Optimizing heat treatments in grain-processing facilities

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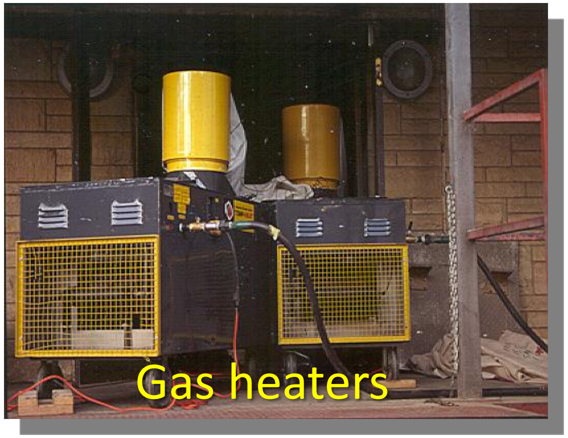
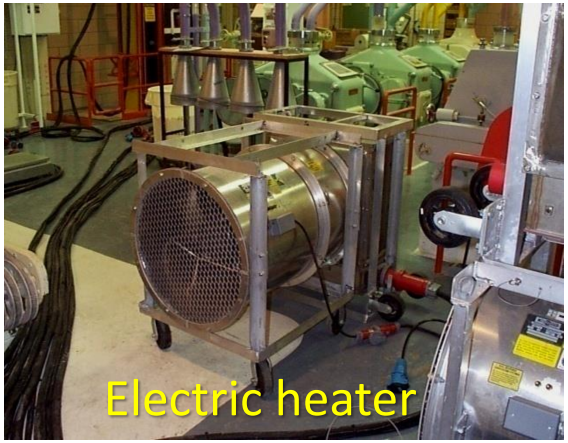
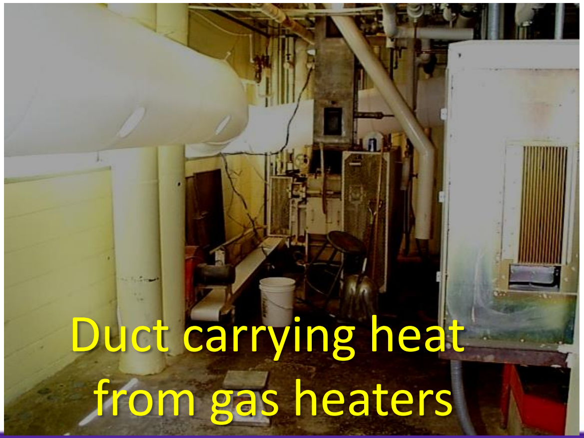
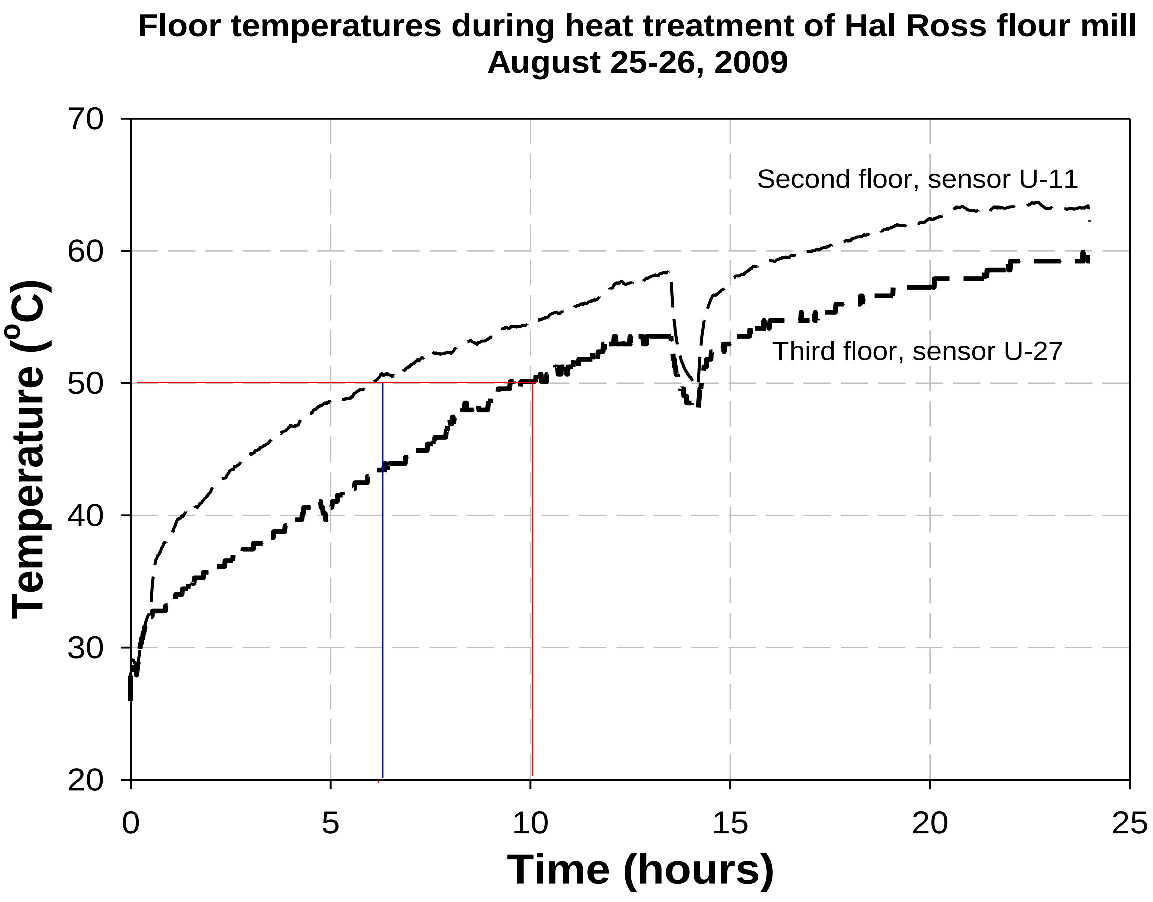
Heat treatment concept: Raising the ambient air temperature of the complete facility, or a part of it, to 122-140ºF (50-60ºC), and maintaining these temperatures for at least 24 hours.







Typical temperature profile



Stored-product insect responses at different temperature ranges*

Temp. ºC (ºF)	Response
25 – 32 (77 - 89.6)	Optimum for development
33 – 35 (91.4 – 95)	Upper limit for reproduction for most stored-product insects
36 – 42 (96.8 – 107.6)	Populations die out, mobile insects seek cooler zones
45 – 49 (113 – 120.2)	Death within a day
50 – 60 (122 – 140)	Death within hours to minutes
Above 62 (> 143.6)	Death within a minute

*After Banks and Fields, 1995.

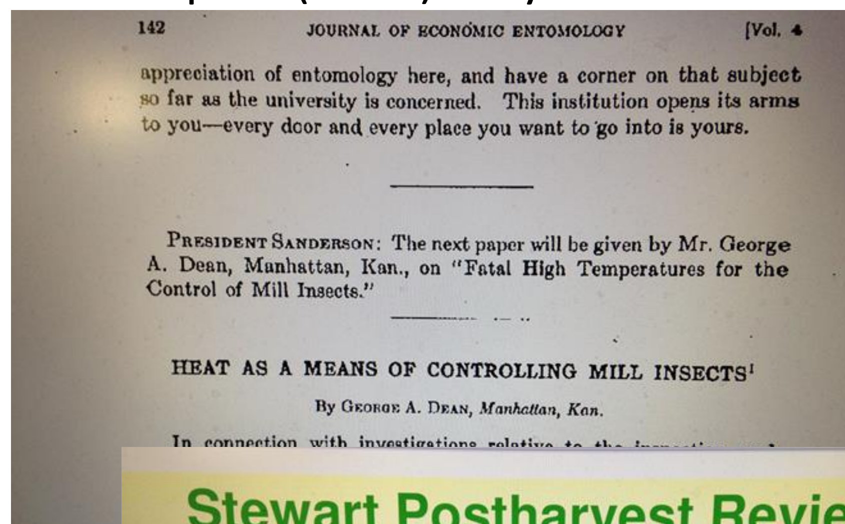
Heat treatment history

In the US

- Dean (1911, 1913)
- Pepper and Strand (1935)
- Oosthüizen (1935)
- Sheppard (1983)
- Heaps (1988)
- Heaps and Black (1994)
- Forbes and Ebeling (1987)
- Pedersen (1994)
- Dosland (1999)
- Dowdy (1999)
- Dowdy and Fields (2002)
- Subramanyam (1999 – present)

Other countries

- Teich (1994) – Germany
- Carpenter (1999) – New Zealand
- Fields (2004-present) – Canada
- Fluerat-Lessard (2012-present)-France
- Campolo (2013)-Italy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appreciation of entomology here, and have a corner on that subject so far as the university is concerned. This institution opens its arms to you—every door and every place you want to go into is yours.

President Sanderson: The next paper will be given by Mr. George A. Dean, Manhattan, Kan., on "Fatal High Temperatures for the Control of Mill Insects."

HEAT AS A MEANS OF CONTROLLING MILL INSECTS[1]

By George A. Dean, Manhattan, Kan.


Stewart Postharvest Review

An international journal for reviews in postharvest biology and technology

Heat treatment of grain-processing facilities for insect management: a historical overview and recent advances

Bhadriraju Subramanyam[1*], Rizana Mahroof[2] and Monika Brijwani[1]
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[2]Department of Biological Sciences, South Carolina State University, Orangeburg, South Carolina, USA

Abstract
Purpose of review: Tactics to manage infestations of stored-product insects in grain-processing facilities historically included the use

Structural heat treatment

- Major food companies have been using heat for many years
  - PepsiCo (Quaker Oats)
  - Con Agra
  - Pillsbury (now General Mills)
  - New World Pasta
  - Nestle Purina
  - Lundberg Farms
  - Anheuser-Busch
  - Gerber Foods
  - Abbott Laboratories
- **Renewed interest since 1999**

Food-processing facilities must find alternatives to methyl bromide

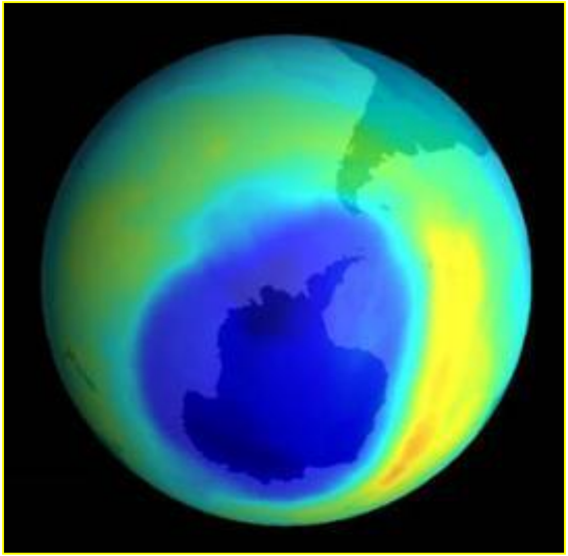
Heat Treatment is a Methyl Bromide Alternative

- 1993 -1998: Freeze at 1991 baseline levels (U.S. consumption ~25,500 Metric Tonnes)
- 1999-2000: 25% reduction
- 2001-2002: 50% reduction
- 2003-2004: 70% reduction
- 2005: 100% phase out
  - Except for critical use exemptions agreed to by the Montreal Protocol Parties
- Beyond 2005, continued production and import of methyl bromide is limited only for critical, emergency, quarantine and preshipment uses

Why is there a renewed interest in using heat treatments?

- Renewed interest because of phase-out of methyl bromide
    - 2005 in US
    - Ozone hole in Antarctica

"Image of the record-size ozone hole taken by NASA satellites on September 9, 2000. Blue denotes low ozone concentrations and yellow and red denote higher levels of ozone".



Locations where heat can be used

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

Important pre-heat treatment checklist

- Remove tension from drive belts to avoid stretching
- Perform sanitation and remove all food products
- Sprinkler heads should withstand 127^{o}C
- Protect heat sensitive equipment

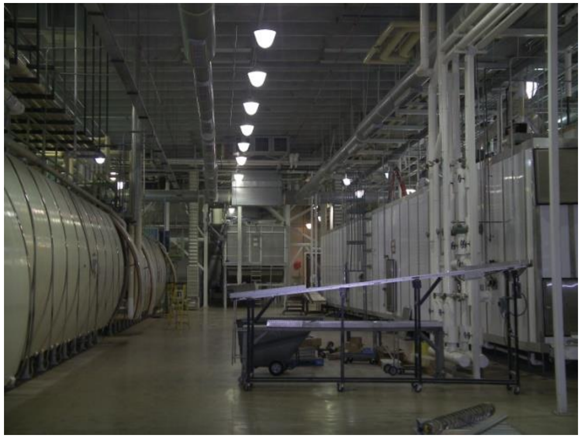
Heat damage

A successful heat treatment depends on...........

