2008 USDA/CSREES Methyl Bromide Transitions Program Proposal

Critical Evaluation of Methyl Bromide, Sulfuryl Fluoride, and Heat Treatment for Disinfesting Food-Processing Facilities

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Summary

The fumigant sulfuryl fluoride (SF) and heat treatment have been identified as potential alternatives to methyl bromide (MB) for disinfesting food-processing facilities. However, the food-processing industry and National Pest Management Association (NPMA) stakeholders applying for critical use nominations since the 2005 phase out of methyl bromide (MB) in the US have cited several limitations for not fully utilizing these MB alternatives. They include questionable efficacy of SF and heat when compared with MB based on current data, lack of solid economic assessment to make alternatives viable, geographic location (related to temperature) effects that make use of SF or heat unsuitable, lack of effectiveness against certain life stages of pests (SF and eggs), increased knowledge and skill required to use Fumiguide (SF), issues related to gas-tightness of facilities (emissions and buffer zones), extended treatment times with heat (>24 h), and possible adverse effects of heat on structural components of facilities.
The proposed multi-institution and multi-year project therefore addresses two of the 15 critical use nominations (5 and 11) for 2009 and beyond, and addresses the concerns raised by the food industry and NPMA. The overall goal of this project, performed in pilot and commercial facilities, is to reduce the use of MB as a structural treatment for food-processing facilities by optimizing the efficacy of MB or SF fumigation through precision fumigant delivery and monitoring, illustrating the efficacy and cost-effectiveness of SF, heat treatment, and other IPM approaches as compared to MB, and determining the effects of structure air-tightness and weather conditions on fumigant emission from and dispersion around fumigated facilities. Successful completion of this project will lead to continuing reduction, and may eventually eliminate, the need for MB use in food-processing facilities. This integrated project supports discovery and implementation of practical pest management alternatives to MB through research in pilot scale and commercial facilities, and involves detailed extension and educational activities that promote adoption of MB alternatives by representatives of the food industry and NPMA.

Project Narrative

(1) Introduction

***(a) Goals of the proposed project*:** The proposed comprehensive multi-institutional research project aims at (1) reducing the use of methyl bromide (MB) as a structural treatment for food- and feed-processing facilities and their associated warehouses, (2) facilitating the adoption of potential MB alternatives such as sulfuryl fluoride (SF), heat treatment and integrated pest management (IPM) approaches, (3) illustrating the efficacy and cost-effectiveness of alternatives as compared to MB, and (4) determining the effects of structure air-tightness and weather conditions on fumigant emissions from and dispersion around fumigated structures. The proposed project is applicable to two of the 15 Critical Use Nominations [CUN]—5 and 11—for 2009. Specifically, outcomes of this project will reduce MB emissions from post-harvest use in food-processing facilities, which include rice, wheat and corn mills, pet food manufacturing facilities, and bakeries, supported under nominations requested by the Rice Miller's Association, Bakeries, Pet Food Institute, North American Millers' Association (NAMA), and from post-harvest uses requested by members of the National Pest Management Association (NPMA) for facilities that manufacture or process chips, crackers, cookies, pasta, spices, herbs, cocoa, and cheese. This integrated project supports discovery and implementation of practical stored-product insect pest management alternatives to MB through research in Kansas State University pilot mill and commercial facilities, and involves detailed extension and educational activities that promote adoption of MB alternatives by the food industry and NPMA stakeholders.

