.4	0.4 ± 0.4	0.7 ± 0.7	2.6 ± 1.2
Sifter Floor	134 ± 24	60 ± 14	106 ± 32	7.5 ± 5.3	0 ± 0	0 ± 0	0 ± 0	1.4 ± 1.4	0 ± 0	0 ± 0	0 ± 0	4.3 ± 2.2

Table 8. Flour beetles (red flour beetle and confused flour beetles, mean ± SEM) as a percent of pre-treatment populations caught in baited dome traps. A methyl bromide fumigation took place on Nov. 7-9, 2003 in Mill 4. There were 18 traps in mill A and 16 traps in Mill B.

Location	Flour beetles as percent of pre-treatment (%± SEM)																
	Pre-treatment									Post Treatment							
	16 Sept.	22 Sept.	29 Sept.	6 Oct.	14 Oct.	20 Oct.	27 Oct.	3 Nov.	7 Nov.	27 Nov.	24 Nov.	1 Dec.	8 Dec.	15 Dec.	22 Dec.	29 Dec.	5 Jan.
Mill A	98 ± 29	37 ± 25	110 ± 30	104 ± 35	80 ± 38	64 ± 24	110 ± 35	146 ± 44	150 ± 63	4 ± 4	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	6 ± 6
Mill B	--	--	94 ± 29	114 ± 29	117 ± 31	86 ± 19	107 ± 31	142 ± 32	38 ± 12	0 ± 0	0 ± 0	2 ± 2	2 ± 2	0 ± 0	0 ± 0	5 ± 5	0 ± 0

Table 9. Insects (dermestids, red flour beetles and confused flour beetles) as a percent of pre-treatment populations sifted from the flour stream at the rebolt sifter in Mill 4. A methyl bromide fumigation took place on Nov. 7-9, 2003.

Insect	Insects as percent of pre-treatment (%)																	
	Pre-treatment										Post treatment							
	Sept. 1-5	Sept. 8-12	Sept 15-19	Sept. 22-26	Sept.29-Oct. 3	Oct. 6-10	Oct. 14-18	Oct. 20-24	Oct. 27-31	Nov. 3-7	Nov. 10-14	Nov. 17-21	Nov. 24-28	Dec. 1-5	Dec. 8-12	Dec. 15-19	Dec. 22-26	Dec. 29-31
Live	31	15	15	15	110	15	204	487	276	94	0	0	0	0	0	0	0	0
Dead	0	181	45	68	113	136	68	136	136	23	23	0	23	0	0	68	0	45

Table 10. Insects as a percent of pre-treatment populations sifted from the flour stream at the rebolt sifter in Mill 2. Heat treatments took place in the mill on Sept 6-7, in the old mill and booster station on Oct. 3-5, in the mill on Nov.1-2 and another part of the plant on Nov. 7-10 2003.

Insect	Insects as percent of pre-treatment (%) Pre-Treatment								
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug	Sept. 1-6
Live	14	0	0	0	0	14	35	391	448
Dead	8	0	0	0	0	0	48	264	580

Insect	Insects as percent of pre-treatment (%) Post Treatment																	
	Sept. 7-13	Sept. 14	Sept. 16	Sept. 18	Sept. 22-26	Sept. 27-Oct 4	Oct. 5-11	Oct. 12-18	Oct. 19-25	Oct. 26-31	Nov. 1-8	Nov. 9-15	Nov. 16-22	Nov. 23-29	Nov. 30-Dec 6	Dec. 7-13	Dec. 14-20	Dec. 21-27
Live	119	3500	0	628	418	93	30	0	60	0	30	238	0	0	0	0	0	0
Dead	34	6200	1300	480	480	133	411	0	34	0	34	137	0	0	0	0	0	0

Figure 1. Propane-fired heater (Temp-Air) heating Mill 1. The door has been sealed with plywood, and a flexible cloth duct delivers heated air through a hole cut in the plywood.

Figure 2. Low-pressure steam heaters waiting to be attached to steam. The metal ducts (on right) were attached to the end of the heaters, and flexible wire and plastic ducts were attached to distribute the heat. A total of 10 blue fans were placed throughout the building, in addition to one Roo-Can fan.

Figure 3. Red flour beetle test insects, two vials with 50 adults per vial, two vials with 20 larvae per vial and one vial with insects from the mill, along with the temperature data logger.

Figure 4. Insects held at one location and pulled approximately every two hours (Mill 1) or every hour (Mill 2).

