Efficacy of structural heat treatments against *Tribolium castaneum* life stages

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IPM techniques commonly used in the food industry

- CHEMICAL
  - Residual sprays
  - Aerosols
  - Structural fumigants (Methyl bromide, ProFume)
- NONCHEMICAL
  - Stock rotation
  - Sanitation
  - Exclusion
  - Heat treatment

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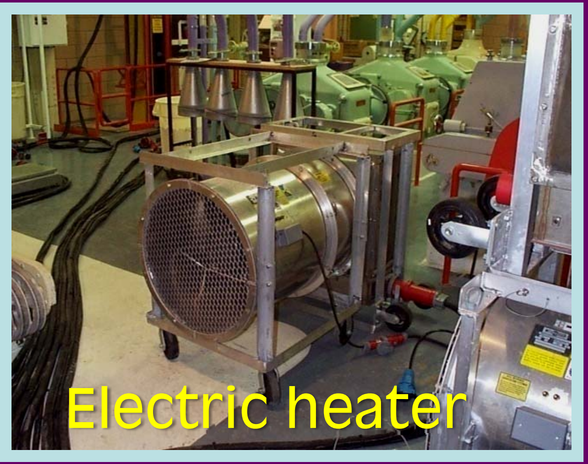
❖Heat treatment concept: Raising the ambient air temperature of the complete or partial facility to 122-140ºF (50-60ºC), and maintaining these temperatures for 24 hours



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Locations where heat can be used

- Bins/silos
- Whole-facility treatment
- Specific rooms
- Specific pieces of equipment

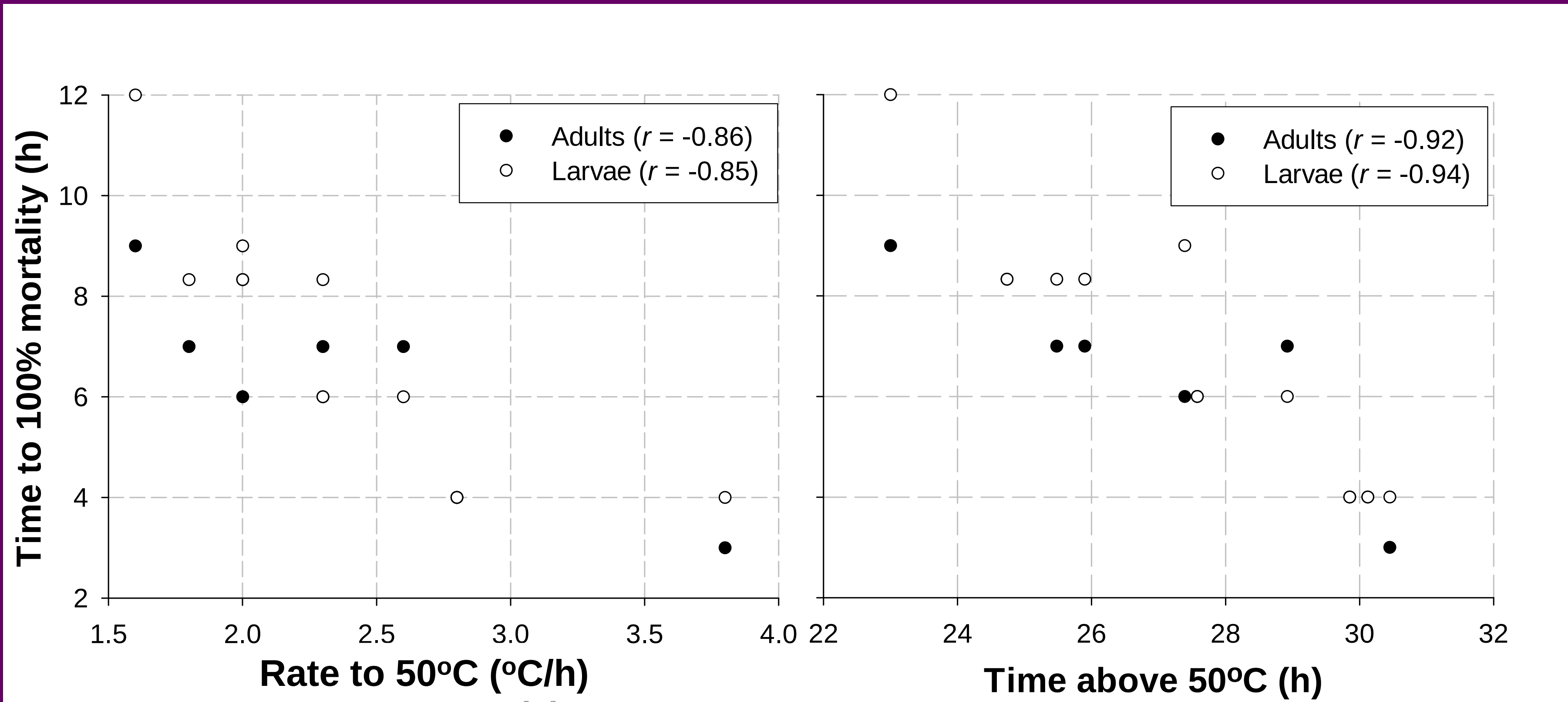
A successful heat treatment depends on………..

- Estimating the amount of heat required (through heat-loss calculations)
  - KSU Heat Treatment Calculator
- Improving pest management efficacy
  - Eliminating cool spots ($<50^{o}$C) through uniform heat distribution (use of fans)
  - Assessing pre- and post-heat treatment insect counts
  - Following good exclusion and sanitation practices