***(b) Need for the proposed project*:** The United States (US) is one of the signatories to the 1987 Montreal Protocol to phase out production and use of ozone-depleting substances to protect stratospheric ozone. Protecting stratospheric ozone is important for reducing the amount of UV-B radiation reaching the earth and for reducing incidence of human skin cancers and cataracts (Makhijani and Gurney 1995). According to the Clean Air Act Amendments of 1990, the US should satisfy its obligations under the Montreal Protocol. MB is classified under the Clean Air Act as a Class I ozone-depleting substance and was intended for phase out by 2005 (40 CFR Part 82, Federal register Vol. 69, No. 246). The schedule for phase out was as follows: 1993-98, freeze production and net imports at 1991 base levels (25,500 metric tons); 1999-2000, 25% reduction from baseline levels; 2001 and 2002, 50% reduction from baseline levels; 2003 and 2004, 70% reduction from baseline levels; and 2005, 100% phase out, except for allowances under the critical use exemptions (CUE) agreed to by the Montreal Protocol Parties. The CUE process provides adequate time for users to transition from relying on MB to technically and economically viable alternatives. CUE for the post-harvest sector in the US are granted for members of the US Rice Millers Association, the Pet Food Institute, bakeries, and the North American Millers' Association. The rice millers and North American millers are major users of MB and use approximately 16 and 68% annually, respectively, of the nominated amount for stored-product pest management. The amount of MB nominated and approved by the Montreal Protocol Parties (United Nationals Environmental Programme Methyl Bromide Transitions Options Committee, UNEP MBTOC) since MB phase out has been steadily declining over time. For example, in 2006, 2007, 2008, and 2009, the CUN for MB granted were 32.03, 26.61, 21.0, and 19.5% of 1991 baseline levels, respectively. The CUN allowed in 2009 for use in the food-processing facilities is 291.4 metric tons and by pest management professionals (NPMA) is 118.7 metric tons. Potential MB alternatives in food-processing facilities for the management of stored-product insect pests, primarily the red flour beetle, *Tribolium castaneum* (Herbst), include SF and heat treatment. These alternatives are promising but they have not been widely adopted by the industry, and therefore, MB continues to be supported through the CUN process. The food industry has raised questions concerning the efficacy of MB alternatives on various life stages of insects (Muhareb et al. 2004), consistent performance under a range of environmental conditions, and cost.

The success of a commercial fumigation depends largely on the knowledge and experience of the applicator, and therefore it has become more of an art than science. Planning and gas monitoring, inside and outside fumigated facilities, has been largely overlooked. Regardless of the type of fumigant used, the leakage of fumigant from the treated structure is a function of fumigant concentration, air-tightness of the structure, and weather conditions (Chayaprasert et al. 2006, 2007a). Predictions of the emission rate would allow for proper planning to achieve the required target dosage with minimal fumigant loss and aeration time. Fumigant dispersion from fumigated structures during both treatment and aeration periods, if not properly monitored and controlled, can affect the safety of fumigation personnel, staff of the fumigated facility, and bystanders. One possible mitigation measure is the utilization of buffer zones in which only the fumigation personnel are permitted. At the present time MB is undergoing its re-registration process and the US-EPA is requesting that implementation of buffer zones be part of the MB label (US-EPA 2006). The knowledge of fumigant dispersion dynamics may provide data for establishing practical buffer zones.

The use of elevated temperatures or heat treatment (50 – 60 °C for 24 – 36 h) in food-processing facilities is another MB alternative (Dosland et al. 2006, Beckett et al. 2007). However, estimating the right amount of heat energy required and stratification of temperatures within a facility resulting in cool spots (locations with $<50^{o}$C), make it difficult to maintain temperatures lethal for insects. The effects of SF and heat on stored-product insect population rebounds also are unknown (Roesli et al. 2003, Campbell and Arbogast 2004, Toews et al. 2006). It is generally believed that the cost of SF fumigation and heat treatment to be 1.3 and 1.5 times that of MB fumigation (Anonymous 2005). No scientific studies were conducted by a neutral, third party that quantitatively and conclusively compares cost effectiveness of MB with SF or heat. Additionally, there are no data showing survival of life stages of stored-product insects, primarily of flour beetles, exposed to MB, SF and heat, in the same commercial facility under similar environmental conditions. Thus, there is an urgent need for a comprehensive economic analysis in which the cost and efficacy of MB, SF and heat, are quantitatively compared and verified under commercial field conditions. Cryer (2008) emphasized that the decision for choosing either MB or SF should be based on efficacy, cost, and environmental impact, because he found both MB and SF to have similar leakage rates from facilities.