- Estimating the amount of heat required (through heat-loss calculations)
  - KSU Heat Treatment Calculator 2.0 [VisualBasic.NET]

- Improving pest management efficacy
  - Eliminating cool spots through uniform heat distribution (use of fans)
  - Assessing pre- and post-heat treatment insect counts
  - Following good exclusion and sanitation practices

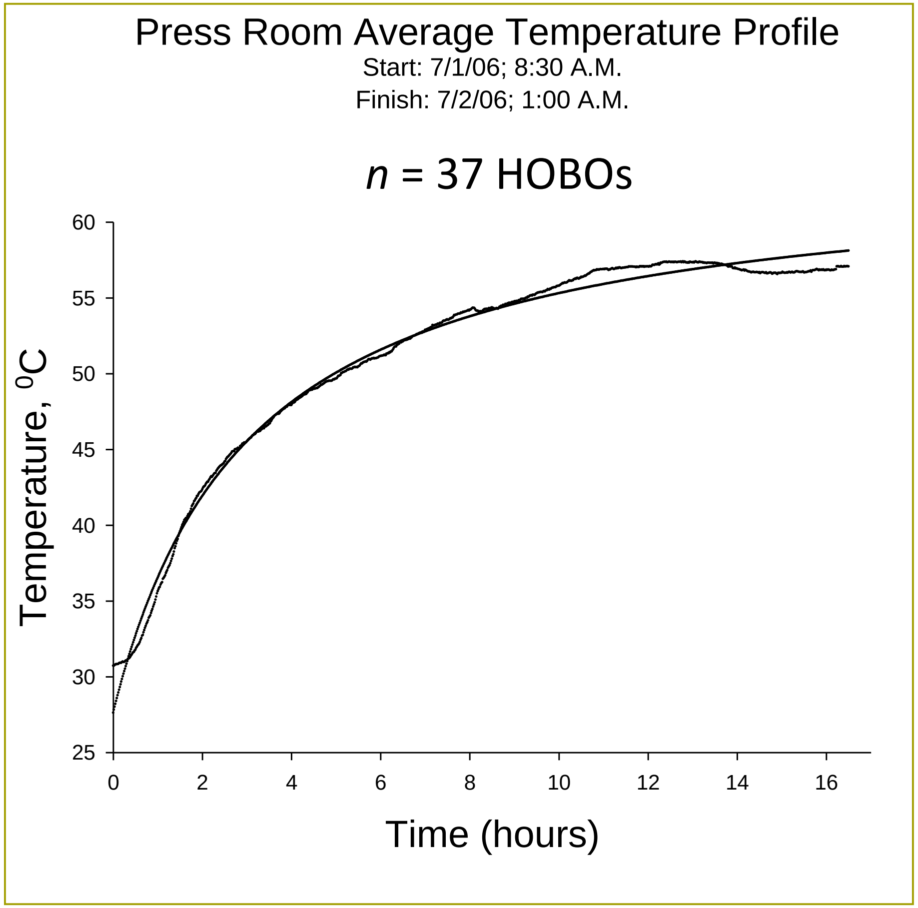
Pasta facility (A)

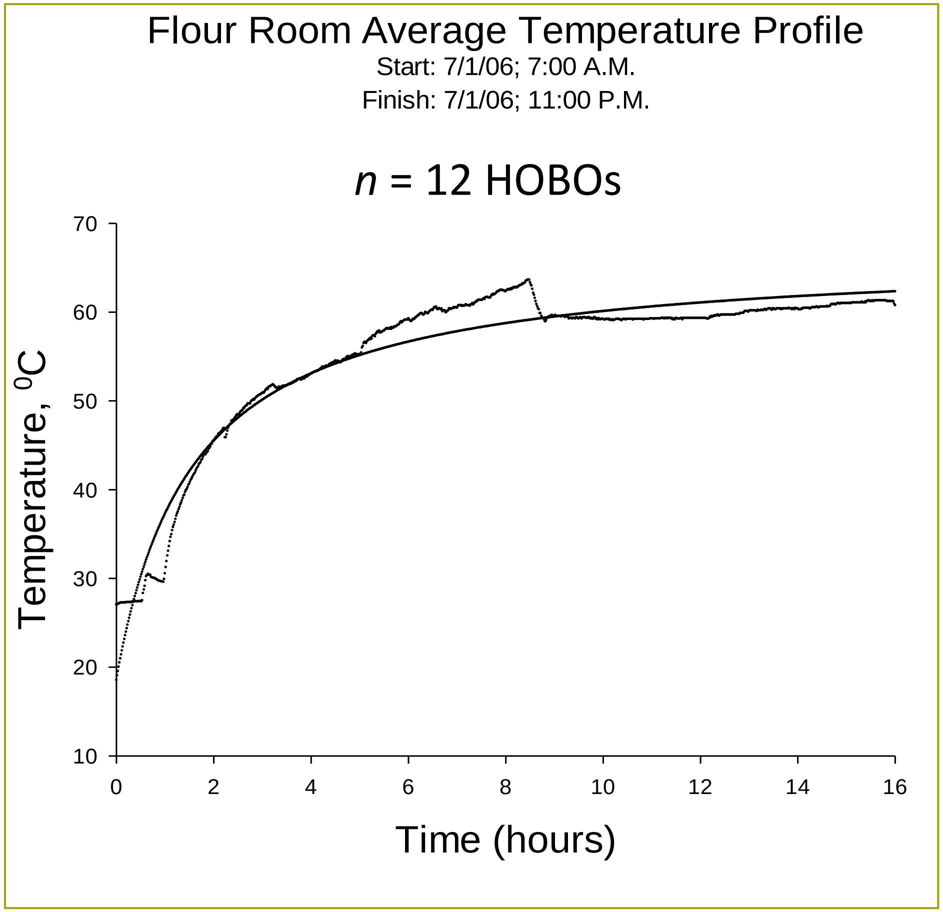


- Press area:
  - Volume: 1.55 million cu ft
  - Surface area: 46,750 sq ft
  - Wt of steel: 9,710,00 lb

- Flour room:
  - Volume: 120,000 cu ft
  - Surface area: 3,600 sq ft
  - Wt of steel: 750,000 lb

Facility A – Temperature Profiles






DANGER
DO NOT OPERATE

Heat energy requirements based on KSU Heat Treatment Calculator

Area	Heat requirements (in million BTU)			BTU/cubic foot/hour			Natural gas usage (in Therms)		
	Hourly		Total	Rise	Hold	Total	Hourly		Total
	Rise	Hold					Rise	Hold	
Flour Room	1.6	0.7	18.24	13.4	5.8	9.6	21.5	9.8	250.4
Press Room	11.53	4.9	142.6	6.3	2.7	4.6	165	70	2041

Total estimated heat required: 160.8 million BTU. Estimated fuel cost: $ 2498

Heat generated at 70% efficiency: 155 million BTU
Natural gas used during heat treatment: 2212 Therms
Cost of fuel used during heat treatment: $ 2411

Heat energy required

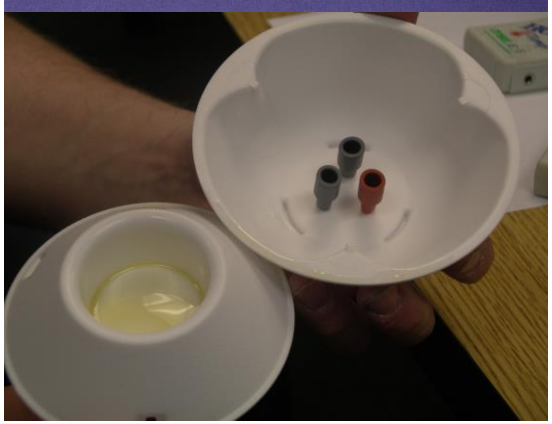
A = 0.10-0.15 Kw/h

B=Volume of facility on cubic meters

C=Duration of treatment (24 h)

Total heat energy=A x B x C

Use traps before and after heat treatment



Food and pheromone-baited trap for crawling insects

Sticky trap for moths/beetles

Captures of red flour beetles (*Tribolium castaneum*)

Mean number of adults/trap/week

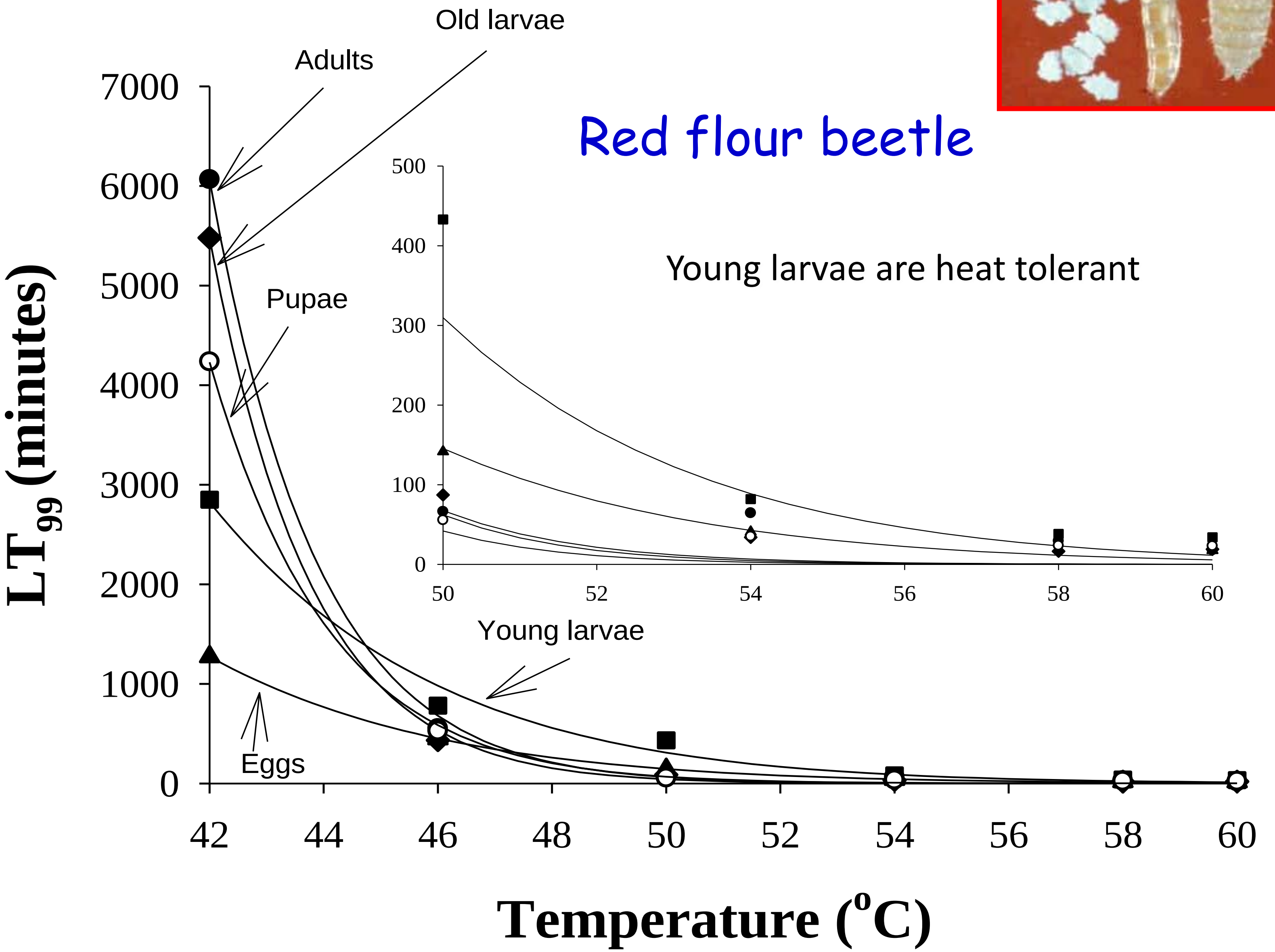
Date	Press room (*n*=35)	Flour room (*n*=10)	Outside (*n*=5)
5/30/2006	0.46	0.40	0.50
6/14/2006	0.20	0.42	0.65
6/28/2006	0.32	0.65	0
7/11/2006	0 (100%)	0.09 (86%)	0
7/25/2006	0.03	0.10	0.38
8/8/2006	0	0.05	0.50
8/23/2006	0.01	0.05	0.20

http://www.spike-international-agencies.com/meer_insecten.htm

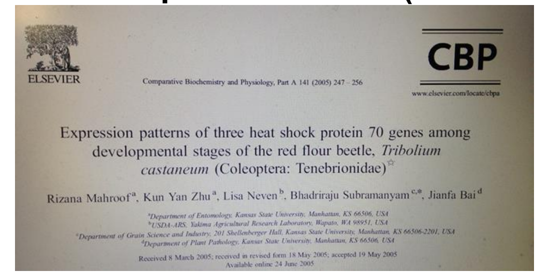
Susceptibility differences among life stages and insect species

Red flour beetle

Young larvae are heat tolerant



HSP Detected in Young Larvae Exposed to Different Temperatures (70 kDa protein)


ELSEVIER

CBP

Comparative Biochemistry and Physiology, Part A 141 (2005) 247 – 256

www.elsevier.com/locate/cbpa

Expression patterns of three heat shock protein 70 genes among developmental stages of the red flour beetle, *Tribolium castaneum* (Coleoptera: Tenebrionidae)☆