- Factors affecting insect mortality

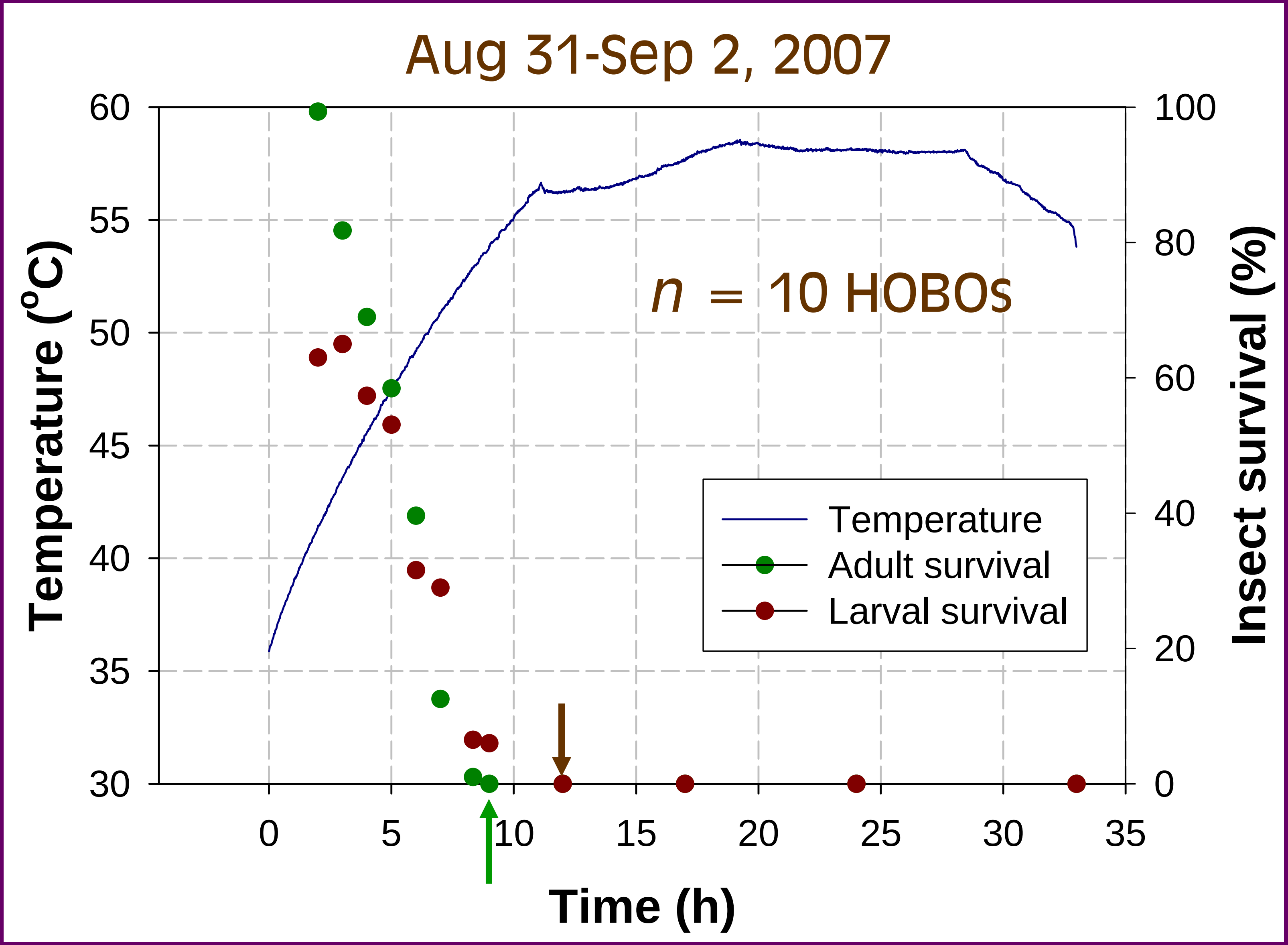
Factors affecting insect mortality (Breakfast cereal facility)

Red flour beetle adults and young larvae



There is an inverse relationship between insect mortality and each of the two factors

Breakfast cereal facility: Do we need a long exposure time?



Thermal death kinetic model for the most heat tolerant stage

$$\log_{10}\left(\frac{N_{t-dt}}{N_t}\right) = \frac{dt}{D(T_t)}$$

where N_{t-dt} is the survival at t-dt time interval N_t is survival at time t upon integration equation becomes

$$\int_0^t \log_{10}\left(\frac{N_{t-dt}}{N_t}\right) = \int_0^t \frac{dt}{D(T_t)}$$

$$\log_{10}\frac{N_o}{N_t} = \int_0^t \frac{dt}{D(T_t)}$$

$$\log_{10}\frac{N_t}{N_0} = -\sum_0^t \frac{dt}{D(T_t)}$$

Boina, Subramanyam, & Alavi (2008)

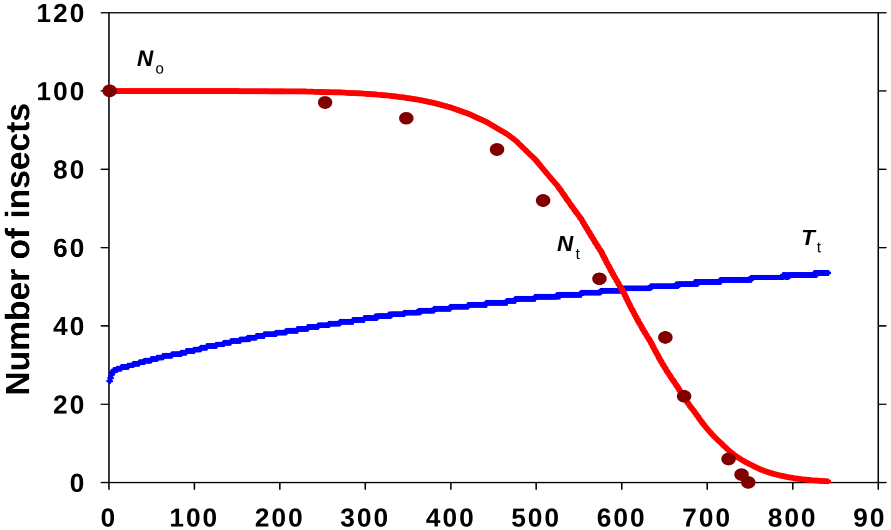
$$N_t = \frac{N_0}{10^{\sum_0^t \frac{\Delta t}{D(T_t)}}}$$

where N_o is the original number of insects; N_t is number of larvae at time t, Δt is the incremental exposure time (1-min), D is the mean instantaneous D-value as a function of temperature (T_t), and T_t is time- dependent temperature profile

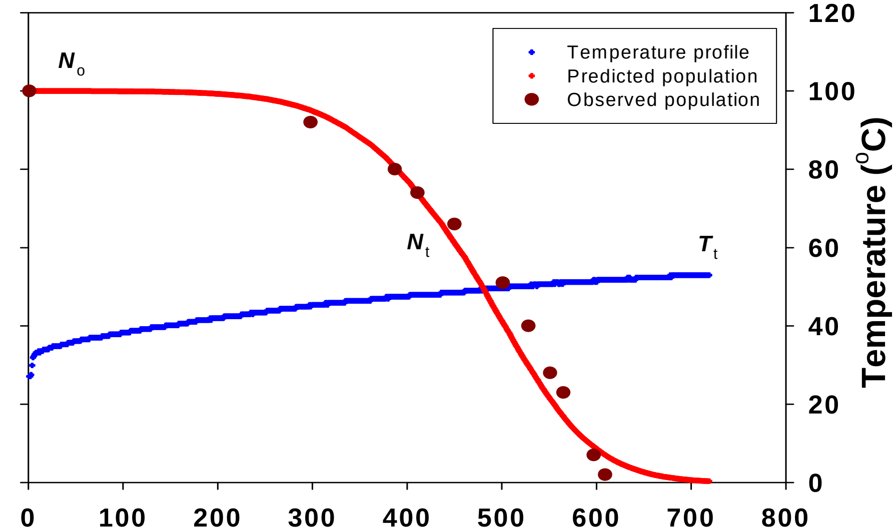
Validation of the thermal death kinetic model against old larvae of the confused flour beetle

(Boina, Subramanyam, and Alavi 2008)

Heating rate (2.12°C/h)