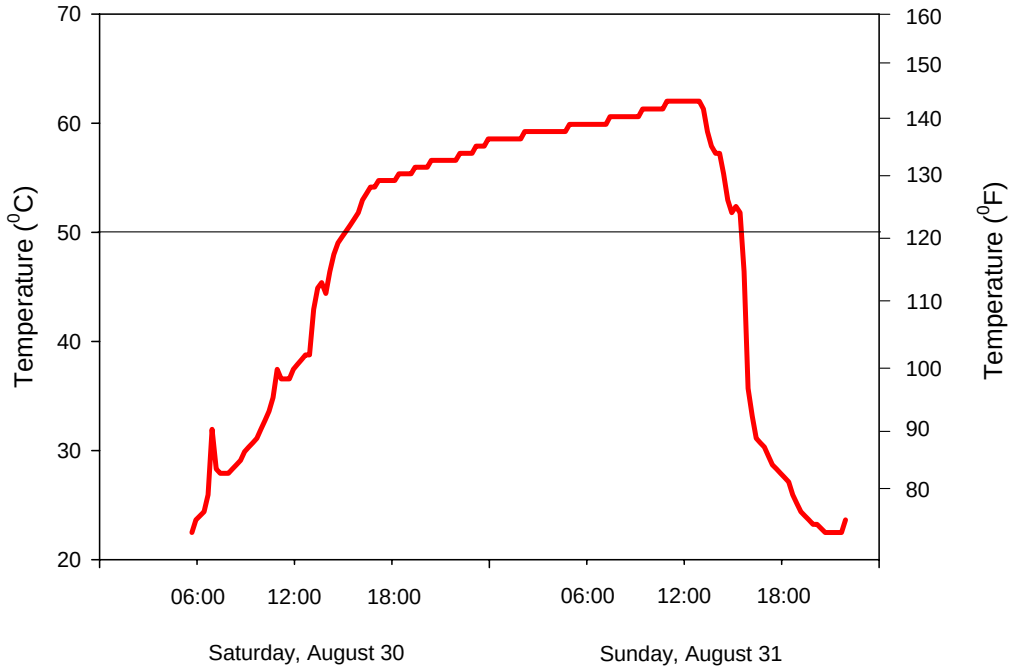

Figure 4. Temperatures in Mill 1 during heat treatment with propane-fired heaters.

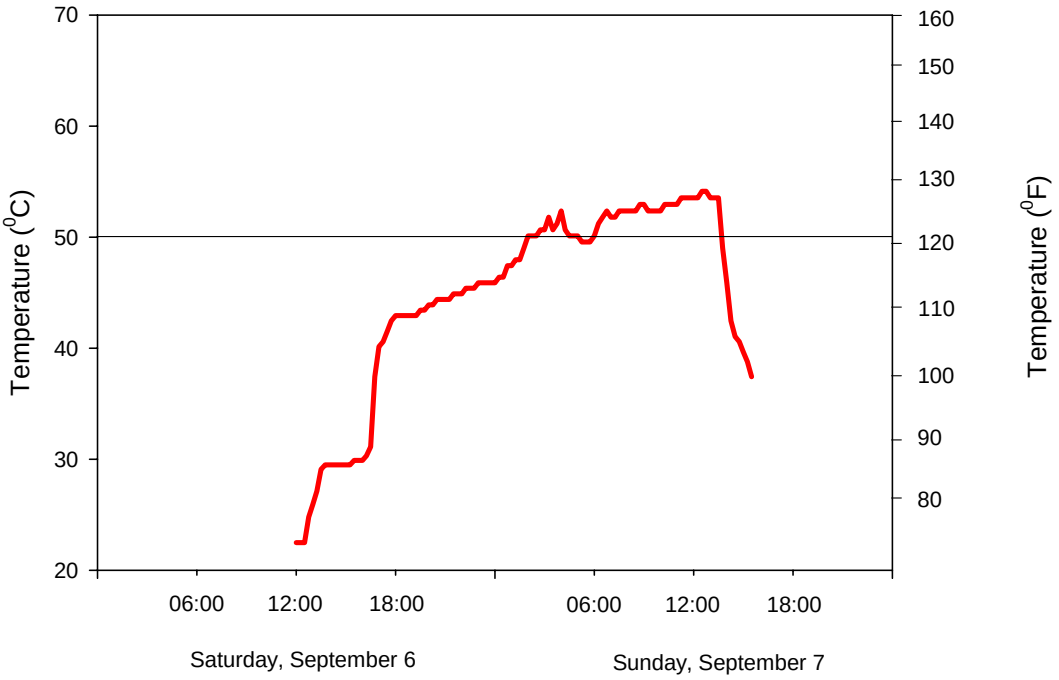

Figure 5. Temperatures in Mill 2 during heat treatment with steam heaters.