(c) Completed and ongoing significant activities—Importance of stored-product insects: Stored-product insects present a constant threat to raw and processed cereal commodities worldwide (Sinha and Watters 1985). These pests cause significant quantitative and qualitative losses to the multi-billion dollar grain, food, and retail industries each year through their feeding, product adulteration, customer complaints, and product rejection at the time of sale. Food-processing facilities, especially flour mills, are ideal habitats for stored-product insect pests, because of year-round warm temperatures and constant availability of food resources (Wagner and Cotton 1935, Smallman and Loschiavo 1952). Stored-product insect species have been reported from moving mill stock (Wagner and Cotton 1935, Good 1937), static mill stock, and within and around milling equipment (Dyte 1965, 1966; Rilett and Weigel 1956). In the US, Good (1937) surveyed 19 flour mills in Kansas, Missouri, and Oklahoma during 1934 to 1935. He reported 30 different species from 17 of the 19 mills, representing 15 families in five orders. Four of the eight most abundant stored product insect species made up nearly 96% of the 73,175 insects found in the samples, and the flour beetles, *Tribolium* spp., made up 85% of the total insects. Adults and larvae of flour beetles were present throughout the milling system, and therefore, management of such widespread infestation requires whole facility treatments with fumigants or heat. A majority of IPM interventions in food-processing facilities that process cereal grains are used to manage flour beetles, primarily the red flour beetle, *Tribolium castaneum* (Herbst).

MB alternative—Sulfuryl fluoride (SF): Several studies, and results from more than 400 commercial fumigations, have documented effectiveness of SF against stored-product insect pests (Bell and Savvidou 1998, Bell et al. 1999, 2003, 2004; Reichmuth et al. 1999, Schneider and Hartsell 1999, Wontner-Smith 2005, Small 2007). Both SF and MB are approximately three and a half times heavier than air, while the heat capacity and thermal conductivity of SF are approximately 35% higher than those of MB (Yaws 2001). The fluid viscosities and mass diffusivities of the two gases are almost identical (Cryer 2008). Despite similarities in the physical properties, SF is different from MB in several aspects. SF is more effective at reaching insects that reside deep in cracks and crevices, treated commodities, or residual flour than MB. Bell (2006) reported that MB sorption on flour was 750 mg/kg while SF sorption was less than 75 mg/kg. Low sorption of SF implies that it leaves little or no residues on treated commodities when compared with MB. However, SF penetrates through nylon and polyethylene sheeting more slowly than does MB, which makes it is easier to confine SF with plastic tarps commonly used in structural fumigation (US-EPA 2006). The registrant of SF introduced the precision fumigation concept, designed to optimize fumigant use, maximize efficacy against insects, and minimize risk to humans and the environment. This is done by considering the effects of temperature, insect stage, and gas loss from enclosures on fumigation efficacy. The precision fumigation concepts can also be applied to MB fumigation, especially in light of the continued use of MB under the CUE category.

MB alternative—Heat treatment: The use of heat treatments in the food-processing facilities is not a new concept (Dean 1911, 1913). Many food- and feed-processing companies such as General Mills, ConAgra, Cargill Inc., Kraft Foods, Quaker Oats (PepsiCo), and Nestle Purina, among others, have been using heat treatment as an alternative to MB. Heat treatment involves raising the ambient temperature of the whole or a portion of the facility to 50 to 60°C using gas, electric, or steam heaters and maintaining these elevated temperatures for 24-36 h (Imholte and Imholte-Tauscher 1999, Dowdy and Fields 2002, Wright et al. 2002). The 24-36 h is necessary for the heat to penetrate wall voids and equipment to kill insects harboring in them. Facility heat treatments are labor-intensive, because grain and grain products, including those susceptible to high temperatures, within the facility should be thoroughly cleaned and/or removed. Insects may hide in these materials and escape the heat treatment. In the last few years there has been an abundance of new research demonstrating the effectiveness of heat treatments for the milling industry (Boina and Subramanyam 2004, Mahroof et al. 2003, Roesli et al. 2003, Dosland et al. 2006, Beckett et al. 2007). However, with heat there is potential risk of damage to structures and finished and packaged food products if not performed properly. There are no published reports comparing the cost-effectiveness of heat treatments with that of MB or SF in the same commercial facility.