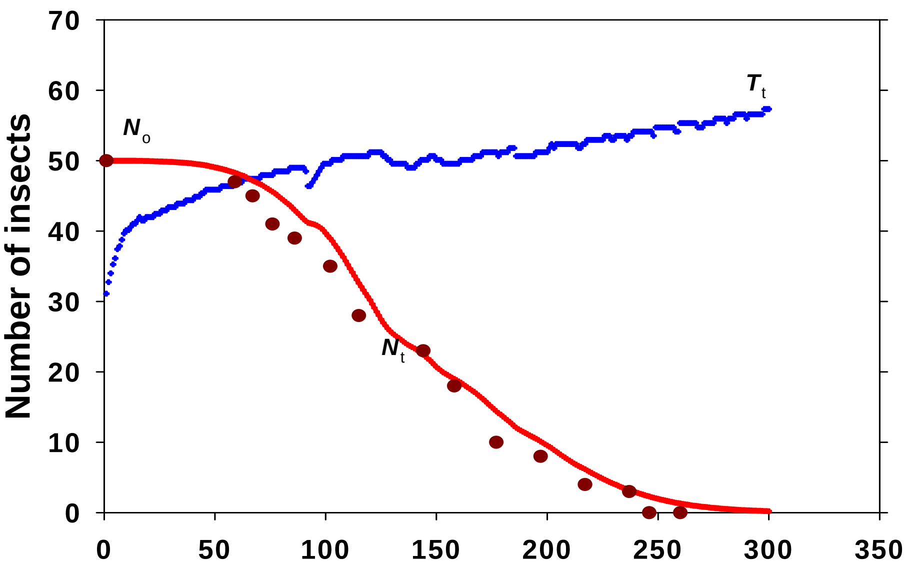


Heating rate (2.44°C/h)

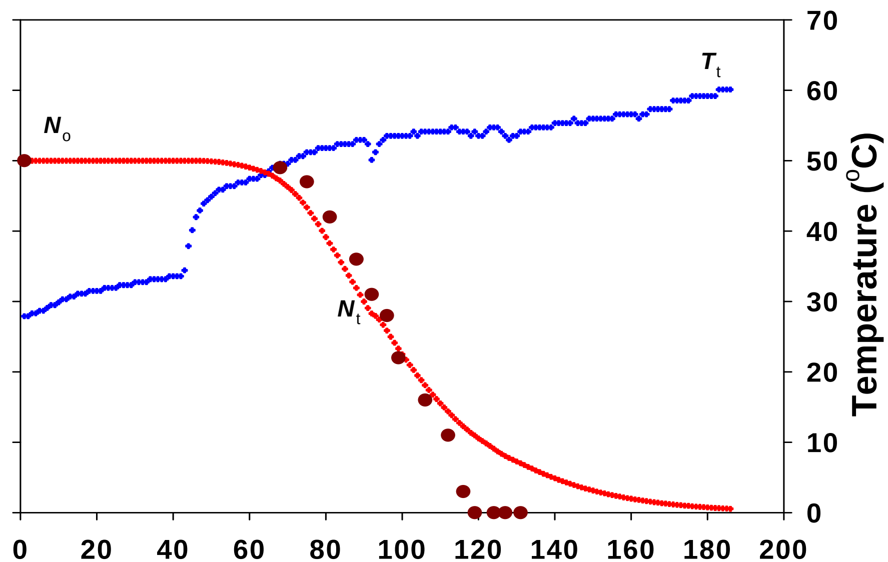


Time (minutes)

Heating rate (5.31°C/h)



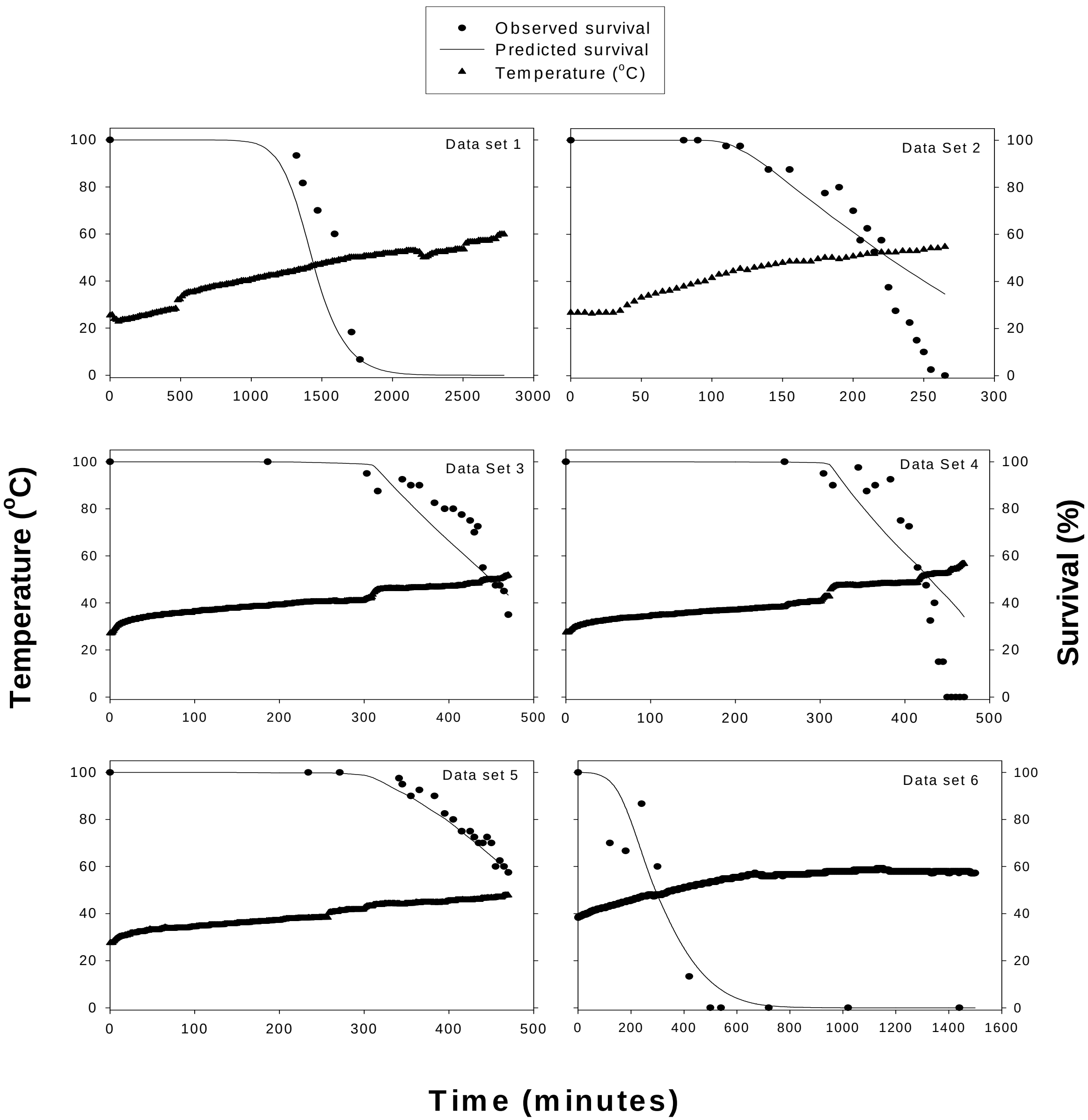
Heating rate (12.02°C/h)



Time (minutes)

Validation of the thermal death kinetic model against young larvae of the red flour beetle

Observed and predicted survival of red flour beetle young larvae (Subramanyam & Mahroof, unpublished)