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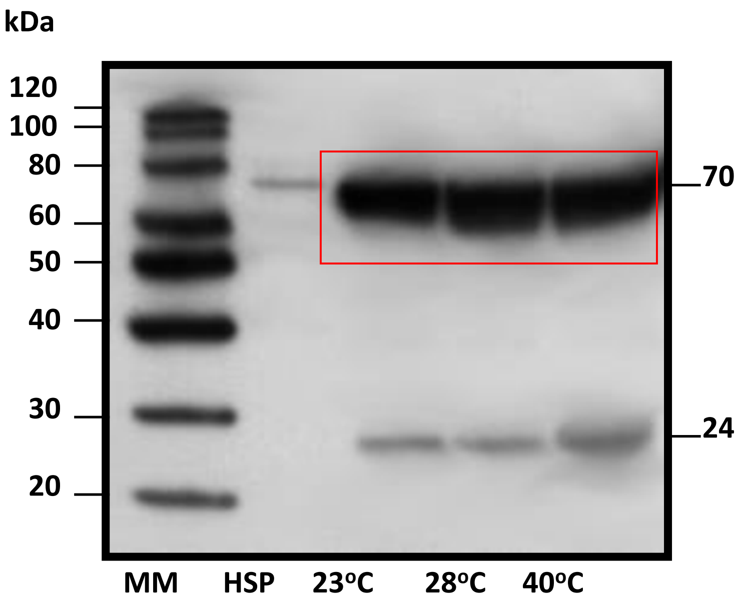
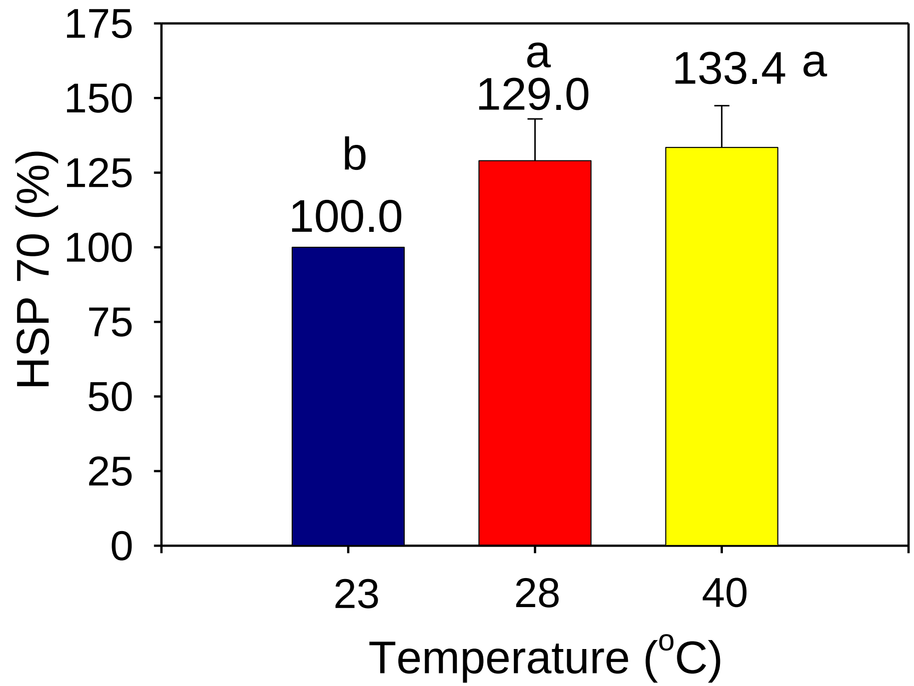
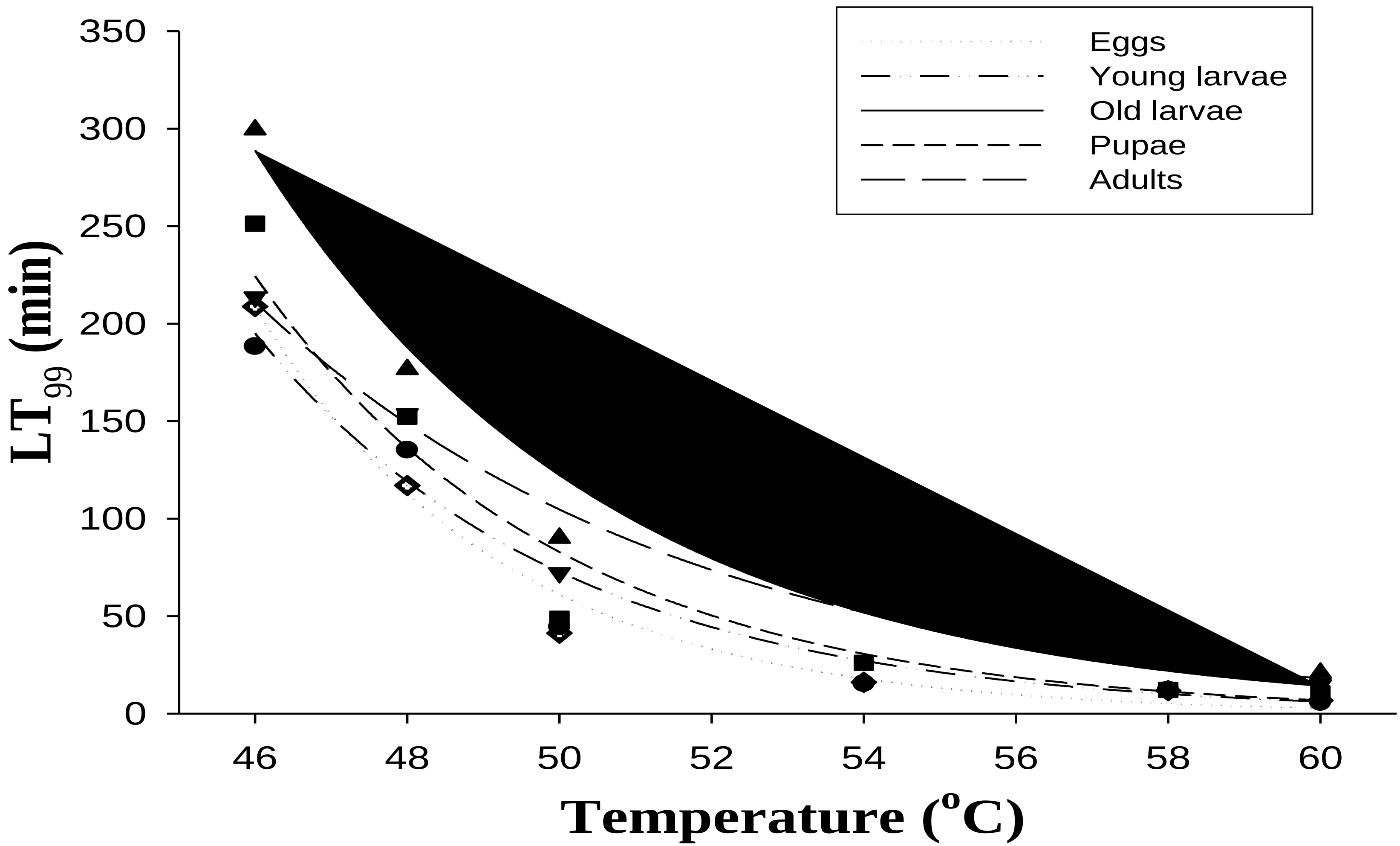




Calculated molecular mass of HSP (70) is 75 kDa

$F = 6.72$; $d.f. = 2$; $P < 0.05$; $n = 4$ (Proc GLM, LSD)

Confused flour beetle (*Tribolium confusum*)



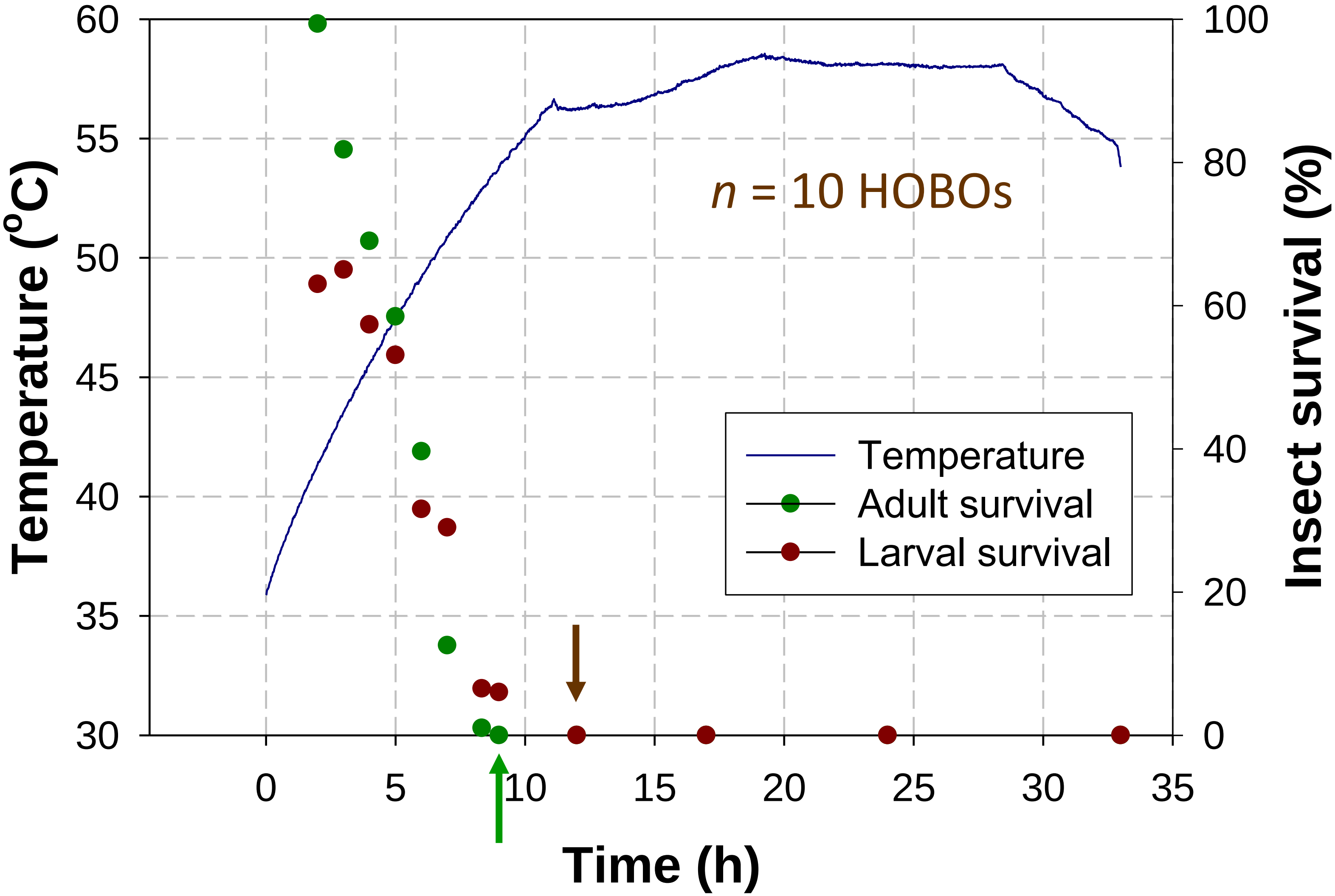
Comparison of heat tolerant stages of four species (LT_{99} in minutes (95% CL))

Species	**Stage**	**46^{o}C**	**50^{o}C**	**54^{o}C**
Cigarette beetle	Eggs	598.1 (571.21-633.10)	165.45 (152.62-182.84)	37.87 (35.14-41.56)
Red flour beetle	Young larvae	430.7 (364.3-573.6)	432.8 (365.3-572.6)	81.9 (60.4-207.7)
Confused flour beetle	Mature larvae	299.46 (281.81-324.88)	90.05 (81.80-102.26)	55.71 (48.75-67.25)
Indianmeal moth	Mature larvae	69 (62-80)	34 (29-43)	Not tested

Do we need a 24-36 h exposure time?


Facility C, Quaker Oats

Aug 31-Sep 2, 2007



Quaker Oats (PepsiCo)

- Heat treat for 24 h instead of 34 hours
- Annual savings are, $25,000
- Email, November 25, 2009

Can mortality of heat tolerant stages of an insect species be predicted during heat treatment?

Thermal death kinetic models

STORED-PRODUCT

Dynamic Model for Predicting Survival of Mature Larvae of *Tribolium confusum* During Facility Heat Treatments

DHANA RAJ BOINA,[1,2] BHADRIRAJU SUBRAMANYAM,[3,4] AND SAJID ALAVI[3]

J. Econ. Entomol. 101(3): 989–997 (2008)

ABSTRACT Structural heat treatment, a viable alternative to methyl bromide fumigation, involves raising the ambient temperature of food-processing facilities between 50 and 60°C by using gas, electric, or steam heaters, and holding these elevated temperatures for 24 h or longer to kill stored-product insects. A dynamic model was developed to predict survival of mature larvae, which is the most heat-tolerant stage of the confused flour beetle, *Tribolium confusum* (Jacquelin du Val), at elevated temperatures between 46 and 60°C. The model is based on two nonlinear relationships: 1) logarithmic survival of *T. confusum* mature larvae as a function of time, and 2) logarithmic reduction in larval survival as a function of temperature. The dynamic model was validated with nine independent data sets collected during actual facility heat treatments conducted on two separate occasions at the Kansas State University pilot flour and feed mills. The rate of increase of temperature over time varied among the nine locations where mature larvae of *T. confusum* were exposed, and the approximate heating rates during the entire heat treatment ranged from 1.1 to 13.2°C/h. The absolute deviation in the predicted number of larvae surviving the heat treatment was within 3–7% of the actual observed data. Comparison of the absolute deviation in the time taken for equivalent larval survival showed that the model predictions were within 2–6% of the observed data. The dynamic model can be used to predict survival of mature larvae of *T. confusum* during heat treatments of food-processing facilities based on time-dependent temperature profiles obtained at any given location.

STORED-PRODUCT

Models to Predict Mortality of *Tribolium castaneum* (Coleoptera: Tenebrionidae) Exposed to Elevated Temperatures During Structural Heat Treatments

FUJI JIAN,[1] BHADRIRAJU SUBRAMANYAM,[2,3] DIGVIR S. JAYAS,[1] AND NOEL D. G. WHITE[4]

J. Econ. Entomol. 106(5): 2247–2258 (2013); DOI: http://dx.doi.org/10.1603/EC12278

ABSTRACT Novel thermal death models were developed with certain assumptions, and these models were validated by using actual heat treatment data collected under laboratory conditions at constant temperatures over time and in commercial food-processing facilities where temperatures were dynamically changing over time. The predicted mortalities of both young larvae and adults of the red flour beetle, *Tribolium castaneum* (Herbst), were within 92–99% of actual measured insect mortalities. There was good concordance between predicted and observed mortalities of young larvae and adults of *T. castaneum* exposed to constant temperatures in laboratory growth chambers and at variable temperatures during structural heat treatments of commercial food-processing facilities. The models developed in this study can be used to determine effectiveness of structural heat treatments in killing young larvae and adults of *T. castaneum* and for characterizing insect thermotolerance.