MB alternative—Miscellaneous techniques: Modified atmospheres have been used with some success to control insects in bulk grains (Adler et al. 2000) and high-value packaged products, but are not generally used by the milling and processing industry as whole plant treatments because of the cost (White and Leesch 1995). A cylinderized formulation of phosphine (ECO_2FUME^{TM}) is approved for use in food-processing facilities, but it is not used because of its corrosive effects on copper (electrical wiring and systems). Other IPM practices used in the food industry include sanitation, exclusion, crack/crevice treatment with residuals, and fogging with aerosols (Subramanyam et al. 2005). Exclusion practices are important because recent studies have shown evidence of resident insect populations in both the interior and exterior environment of mills, processing plants, and areas where packaged food is stored (Doud and Phillips 2000, Campbell and Mullen 2004, Campbell and Arbogast 2004). Surface and spot applications are effective treatments in specific locations within mills and storage facilities, but they may be too limiting for large-scale use. Fogging may be a viable alternative to MB; however, recent research has shown that these treatments fail to manage resident insect populations (Arthur and Campbell 2008). Therefore, whole-structure treatments with fumigants and heat will likely continue to be needed even with the adoption of more intensive IPM programs.

***(d) Issues in adopting MB alternatives—Effectiveness of alternatives*:** Whole facility treatments with MB, SF or heat treatment often fail to provide effective insect management because of inadequate inspection of inbound materials, and poor sanitation and exclusion practices (Heaps 2006, Subramanyam et al. 2005), and improper timing of pest management interventions (Roesli et al. 2003, Toews et al. 2006). The timing of IPM intervention in commercial facilities is done when the facility is shut down on major US holidays, and in many cases is asynchronous with pest population dynamics. Consequently, the cost-effectiveness of MB, SF, and heat treatments cannot be accurately evaluated.

Previous comparisons of effectiveness of MB, SF, and heat in managing stored-product insects were based on data collected from different facilities receiving these treatments at different times of the year. It is invalid to compare the effectiveness of MB and MB alternatives even in the same commercial facility treated at different conditions, because only one of the treatments can be applied during major holidays, and the degree and duration of insect suppression obtained is affected by resident population densities and prevailing environmental conditions.

Furthermore, treatment effectiveness is generally gauged by comparing captures of adult insects in traps before and after an intervention (Campbell and Arbogast 2004, Toews et al. 2006, Subramanyam 2006, Small 2007), making it difficult to accurately and directly sample the true insect populations in a facility. The use of traps provides some measure of treatment effectiveness, but basing treatment effectiveness exclusively on adult captures is not valid because it is possible for traps to capture adults immigrating into a facility after a treatment (Figs. 1 and 2). Data from Campbell and Arbogast (2004) and Toews et al. (2006) illustrates some of the difficulties in evaluating effectiveness of heat treatments or fumigation solely based on trap captures of adults. A better approach would be to compare MB, SF, and heat treatment effectiveness in the same facility under similar environmental conditions with direct assessment of mortality of all life stages of a pest species. There is practically no data that shows the survival of life stages of stored-product insects, primarily of flour beetles, exposed to MB, SF, and heat in the same pilot-scale or commercial facility under similar environmental conditions. Therefore, in this proposal we intend to perform these tests in the Kansas State University Hal Ross flour mill. These data, along with economic analysis proposed here and additional monitoring in commercial facilities, will provide the first accurate side-by-side evaluation of cost-effectiveness of MB, SF, and heat.