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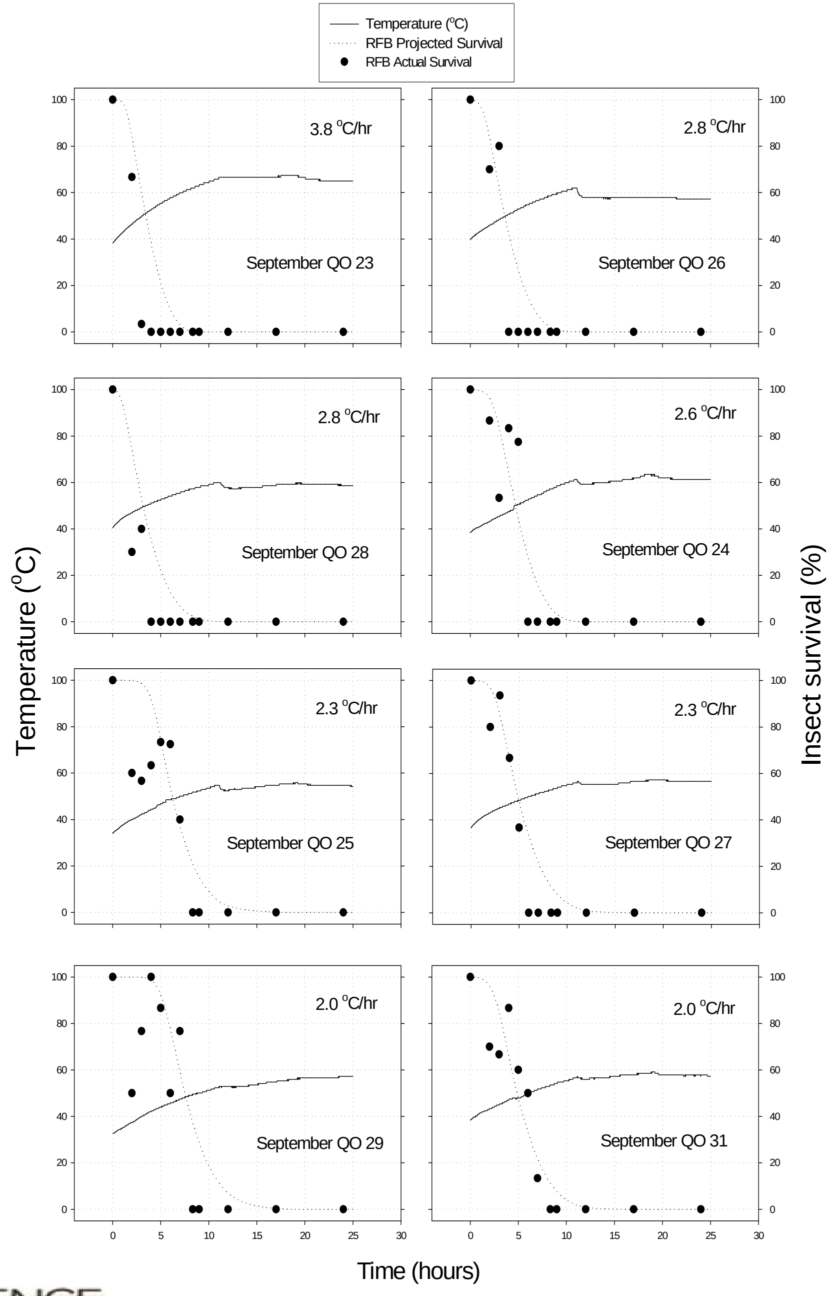

Observed and predicted survival of young larvae of red flour beetle in breakfast cereal facility

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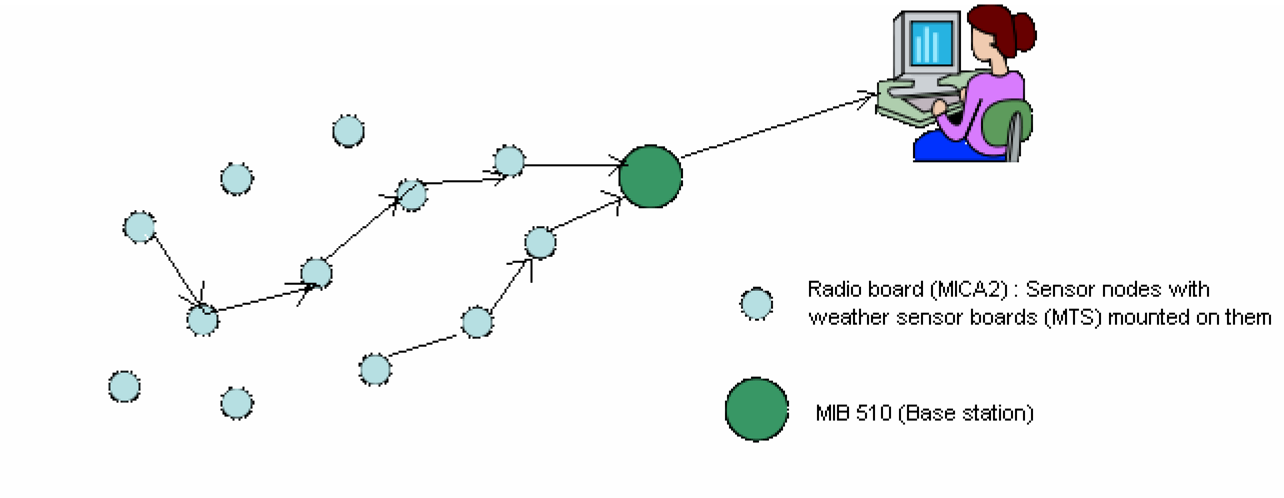
- Integrating remote temperature monitoring with the thermal death kinetic model
    - Take corrective action in “real time”