KEY WORDS *Tribolium castaneum*, mortality, heat treatment, food-processing facility, model

Thermal death kinetic model for the most heat tolerant stage

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

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

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

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

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

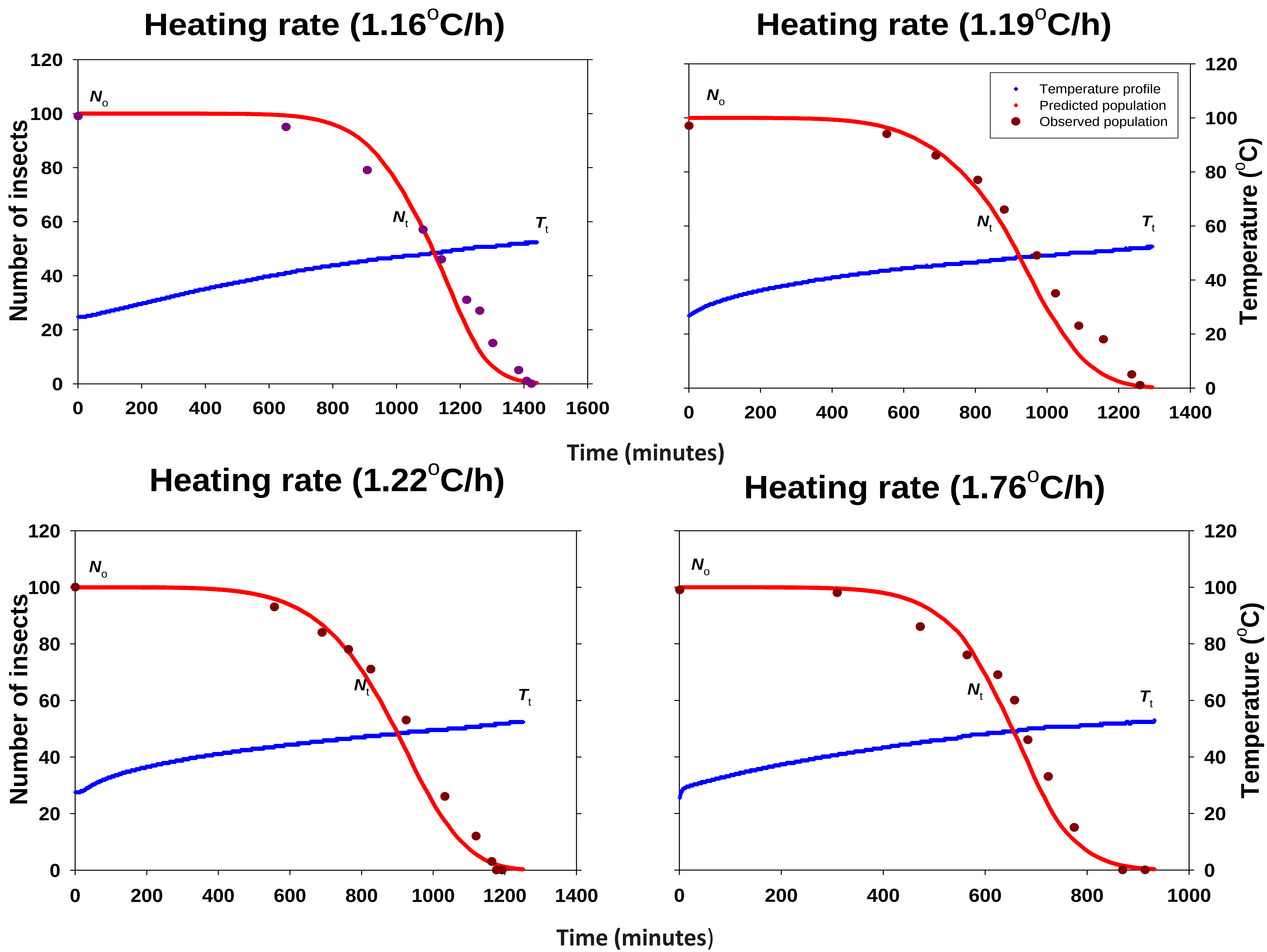
where N_o is the original number of insects; N_t is number of larvae at time *t*; Δt is the incremental exposure time (1-min), *D* is the mean instantaneous *D*-value as a function of temperature *(T_t)*, and T_t is time- dependent temperature profile

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

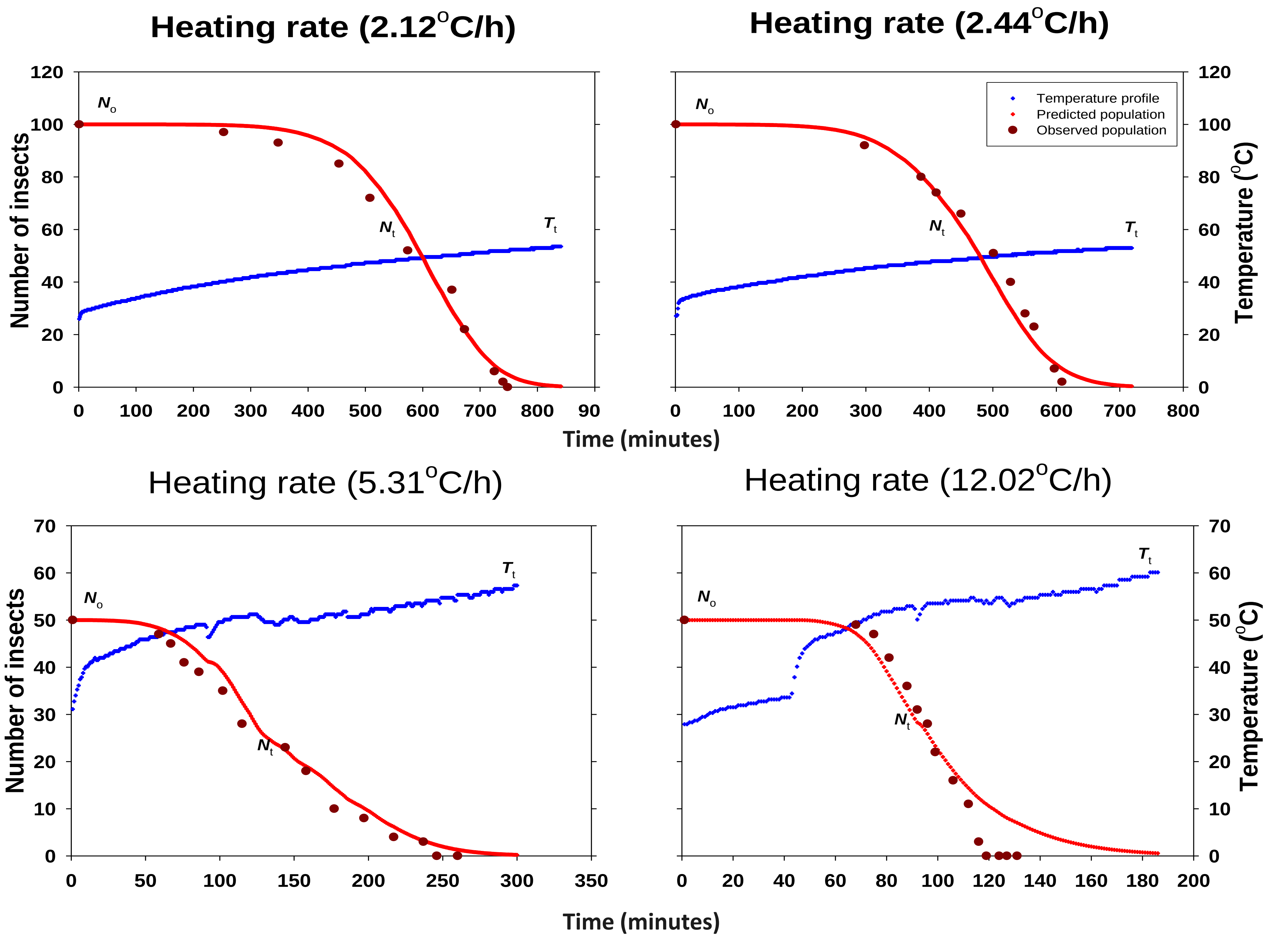
Boina et al. (2008)

Survival of old larvae of *Tribolium confusum* as a function of temperature

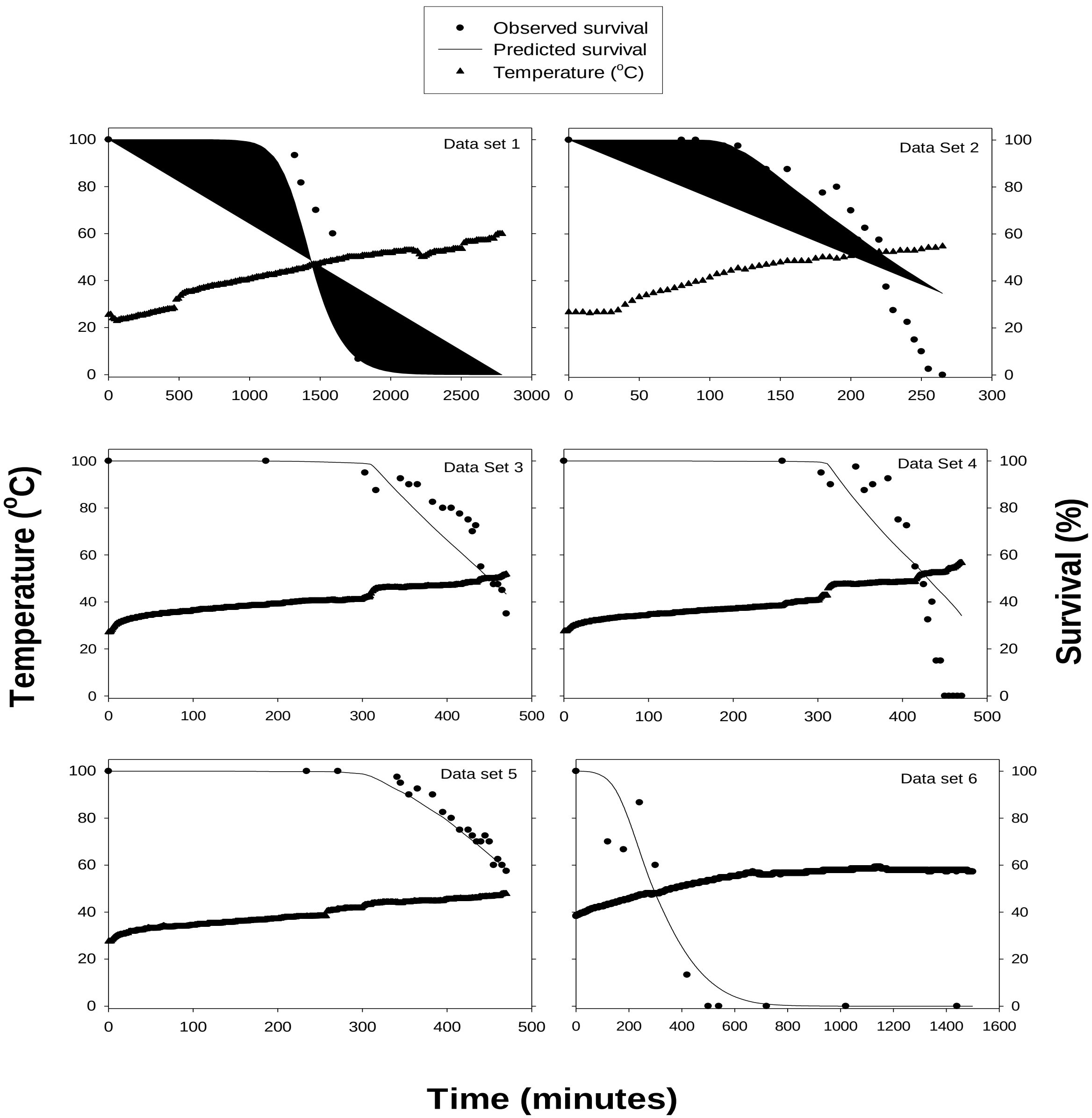
Comparison of model predictions to actual
Insect survival



Heating rate (1.16°C/h)
Heating rate (1.19°C/h)
Heating rate (1.22°C/h)
Heating rate (1.76°C/h)
Number of insects
Temperature (°C)
Time (minutes)
Temperature profile
Predicted population
Observed population
N o
N t
T t


Heating rate (2.12°C/h)
Heating rate (2.44°C/h)
Heating rate (5.31°C/h)
Heating rate (12.02°C/h)
Number of insects
Temperature (°C)
Time (minutes)
Temperature profile
Predicted population
Observed population
N_o
N_t
T_t

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

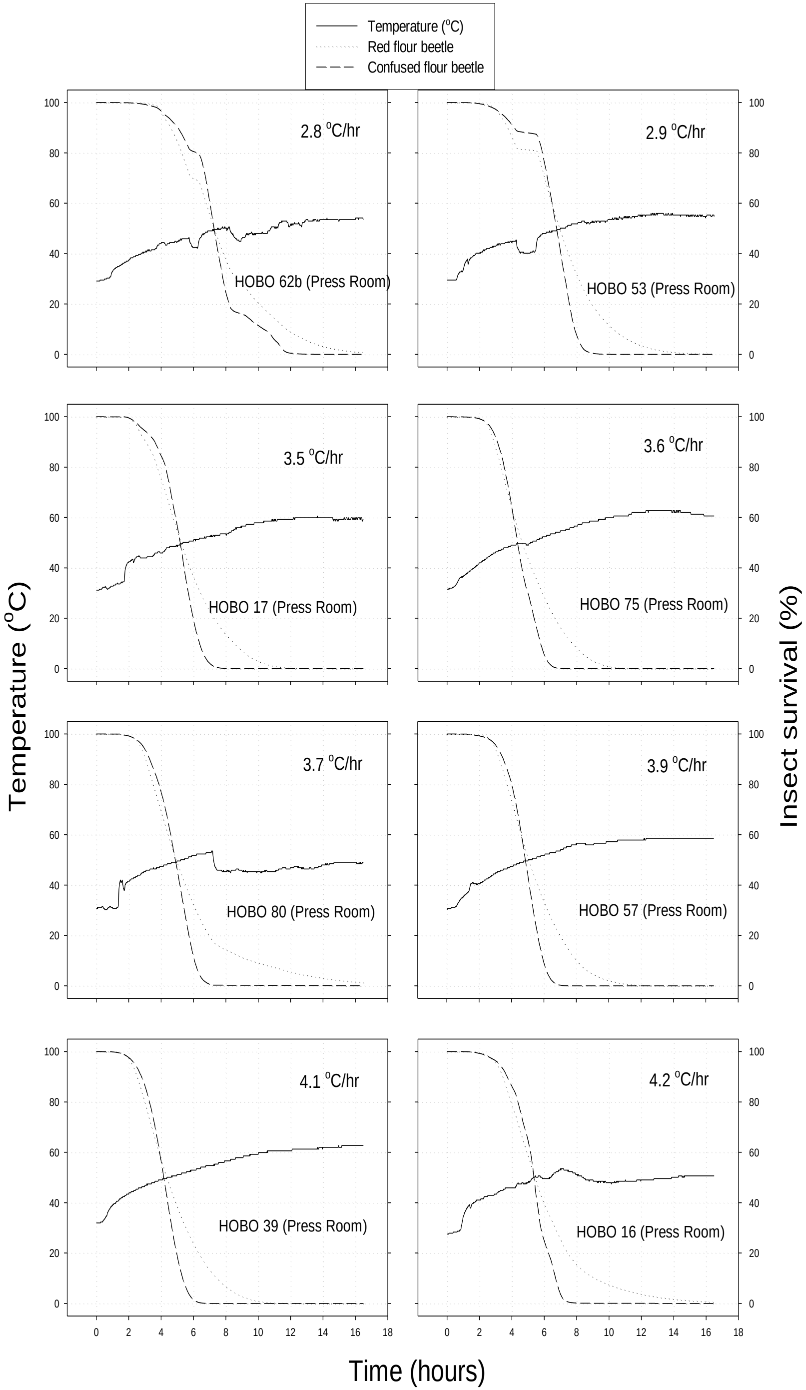


Supernova (C-Sharp)

- A software program (requires data in Excel xls format)
- Predicts survival of young larvae of *T. castaneum* and old larvae of *T. confusum* based on time-dependent temperature profile
- Gives information on heating rate ($^{o}C/h$)
- Gives information on 90, 95, and 99% mortality
- Saves output data in an Excel file for graphing purposes