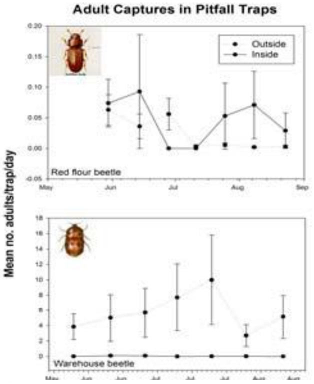

Fig. 1. Trap captures of red flour beetles and warehouse beetles inside and outside a 47,261 m^3 pasta plant subjected to heat treatment during July 1-2, 2006. There were 45 traps inside and 5 outside and trap captures were measured every 8-14 days. Very few warehouse beetles were found inside the facility, but the impact of heat treatment lasted only one to two weeks inside the facility (Subramanyam unpublished data).

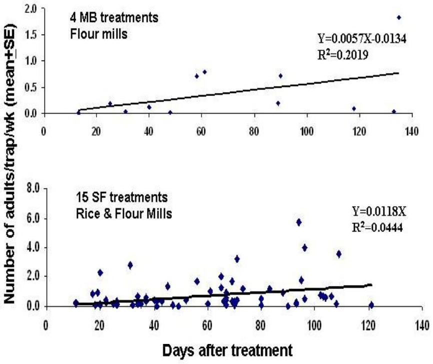

Fig. 2. Trap captures of red flour beetles from 6 rice and 3 flour mills during 2005-2007 receiving 15 SF treatments and 4 MB treatments. These data show number of beetles captured soon after intervention in mills receiving MB or SF treatment. How quickly insects are captured in traps may be related to environmental conditions, differences among facilities, and level of sanitation practices followed (Subramanyam, unpublished data).

Estimating gas loss from structures: The ability of a fumigant to kill insects within a facility is based on all stages of insects being exposed to lethal gas concentrations. The ability to maintain lethal concentration is related to fumigant decay due to the transfer between the fresh air outside and the fumigant-air mixture in the fumigated space. These movements are created by pressure differences across the building envelope. Two main forces that create pressure differences across the building envelope driving natural ventilation and infiltration are the wind and stack effects (ASHRAE 2001). The computational fluid dynamics (CFD) model developed from a previous MBT grant consists of the external and internal flow models. The external flow model predicts stagnation pressures on the mill's walls as a function of the wind speed and direction data (Fig. 3a). The pressure differences due to density differences between the gas inside and the air outside of the mill (stack effect) are calculated using the estimation equation suggested by ASHRAE (2001). The combined effect of the stagnation pressure and stack effect is used as boundary conditions of the internal flow model in which the actual fumigation process was simulated. The internal flow model (Fig. 3b) incorporated interior details of the mill such as building plans, locations of major equipment, partitions and ducting. The CFD model was able to predict a half-loss time (HLT) value identical to the experimental HLT (17 h) and minimized the prediction of the concentration x time (Ct) value to within 10.5% of the observed value. Detailed explanations of the model's mechanics can be found in a recent paper by Chayaprasert et al. (2008). This model allows for evaluations of various "what if" fumigation scenarios without the high cost of conducting full-scale fumigation experiments. It has been successfully used to evaluate the effect of environmental (wind speed and direction, as well as ambient and internal air temperature) and fumigation process (sealing quality, number and placement of gas release lines, as well as number, capacity and placement of circulation fans) variables on fumigation performance (Chayaprasert et al. 2007a,b). The model also can be used to predict fumigant leakage rates under any environmental condition. Additionally, it can be used to design different fumigation strategies that minimize fumigant emission. The dispersion characteristics of fumigant emitted from fumigated structures and the dynamics of the heat treatment process can be computationally studied with slight modification of the model, and we plan to undertake this aspect as part of this project.