Wireless sensor networks



Typical wireless sensor network architecture

E.A.R.T.H. Software

Efficacy Assessment in Real Time during Heat treatment

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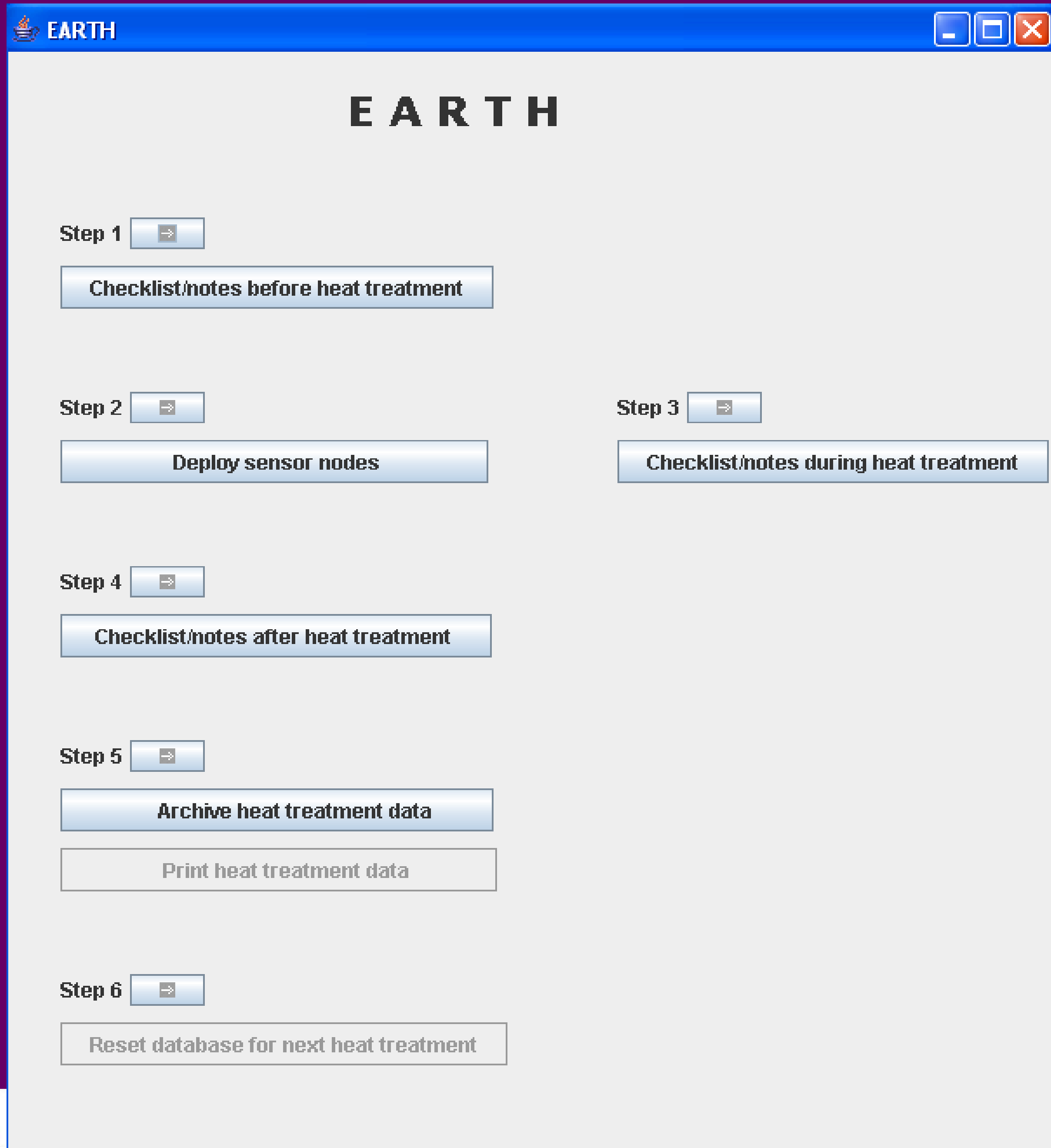

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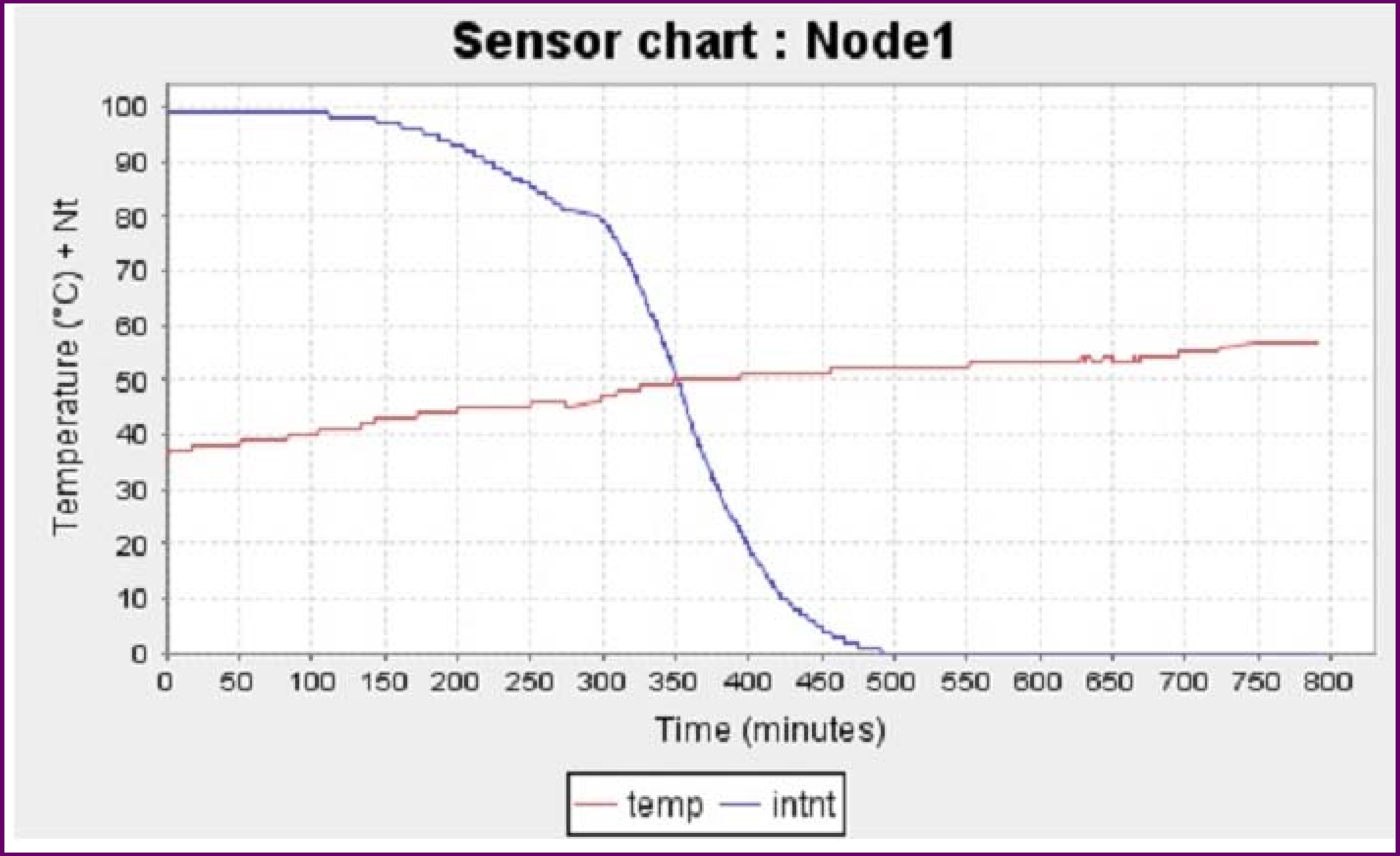
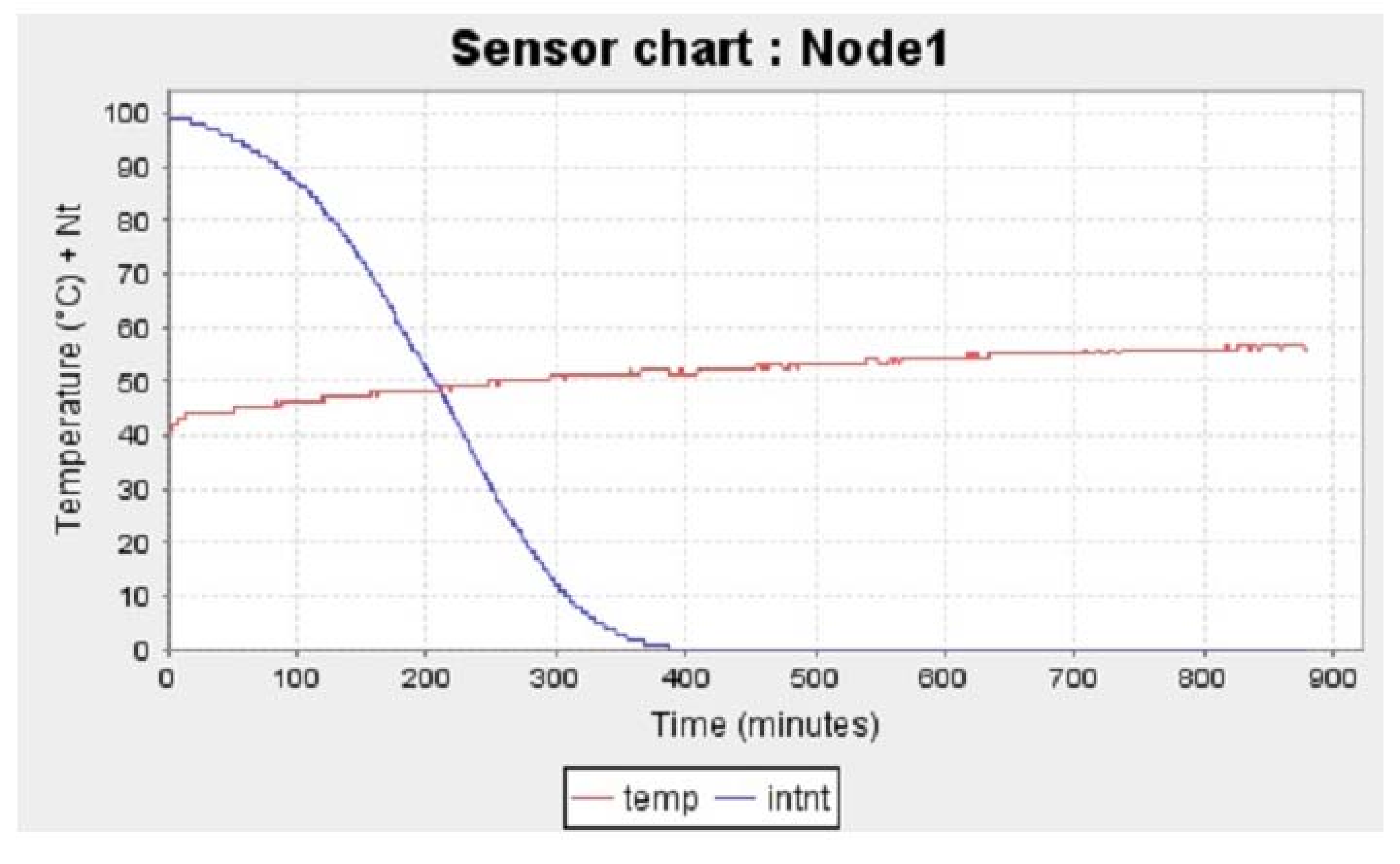
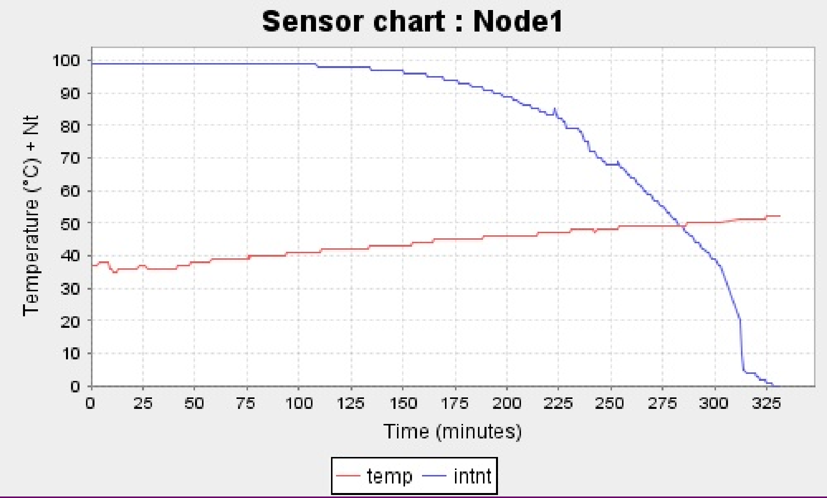
Hal Ross Flour Mill, K-State
May 13-14, 2009 Heat treatment
Validation