An example: Quaker Oats

	Temp 22	Temp 23	Temp 24
Heating Rate	1.6 °C/hr	3.8 °C/hr	2.6 °C/hr
RFB 99%	16.07 Hr	7.72 Hr	10.00 Hr
RFB 95%	13.58 Hr	6.65 Hr	8.60 Hr
RFB 90%	12.33 Hr	5.98 Hr	7.75 Hr
CFB 99%	11.52 Hr	4.52 Hr	6.42 Hr
CFB 95%	11.27 Hr	4.17 Hr	5.97 Hr
CFB 90%	11.13 Hr	3.97 Hr	5.73 Hr

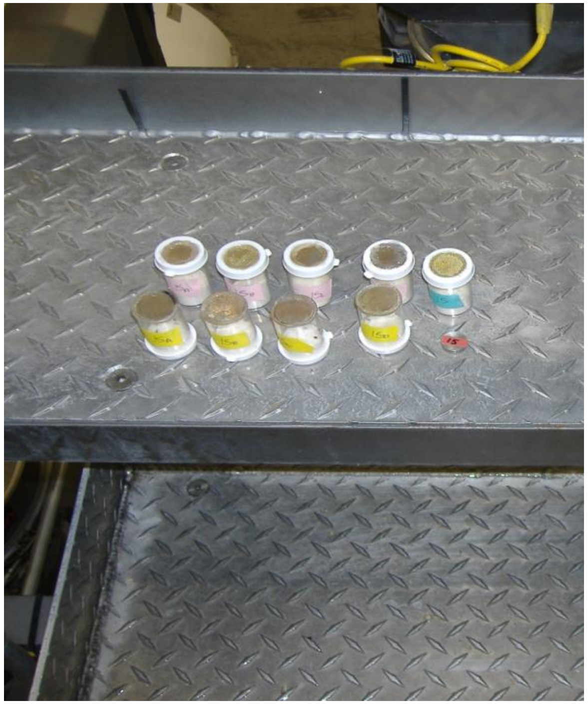


Predicted survival of young larvae of *T. castaneum* and old larvae *of T. confusum* in a pasta plant

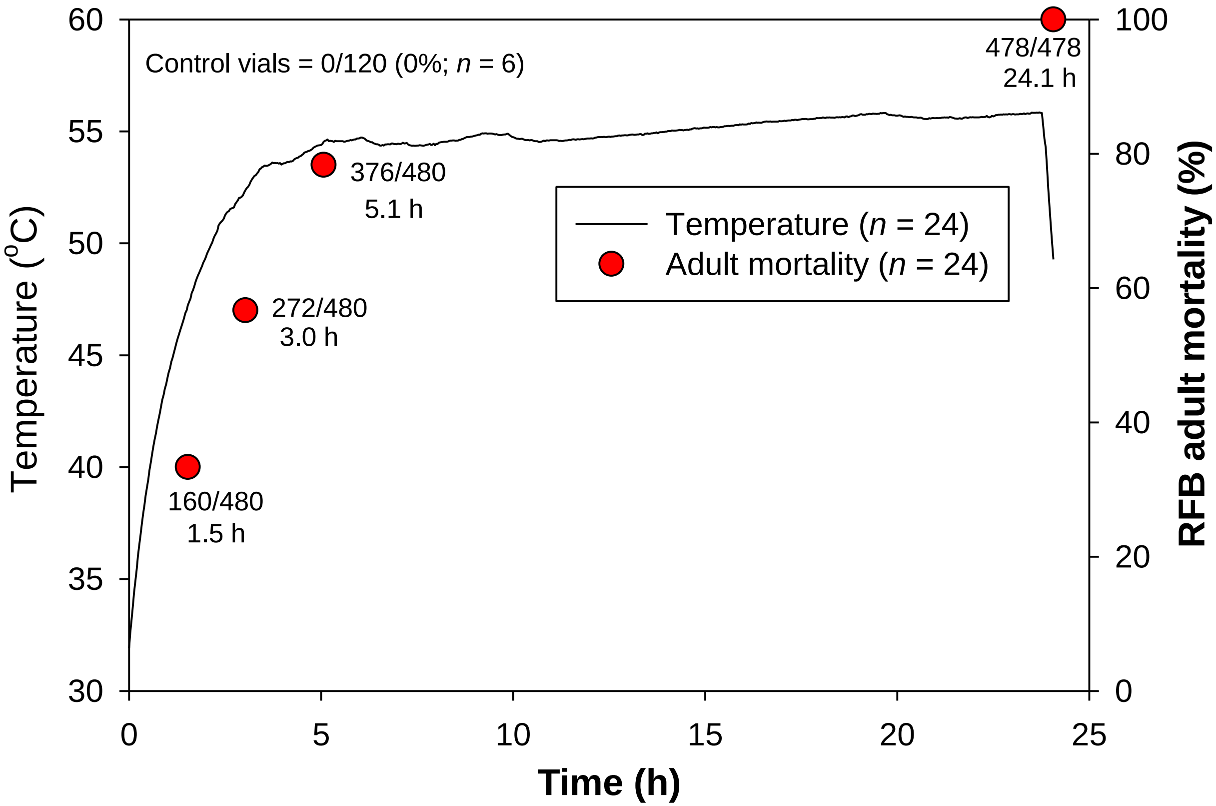
Recent data from a commercial facility


070W

Red flour beetle bioassays



Columbia, MO

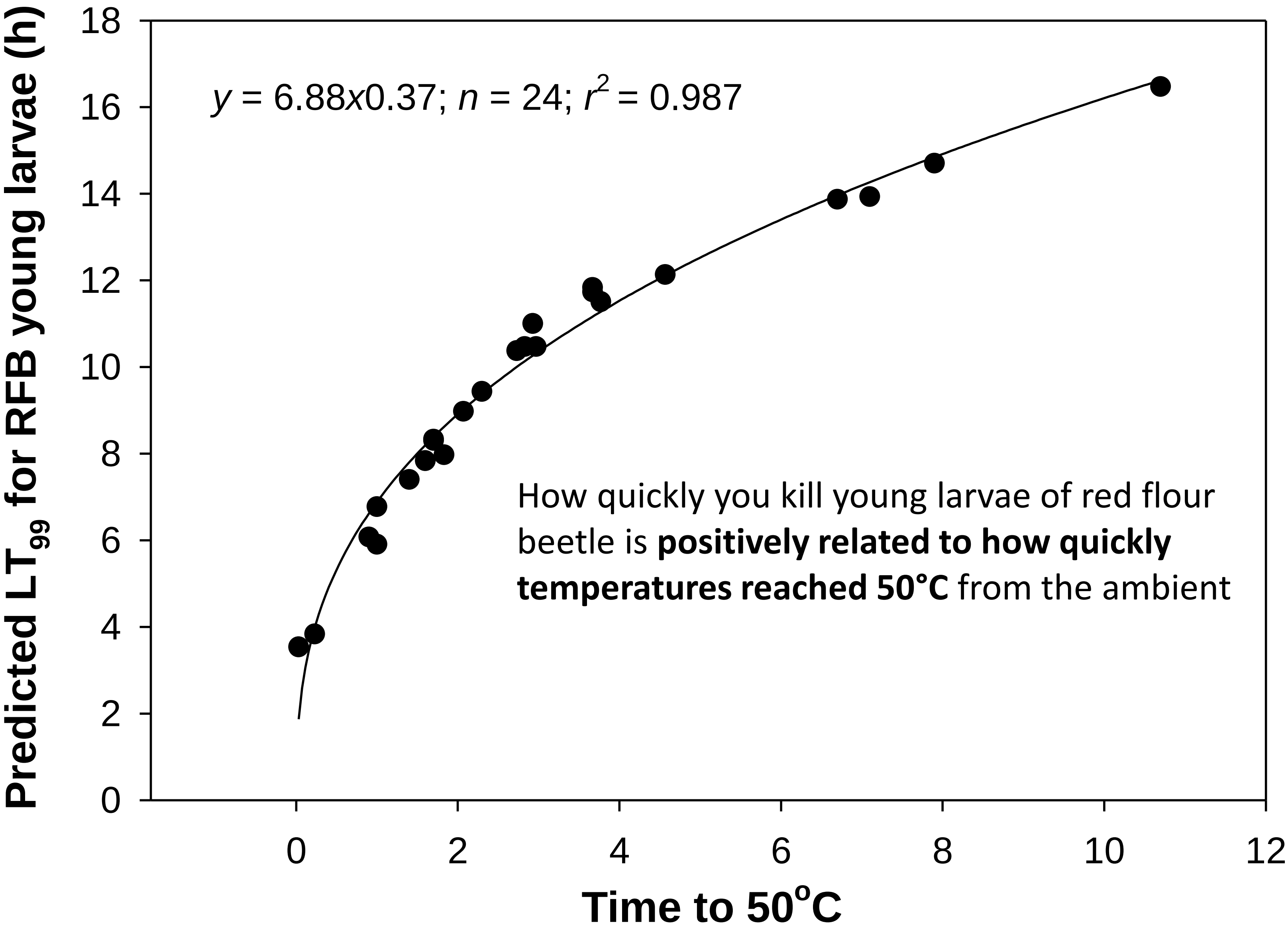


Egg –to-adult survival

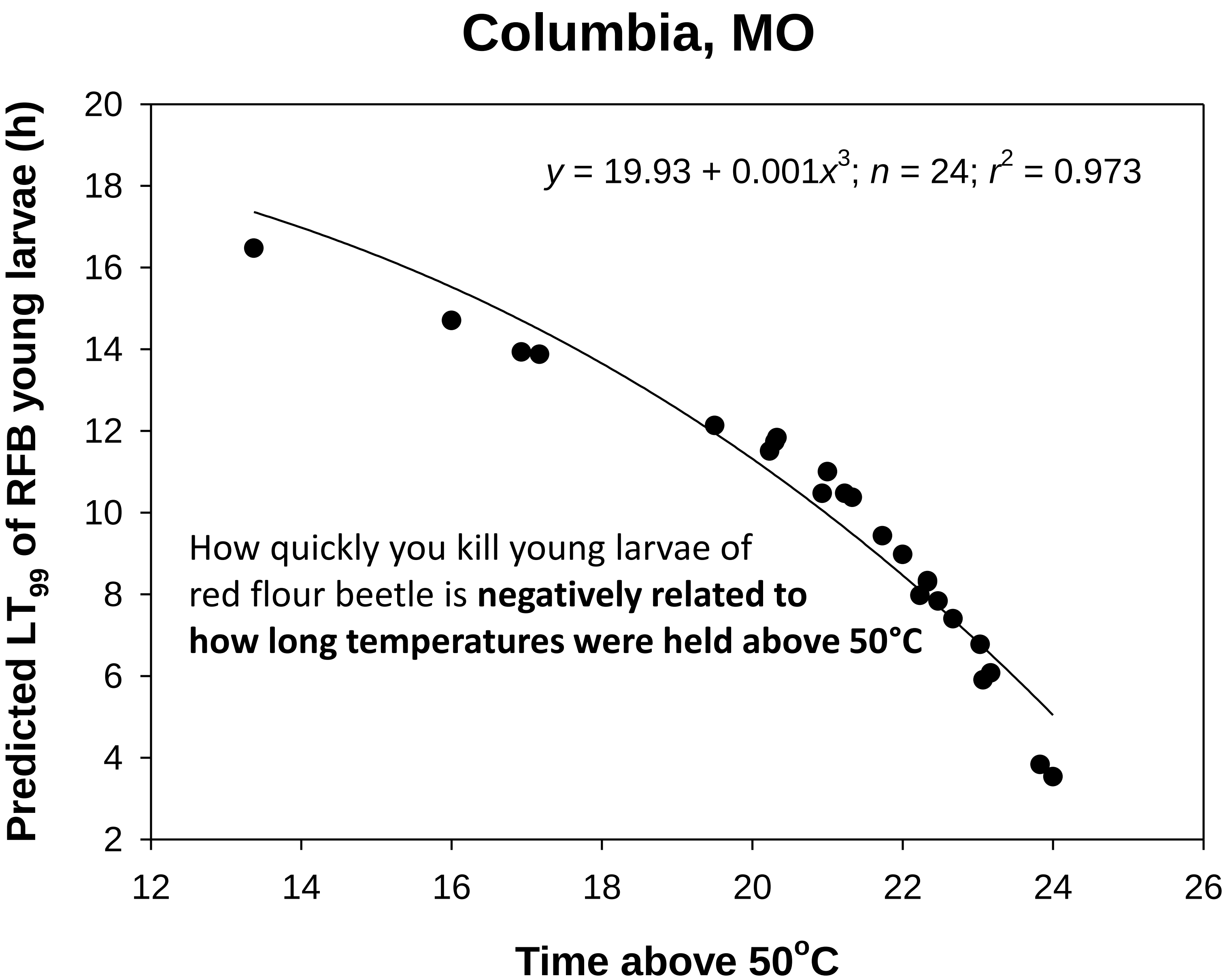
Time (h)	Control (*n*=6 vials)	Heat exposed (*n* = 24 vials)
1.5	81/120	84/480
3.0	79/120	0/480
5.1	84/120	0/480
24.1	80/120	0/480

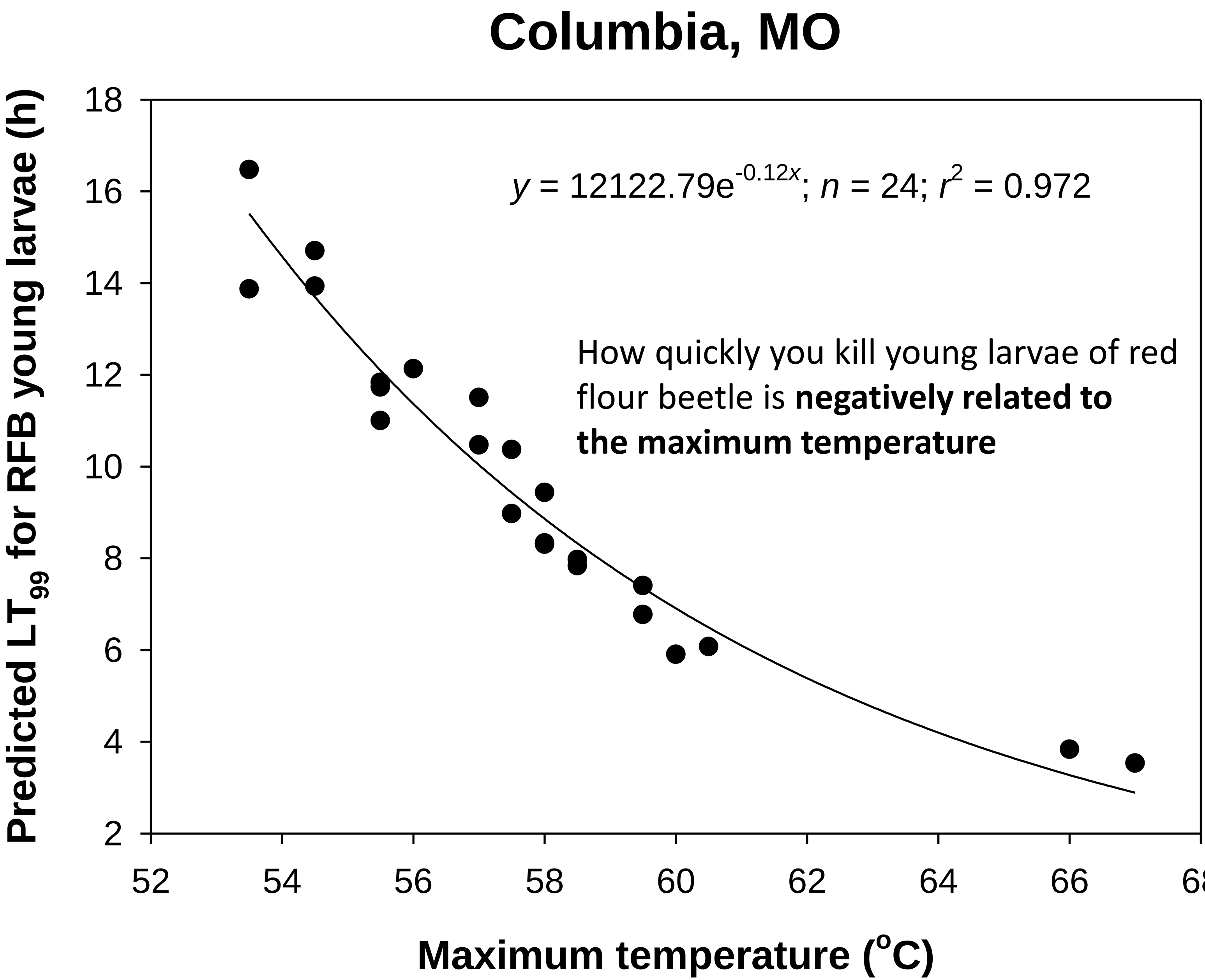
Each via has 20 eggs.

Columbia, MO



y = 6.88x0.37; n = 24; r2 = 0.987
How quickly you kill young larvae of red flour beetle is **positively related to how quickly temperatures reached 50°C** from the ambient
Predicted LT99 for RFB young larvae (h)
Time to 50oC
0
2
4
6
8
10
12
14
16
18
0
2
4
6
8
10
12

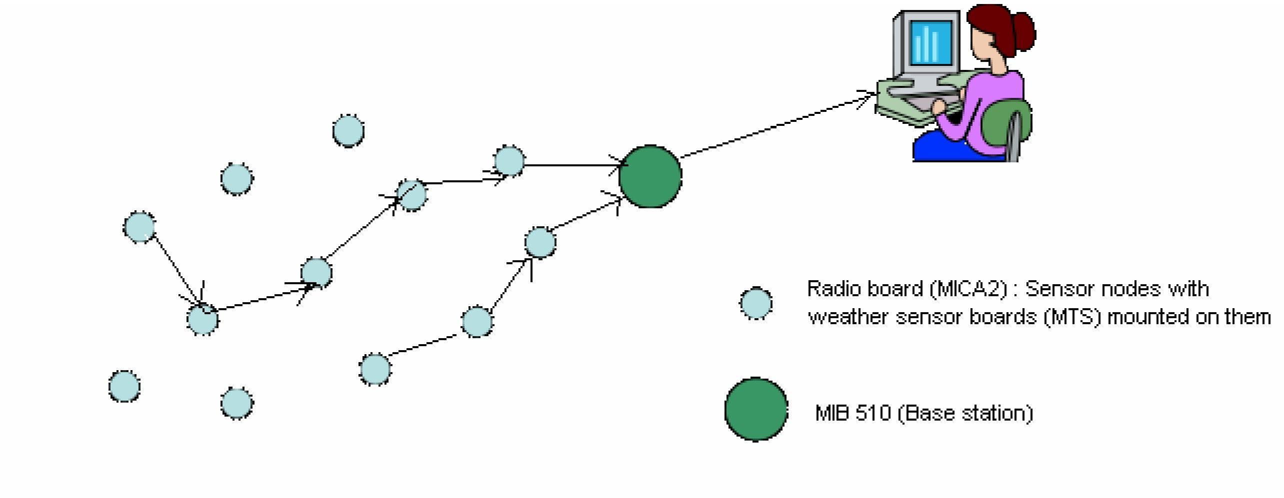

Columbia, MO
$y = 19.93 + 0.001x^3$; $n = 24$; $r^2 = 0.973$
How quickly you kill young larvae of red flour beetle is **negatively related to how long temperatures were held above 50°C**
Predicted LT_{99} of RFB young larvae (h)
Time above 50°C
20
18
16
14
12
10
8
6
4
2
12
14
16
18
20
22
24
26


Columbia, MO
$y = 12122.79e^{-0.12x}$; $n = 24$; $r^2 = 0.972$
How quickly you kill young larvae of red flour beetle is **negatively related to the maximum temperature**
Predicted LT_{99} for RFB young larvae (h)
Maximum temperature (°C)
18
16
14
12
10
8
6
4
2
52
54
56
58
60
62
64
66
68

- Predicting insect survival or mortality during a heat treatment

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

Wireless sensor networks



Typical wireless sensor network architecture

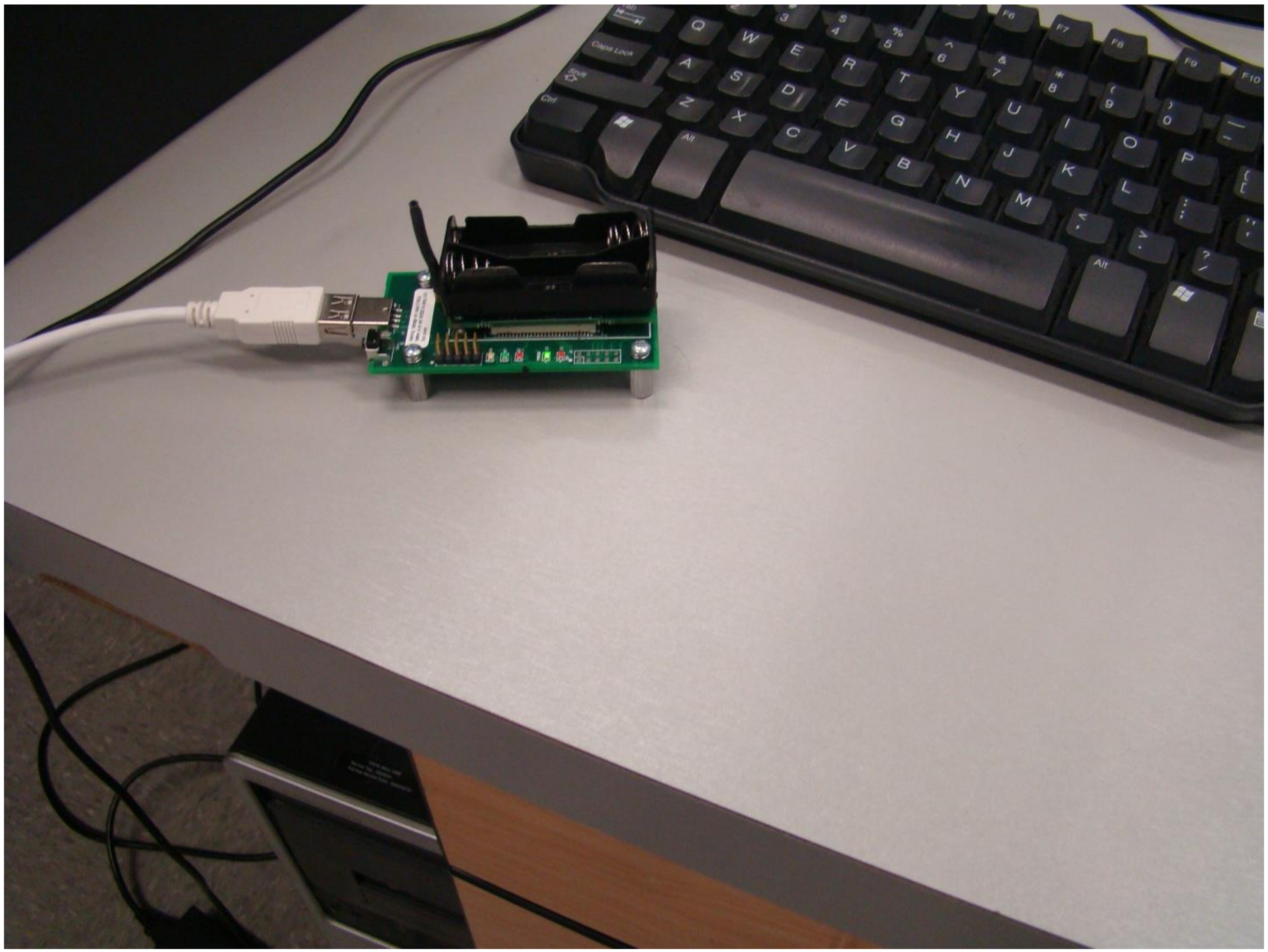
MIB/MICA2/MTS technology from Crossbow Technology Inc, San Jose, CA

MICA2 Processor/Radio board
MPR 400 CB

MTS weather sensor boards (MTS 400 CB)

MIB510 Serial interface and programming board (Base station for wireless sensor networks)