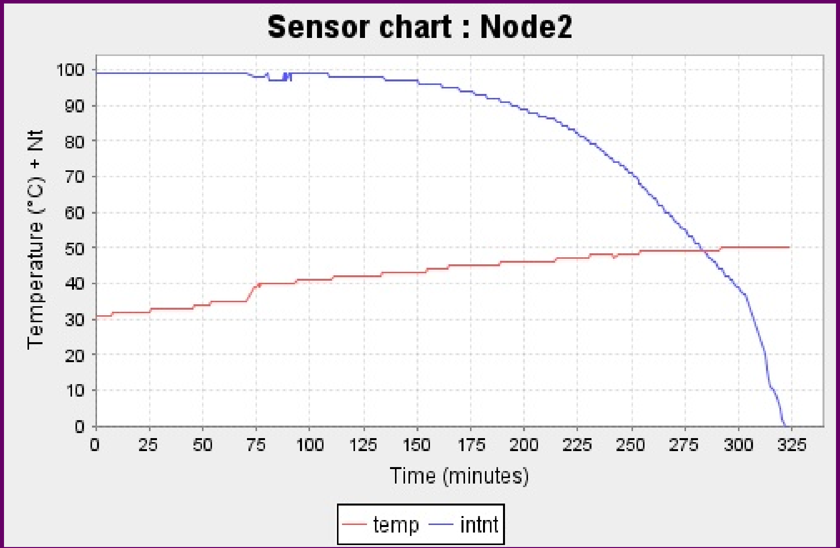


Hal Ross Flour Mill, K-State
August 25-26, 2009 Heat treatment
Validation



Sunflower seed facility, Saint Louis, MO September 25-26, 2009 Heat treatment





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Effectiveness against all life stages of red flour beetle

-May 13-14, 2009 Heat treatment
-August 25-26, 2009 Heat treatment

K-State's Hal Ross Flour Mill

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Bioassay box and PVC rings

August trt only

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Temperatures attained in bioassay boxes, May 13-14

Box no. (Floor)	Hours to 50ºC	Hours above 50ºC	Max temp. (ºC)	Hours to 50ºC	Hours above 50ºC	Max temp. (ºC)
	Dusting of flour			2 cm deep flour		
1(1F)	17.3	6.7	53.0	17.0	7.0	52.5
2 (1F)	17.6	6.4	55.5	20.5	3.5	52.5
3 (1F)	-	-	42.0	-	-	42.5
4 (1F)	22.3	1.7	51.0	-	-	48.5
5 (1F)	17.5	6.5	51.5	18.8	5.2	50.5
6 (2F)	11.0	13.0	54.5	14.2	9.8	54.0
7 (2F)	16.7	7.3	56.5	19.6	4.4	55.0
8 (2F)	13.5	10.5	58.0	17.2	6.8	55.0
9 (2F)	12.4	11.6	58.0	16.5	7.5	55.5
10 (2F)	11.3	12.7	57.5	16.6	7.4	54.5
11 (3F)	11.6	12.4	60.0	12.8	11.2	58.5
12 (3F)	10.4	13.6	63.0	13.2	10.8	60.0
13 (3F)	11.9	12.1	61.5	13.8	10.2	59.0
14 (3F)	8.7	15.3	66.0	11.8	12.2	62.5
15 (3F)	12.5	11.5	59.5	14.5	9.5	57.0