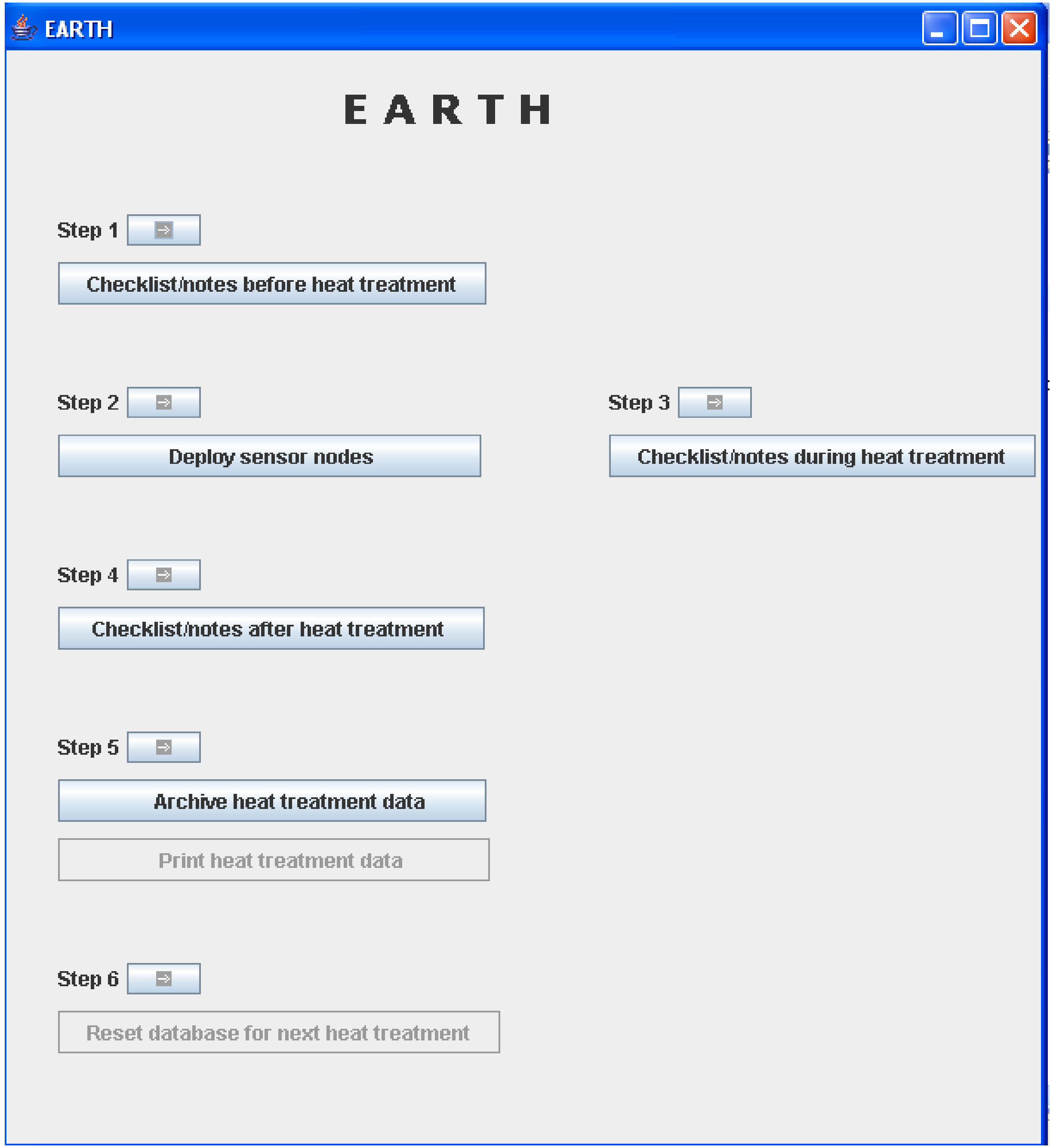

LOCKOUT CENTER
BUHLER



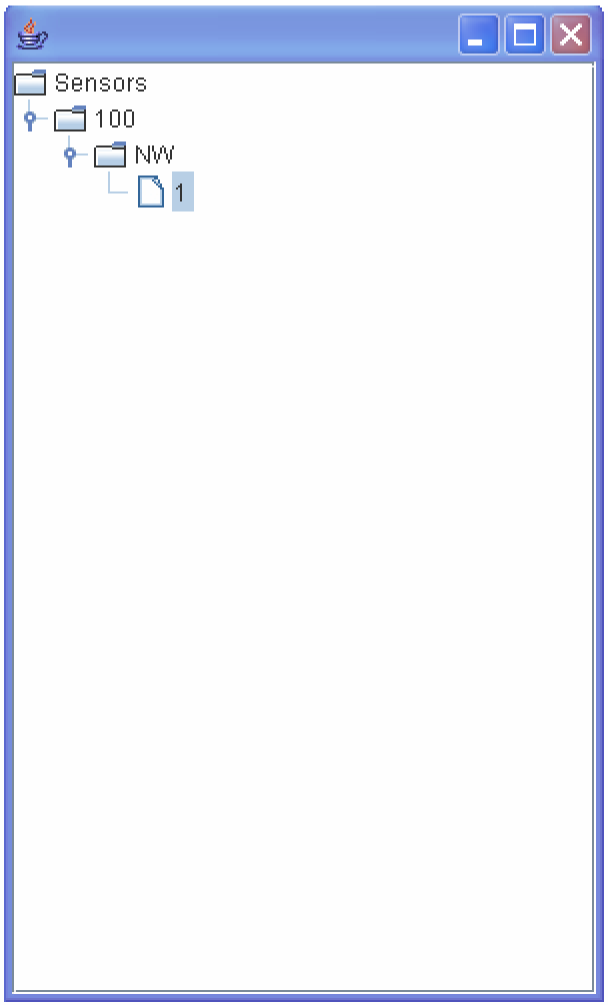

Panasonic
DURACELL

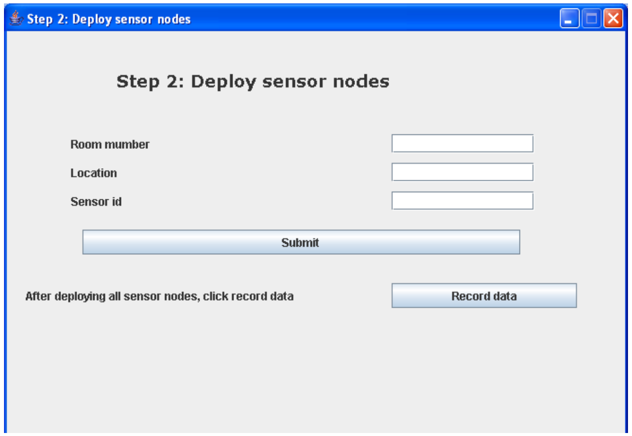
E.A.R.T.H. Software

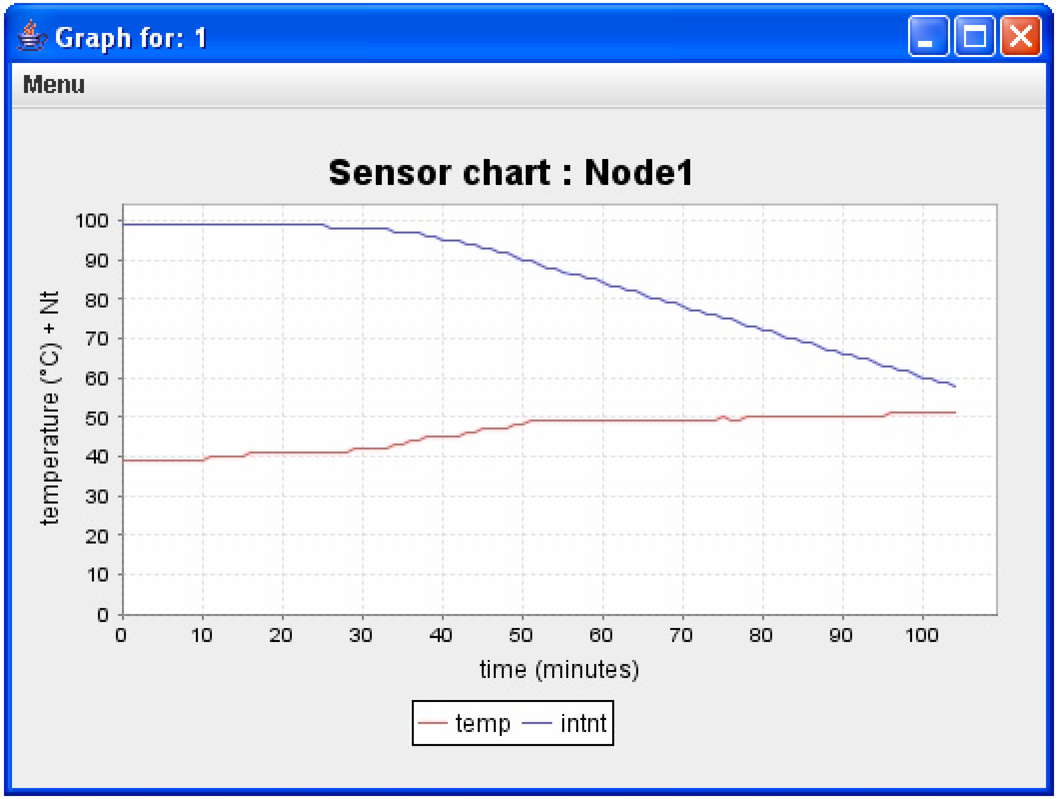
Efficacy Assessment in Real Time during Heat treatment


EARTH
E A R T H
Step 1
Checklist/notes before heat treatment
Step 2
Deploy sensor nodes
Step 3
Checklist/notes during heat treatment
Step 4
Checklist/notes after heat treatment
Step 5
Archive heat treatment data
Print heat treatment data
Step 6
Reset database for next heat treatment

Graph of sensor nodes (tree view)







Heat treatment data

Generated on : 02/25/2008 13:37:27

Company information

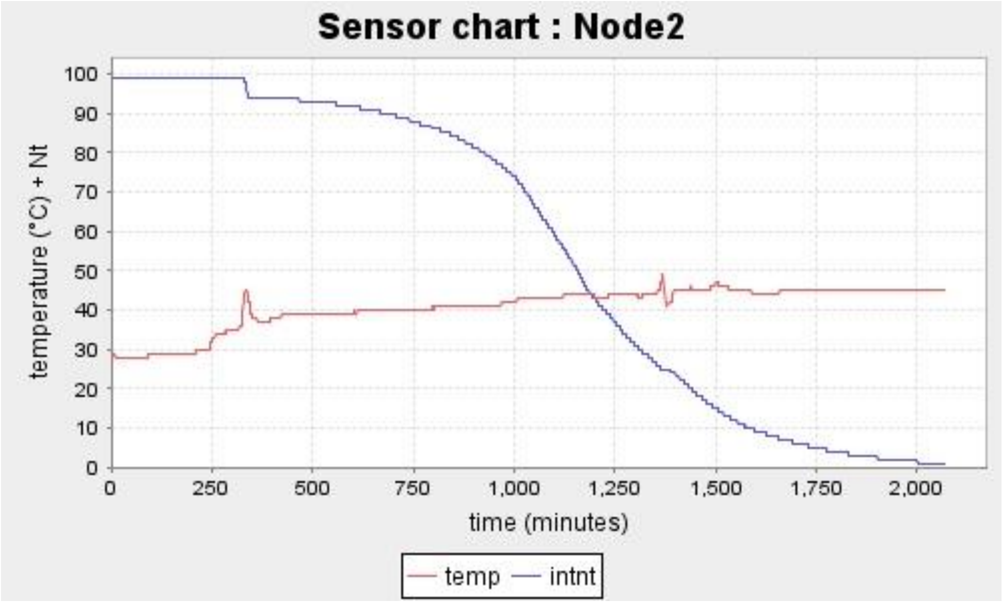
Company name : KSU flour mill
Employee name : Dr. Subramanyam Bhadriraju
Address : Kansas State University, Manhattan, Kansas-66506
Telephone no : 785-532-4092
Fax number : 785-532-4017
Email address : sbhadrir@ksu.edu
Website : http://www.oznet.ksu.edu/grsc_subi

Checklist/notes before heat treatment

Start date : 02/18/2006
Start time : 15/30/00
Time heaters turned on : 15/35/00
No sensors : 1
Species : Red flour beetle (young larvae)
No insects : 100
Target temperature (°C) : 60
Room temperature (°C) : 39
Room humidity (%) : 45
Measured by : Thermometer

Checklist (pre-heat treatment)

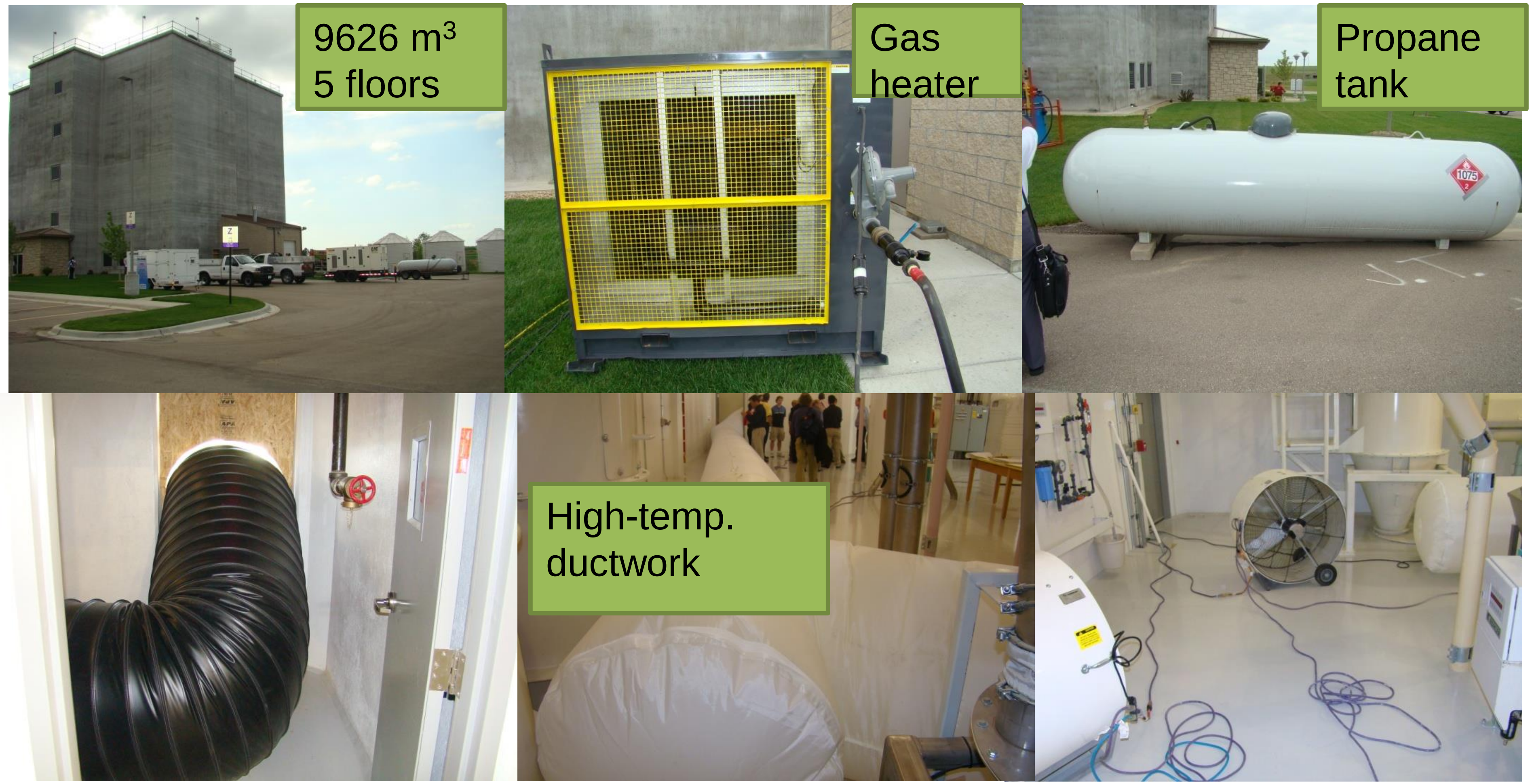
Yes : Appoint site heat-up planning team (including engineer). Elect a team leader to coordinate the effort.
Yes : Identify specific areas to be heated and make site plan. Determine local heat/air sources
Yes : Identify heat sensitive structure and supports, including roofs. If protection or engineering assurances can not be



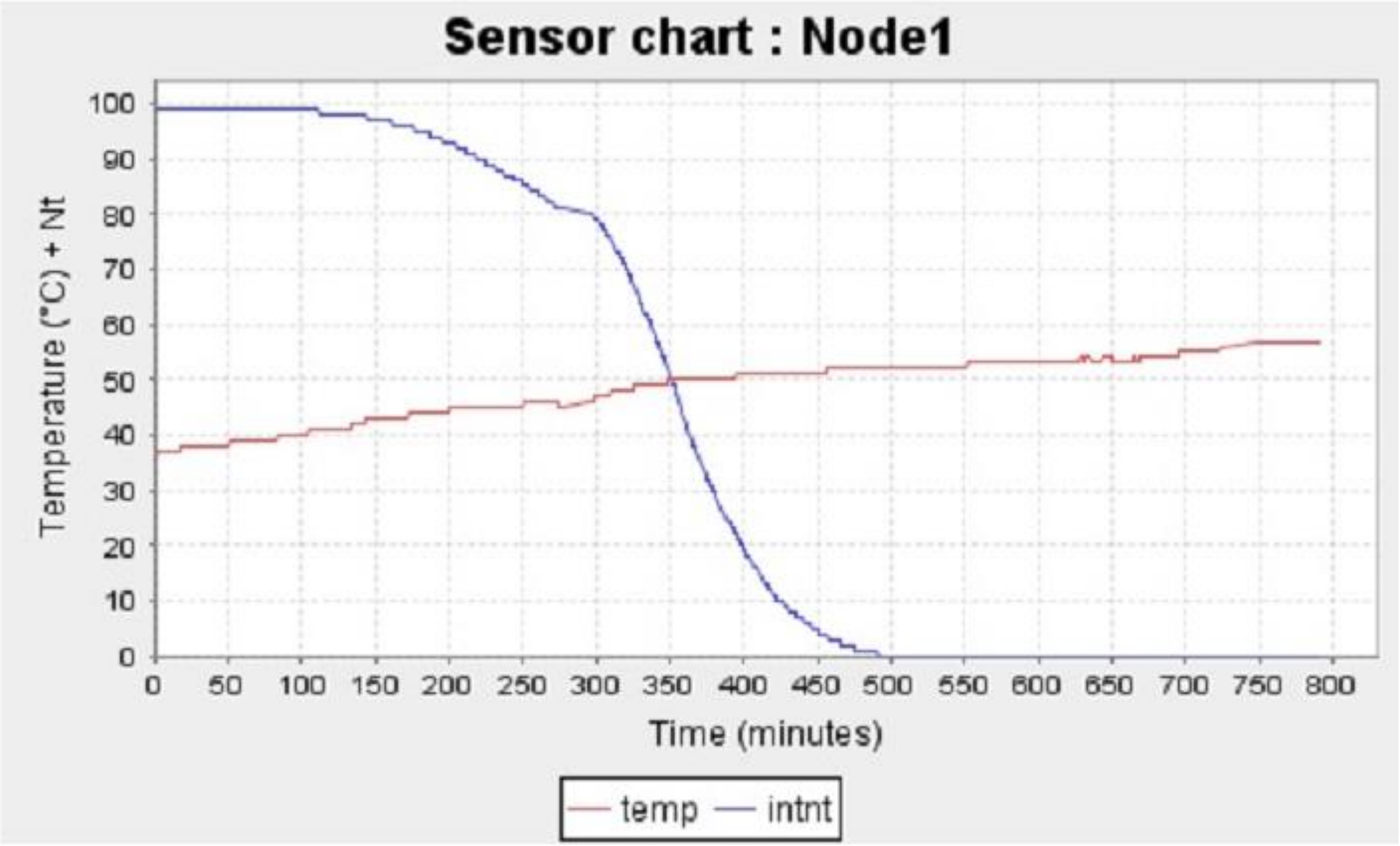
Location: Milling facility, Dept. of Grain Science and Industry
Date: 05/12/2008
Total time: 35 hours
Heat rate: 0.54℃ /hour
Species: Red flour beetle young larvae