Box no. (Floor)	Hours to 50°C	Hours above 50°C	Max temp. (°C)	Hours to 50°C	Hours above 50°C	Max temp. (°C)
	Dusting of flour			2 cm deep flour		
16 (4F)	11.2	12.8	66.5	13.4	10.6	60.5
17 (4F)	15.2	8.8	54.0	19.6	4.4	52.0
18(4F)	14.7	9.3	56.5	18.0	6.0	54.0
19 (4F)	15.9	8.1	57.0	18.5	5.5	54.0
20 (4F)	16.9	7.1	54.5	20.7	3.3	52.0
21 (5F)	9.9	14.1	61.0	14.8	9.2	58.0
22 (5F)	18.3	5.7	53.0	21.9	2.1	50.5
23 (5F)	14.6	9.4	56.0	16.3	7.7	53.5
24 (5F)	11.9	12.1	57.5	14.6	9.4	54.5
25 (5F)	15.0	9.0	55.5	18.4	5.6	53.5

Percentage mortality of red flour beetle life stages

Box no. (Floor)	Eggs (Dust)	Eggs (2 cm)	Young larvae (Dust)	Young larvae (2 cm)	Old larvae (Dust)	Old larvae (2 cm)	Pupae (Dust)	Pupae (2 cm)	Adults (Dust)	Adults (2 cm)
1(1F)	100	100	100	100	98	100	100	100	100	100
2 (1F)	100	100	100	100	100	71	100	98	100	4
3 (1F)	94	80	90	24	0	0	0	17	0	2
4 (1F)	100	100	100	100	100	98	98	100	100	98
5 (1F)	100	100	100	100	100	100	100	100	100	100
6 (2F)	100	100	100	100	100	100	100	100	100	100
7 (2F)	100	100	100	100	100	100	100	100	100	100
8 (2F)	100	100	100	100	100	100	100	100	100	100
9 (2F)	100	100	100	100	100	100	100	100	100	100
10 (2F)	100	100	100	100	100	100	100	100	100	100
11 (3F)	100	100	100	100	100	100	100	100	100	100
12 (3F)	100	100	100	100	100	100	100	100	100	100
13 (3F)	100	100	100	100	100	100	100	100	100	100
14 (3F)	100	100	100	98	100	96	100	100	100	100
15 (3F)	100	100	100	100	100	100	100	100	100	100

Box no. (Floor)	Eggs (Dust)	Eggs (2 cm)	Young larvae (Dust)	Young larvae (2 cm)	Old larvae (Dust)	Old larvae (2 cm)	Pupae (Dust)	Pupae (2 cm)	Adults (Dust)	Adults (2 cm)
16 (4F)	100	100	100	100	100	100	100	100	100	100
17 (4F)	100	100	100	100	100	98	100	100	100	100
18(4F)	100	100	100	100	100	100	100	100	100	100
19 (4F)	100	100	100	100	100	100	100	100	100	100
20 (4F)	100	100	100	100	100	100	100	100	100	100
21 (5F)	100	100	100	94	100	95	100	100	100	100
22 (5F)	100	100	100	100	98	100	100	100	100	100
23 (5F)	100	100	100	100	96	100	100	100	100	100
24 (5F)	100	100	100	100	100	100	100	100	100	100
25 (5F)	100	100	100	100	100	100	100	100	100	100

May heat treatment conclusions

- Bioassay boxes
  - In compartments with flour dust, maximum temp. attained ranged from 42-67ºC and in 2 cm deep flour it was 43-63ºC
  - At every location in compartments with 2 cm deep flour it took 1 to 5 h longer than compartments with flour dust to reach 50ºC
  - Time to 50ºC was 9-22 h in compartments with flour dusting and 12-22 h in compartments with 2 cm deep flour
  - Mortality of insects was 100% for all life stages except for boxes in 9.2% of the 250 compartments
  - Mortality less than 100% can be attributed to slow heating rates and/or not holding temperatures above 50ºC for several hours

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Temperatures attained in bioassay boxes, August 25-26

Box no. (Floor)	Hours to 50°C	Hours above 50°C	Max temp. (°C)	Hours to 50°C	Hours above 50°C	Max temp. (°C)
	Dusting of flour			2 cm deep flour		
1(1F)	8.8	2.4	52.5	11.0	0.1	50.0
2 (1F)	22.0	2.0	50.0	21.0	2.3	50.5
3 (1F)	22.2	1.9	50.5	-	0.0	48.5
4 (1F)	18.1	5.9	54.5	21.3	2.8	51.5
5 (1F)	7.2	16.9	59.0	8.3	15.8	59.5
6 (2F)	10.5	13.5	57.5	12.2	11.9	57.0
7 (2F)	7.5	16.5	64.0	10.6	13.4	62.5
8 (2F)	7.7	16.4	63.0	10.1	14.0	60.5
9 (2F)	7.0	17.1	62.5	8.2	15.8	61.0
10 (2F)	6.3	17.7	64.0	9.3	14.7	62.0
11 (3F)	11.7	12.4	59.5	13.1	11.0	58.5
12 (3F)	5.8	18.3	62.5	8.0	16.1	60.5
13 (3F)	8.9	15.1	61.0	11.1	12.9	59.0
14 (3F)	9.0	15.1	62.5	10.7	13.4	60.0
15 (3F)	14.9	9.1	58.0	16.3	7.7	56.0

Box no. (Floor)	Hours to 50°C	Hours above 50°C	Max temp. (°C)	Hours to 50°C	Hours above 50°C	Max temp. (°C)
	Dusting of flour			2 cm deep flour		
16 (4F)	8.6	15.4	60.0	11.0	13.0	58.0
17 (4F)	15.6	8.4	56.5	18.0	6.0	54.0
18(4F)	6.8	17.3	63.0	9.1	15.0	60.5
19 (4F)	10.4	13.7	60.0	12.3	11.7	58.0
20 (4F)	10.3	13.7	60.5	13.3	10.8	58.5
21 (5F)	9.4	14.6	58.0	16.1	7.9	54.0
22 (5F)	9.4	14.6	59.0	11.1	13.0	57.5
23 (5F)	8.7	15.3	60.0	10.3	13.7	58.0
24 (5F)	7.5	16.6	61.0	8.7	15.3	59.5
25 (5F)	15.5	8.5	56.0	17.2	6.8	54.5

Percentage mortality of red flour beetle life stages

Box no. (Floor)	Eggs (Dust)	Eggs (2 cm)	Young larvae (Dust)	Young larvae (2 cm)	Old larvae (Dust)	Old larvae (2 cm)	Pupae (Dust)	Pupae (2 cm)	Adults (Dust)	Adults (2 cm)
1(1F)	98	100	100	82	100	88	100	100	100	0
2 (1F)	100	100	100	100	100	86	100	98	100	2
3 (1F)	100	100	100	42	100	91	100	95	100	0
4 (1F)	100	100	100	96	100	100	100	100	100	100
5 (1F)	100	100	100	100	100	100	100	100	100	100
6 (2F)	100	100	100	100	100	100	100	100	100	100
7 (2F)	100	100	96	100	100	100	100	100	100	100
8 (2F)	100	100	100	100	100	100	100	100	100	100
9 (2F)	100	98	100	100	100	100	100	100	100	100
10 (2F)	100	100	98	100	100	100	100	100	100	100
11 (3F)	100	100	94	100	100	100	100	100	100	100
12 (3F)	100	100	100	100	100	100	100	100	100	100
13 (3F)	100	100	100	100	100	100	100	100	100	100
14 (3F)	100	100	100	100	100	100	100	100	100	100
15 (3F)	100	100	100	100	100	100	100	100	100	100

Box no. (Floor)	Eggs (Dust)	Eggs (2 cm)	Young larvae (Dust)	Young larvae (2 cm)	Old larvae (Dust)	Old larvae (2 cm)	Pupae (Dust)	Pupae (2 cm)	Adults (Dust)	Adults (2 cm)
16 (4F)	100	100	100	100	100	100	100	100	100	100
17 (4F)	100	100	100	100	100	100	100	100	100	100
18(4F)	100	100	100	100	100	100	100	100	100	100
19 (4F)	100	100	100	100	100	100	100	100	100	100
20 (4F)	100	100	100	100	100	100	100	100	100	100
21 (5F)	100	100	100	100	100	100	100	100	100	100
22 (5F)	100	100	100	100	98	100	100	100	100	100
23 (5F)	100	100	98	100	100	100	100	100	100	100
24 (5F)	100	100	100	100	100	100	100	100	100	100
25 (5F)	100	100	100	100	100	100	100	100	100	100

August heat treatment conclusions

- Bioassay boxes
  - In compartments with flour dust the maximum temperatures attained were 50-64ºC
  - In compartments with 2 cm flour maximum temperatures attained were 49-63ºC.
  - Time to reach 50ºC took 6-22 h in compartments with flour dust and in compartments with 2 cm deep flour it took 8-21 h
  - At every location compartments with 2 cm deep flour took 1 to 7 ho longer than compartment with flour dust chambers to reach 50ºC
  - Mortality of insects was 100% for all life stages except in 7.6% of the 250 compartments, and less than 100% mortality can be easily explained by the rate of heating to 50ºC and time above 50ºC

Mortality of adults in PVC rings, August 25-26, 2009

Table 1: RESULTS FOR PVC RINGS ADULTS MORTALITY DATA – 25th-26th AUGUST2009

	FIRST FLOOR				THIRD FLOOR				CONTROL	
	12 HOURS HEAT TREATMENT									
Flour Depth (cm)	Hours to 50 C	Hours above 50 C	Max. Temp. (C)	**% Adult Mortality**	Hours to 50 C	Hours above 50 C	Max. Temp. (C)	**% Adult Mortality**	Maximum Temp. (C)	**% Adult Mortality**
0.1	-	-	45	**0**	-	-	47	**100**	29	**0**
0.2	-	-	41.5	**0**	-	-	45.5	**10**	29	**0**
1.0	-	-	39.5	**0**	-	-	45	**75**	29.5	**0**
3.0	-	-	37	**3**	-	-	44	**5**	30	**0**
6.0	-	-	35	**0**	-	-	44	**0**	29	**0**
10.0	-	-	35.5	**0**	-	-	44.5	**10**	29.5	**4**
	FIRST FLOOR				THIRD FLOOR				CONTROL	
	24 HOURS HEAT TREATMENT									
Flour Depth (cm)	Hours to 50 C	Hours above 50 C	Max. Temp. (C)	**% Adult Mortality**	Hours to 50 C	Hours above 50 C	Max. Temp (C)	**% Adult Mortality**	Maximum Temp. (C)	**% Adult Mortality**
0.1	-	-	48.5	**89**	15.0	9.0	58	**100**	29	**0**
0.2	-	-	47	**20**	15.8	8.3	57.5	**100**	29	**0**
1.0	-	-	46	**5**	15.9	8.1	58	**100**	29.5	**1**
3.0	-	-	44	**2**	16.4	7.7	57.5	**100**	30	**0**
6.0	-	-	42.5	**2**	16.7	7.3	56.5	**100**	29	**0**
10.0	-	-	42.5	**9**	16.3	7.7	57	**100**	29.5	**0**

Mortality of eggs in PVC rings, August 25-26, 2009

Table 2: RESULTS FOR PVC RINGS EGGS MORTALITY DATA – 25th-26th AUGUST2009

	FIRST FLOOR				THIRD FLOOR				CONTROL	
	12 HOURS HEAT TREATMENT									
Flour Depth (cm)	Hours to 50 C	Hours above 50 C	Max. Temp. (C)	**% Eggs Mortality**	Hours to 50 C	Hours above 50 C	Max. Temp. (C)	**% Eggs Mortality**	Maximum Temp. (C)	**% Eggs Mortality**
0.1	-	-	49.5	**99**	-	-	46.5	**60**	29	**21**
0.2	-	-	42.5	**80**	-	-	47	**26**	29.5	**29**
1.0	-	-	41	**35**	-	-	49	**87**	29.5	**27**
3.0	-	-	44	**71**	11.4	0.6	50.5	**100**	29.5	**23**
6.0	-	-	42	**76**	10.5	1.6	52	**100**	29.5	*** (530)**
10.0	-	-	37.5	**33**	9.5	2.5	53.5	**100**	29	*** (299)**
	FIRST FLOOR				THIRD FLOOR				CONTROL	
	24 HOURS HEAT TREATMENT									
Flour Depth (cm)	Hours to 50 C	Hours above 50 C	Max. Temp. (C)	**% Eggs Mortality**	Hours to 50 C	Hours above 50 C	Max. Temp (C)	**% Eggs Mortality**	Maximum Temp. (C)	**% Eggs Mortality**
0.1	13.3	10.8	55.5	**100**	15.2	8.8	58	**100**	29	**10**
0.2	22.0	2.1	50.5	**100**	15.6	8.4	58	**100**	29.5	*** (338)**
1.0	-	-	46.5	**91**	14.7	9.3	59	**100**	29.5	*** (149)**
3.0	-	-	45	**92**	14.4	9.6	59.5	**100**	29.5	**17**
6.0	-	-	45	**99**	15.4	8.6	57.5	**100**	29.5	*** (397)**
10.0	-	-	44	**77**	14.8	9.2	58.5	**100**	29	**26**

Conclusions

- Heat treatment is an effective tool to disinfest structures
- Heat was effective in controlling all life stages of red flour beetle, provided temperatures reached 50ºC and were held for several hours above 50ºC
- Flour depth did not affect red flour beetle egg and adult mortality after 24 h provided temperatures were above 50ºC
- Thermal death kinetic models and the EARTH software are useful tools to optimize heat treatments and to take corrective action in "real time"

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