E.A.R.T.H. validation

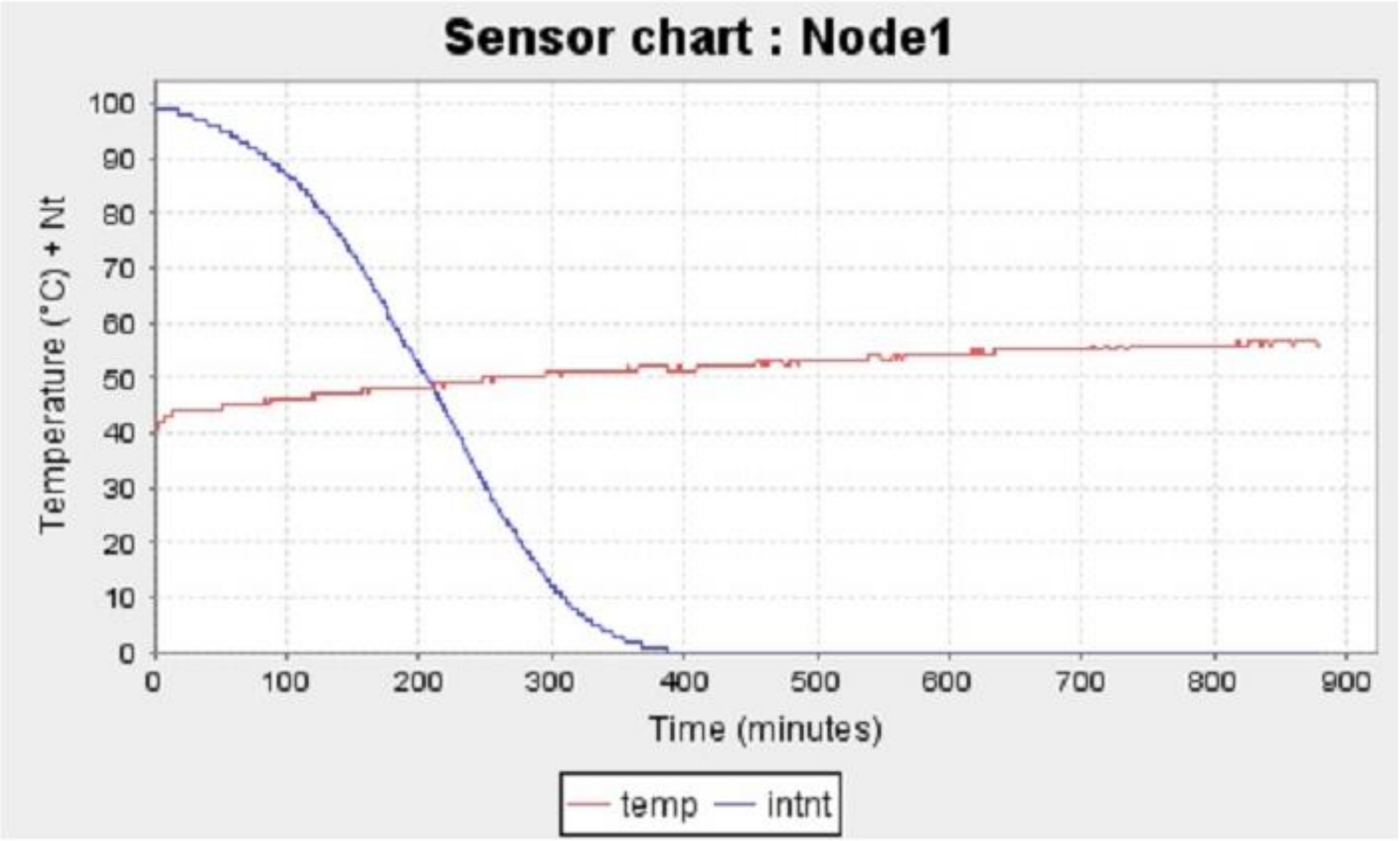
KSU Hal Ross flour mill



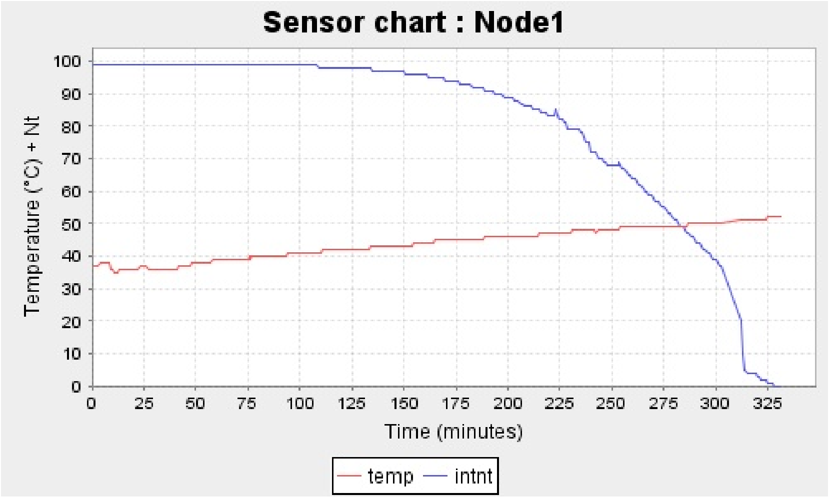
Hal Ross Mill, KSU
Heat Treatment
May 14, 2009

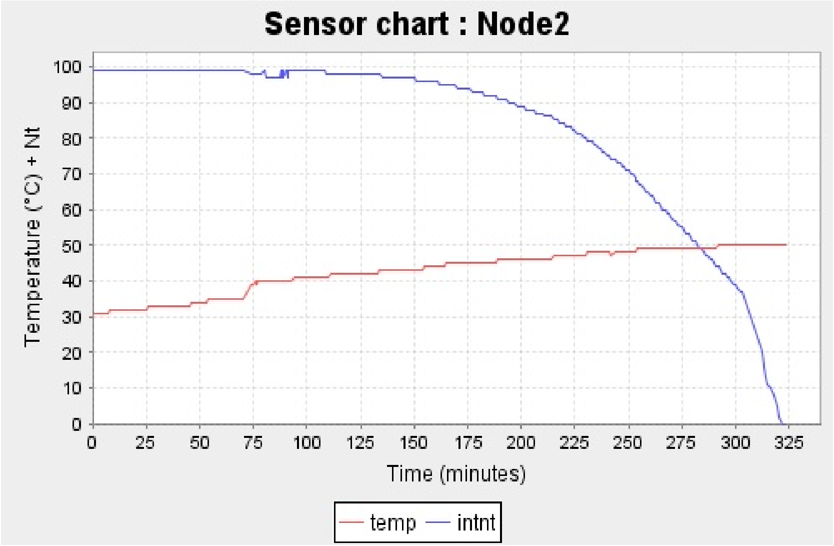


Hal Ross Mill, KSU
Heat Treatment
August 26, 2009

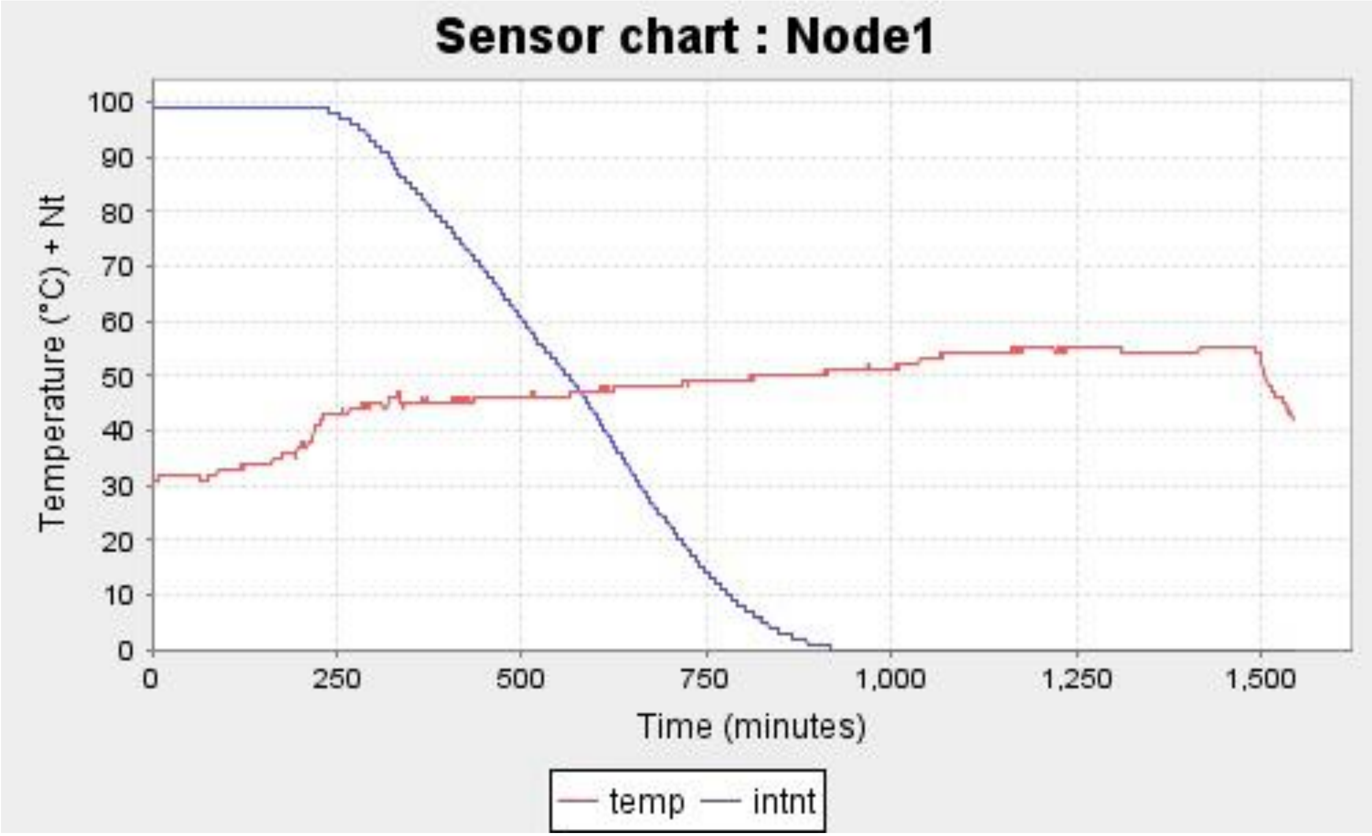


ConAgra Foods, Saint Louis, MO
Heat Treatment
September 25-26, 2009





LifeLine Foods Sensor: 1
April 20-21, 2010



Commercial facilities

- New World Pasta, VA
- Quaker Oats (PepsiCo-Oats & Corn Milling), IA
- Grain Processing Corporation, IA
- Hills Pet Foods, IN
- ConAgra (David Sunflower Seeds), MO
- Gerber Foods, MI
- Anheuser Busch, AR
- Quaker Oats (PepsiCo-Rice Cakes Facility), MO
- PepsiCo (Rice-O-Roni facility), IL
- Loulis Flour Mill, Volos, Greece

Optimizing heat treatments

- Using the right amount of heat energy (0.1 kW/h/m^3)
- Eliminate cool spots (Temp. <50^oC)-fans/heaters
- Determining when to stop a heat treatment
  - Achieving 100% kill of insects without adverse effects on structure or equipment
- Making it cost-competitive with other responsive tactics
- Delaying population rebounds
- Use K-State software programs☺

Heat treatment workshops

Workshops and presentations

- Conducted 6 heat treatment workshops since 1999, 2001, 2002, 2003, 2004, & 2009
  - Lectures and heat treatment demonstrations
  - http://www.ksre.ksu.edu/grsc_subi under the "Workshop/Conferences" link
  - Presentations and pictures
- Recent workshop: May 13-15, 2009

TEMPAIR®

Thermal Remediation™

MHT-1500 at Purdue University

collaborated with Purdue University on demonstrating the efficacy of heat to control stored product pests in bins and silos (2007-09) and with the University of Minnesota (2008-09) on the effect of high temperatures on bed bugs. As part of the MBT (methyl bromide transition) grant, TEMP-AIR, with support from PERC, sponsored the 6th Heat Treatment Workshop organized by Dr. Subi, Department of Grain Science & Industry, KSU, Manhattan, KS, where TEMP-AIR heat-treated the state-of-the-art Hal Ross Flour Mill.

Recently (2010-2011), TEMP-AIR again collaborated with the Propane Education and Research Council (PERC) and Kansas State University on a project entitled "Demonstration of Heat Treatment as a Viable Methyl Bromide Alternative for Disinfesting Grain-processing Facilities" under a grant from the Environmental Protection Agency (EPA).

Research Partners:

Propane Education and Research Council
Gas Technology Institute
University of Minnesota

Researchers

Collaborators

- Paul Fields-Agri-Food Canada
- Fuji Jian –
- University of Manitoba
- Paul Flinn-USDA-CGAHR
- Sajid Alavi-K-State
- Gurdip Singh-K-State

- **Postdocs**
- Rennei Roesli
- Anil Menon

Graduate students/research assts.

- Rizana Mahroof
- Monika Brijwani
- Boina Dhana Raj
- Sham Kashyap
- Habel Kurian
- Roshan Chetry
- Chun Yu
- Chelle Hartzer
- Blossom Sehgal
- Jennifer Frederick

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- Armstrong-Hunt International
- Aggreko
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- Temp-Air, Burnsville, MN
- Propane Educational and Research Council, Washington, D.C.


Thank You