Automatic fumigation monitoring and decision support system: As part of our previous MBT program project, we developed an automatic fumigation monitoring and decision support system that is able to (1) continuously monitor gas concentration in the fumigated space, (2) detect a concentration deficit as soon as it occurs, and (3) provide a recommendation to the fumigator as to when and how much fumigant dosing and/or re-dosing is needed. Fig. 4 shows the hardware schematic of the automatic model fumigation monitoring system. The purge pump draws a sample of gas through nylon tubing from the fumigated structure. The custom-made port selection panel consists of one three-way and 14 two-way DC solenoid valves. The inlet of each valve is connected to a monitoring line and the outlet is attached to a manifold with its outlet connected to the gas concentration sensor. The gas concentration sensor compatible with the system is either the SF Single Zone (SFSZ) Monitor (Spectros Instruments Inc., Hopedale, MA) for SF or the RDA Fumiscope (Key Chemical and Equipment Co., Clearwater, FL) for MB. The opening and closing sequence of the valves and the gas concentration acquisition are controlled by the modular distributed I/O system called FieldPoint (National Instruments Corp., Austin, TX). The FieldPoint system actuates the solenoid valves and acquires concentration readings from the gas sensor according to a control program written in LabVIEW (National Instruments Corp., Austin, TX), which is part

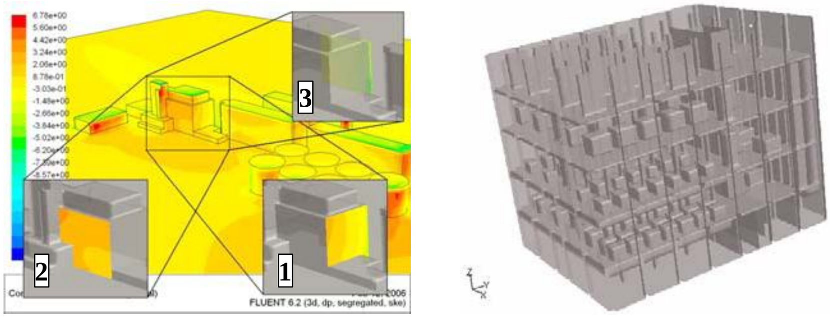

Fig. 3. (a, left) Example of a stagnation pressure contour on the building's surfaces generated by a 4 m/s wind traveling from the north-east direction. (b, right) Domain of the internal flow (D. Maier, unpublished).

of the fumigation decision support (FDS) program. The FDS program can be modified and customized to support MB and SF fumigants and/or insect species/life-stages, if the required dosage rate information for those particular fumigants and insect species/life-stages is available. The FDS program determines the expected initial concentration, target Ct value, and required amount of SF based on four input parameters (i.e., temperature, HLT, exposure time, and size) estimated for the fumigated volume. Based on the measured concentrations, the FDS program predicts the Ct value that would be achieved at the end of the exposure time. If the predicted value is less than the target value, it displays an alarm message and provides a recommendation as to how much additional SF is needed and/or how long the exposure time needs to be extended in order to attain the target Ct value by the end of the fumigation.

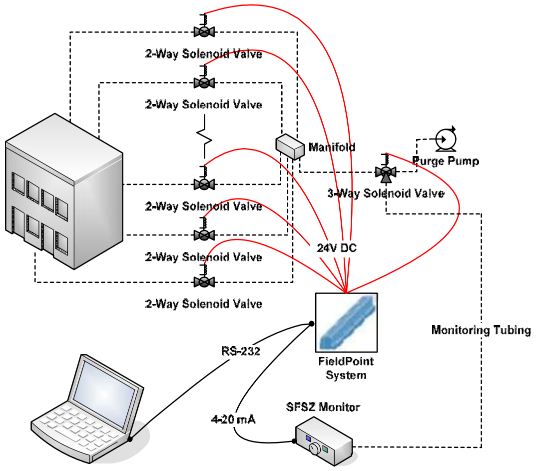

Fig. 4. Hardware diagram of the fumigation monitoring system (Dirk Maier, unpublished).

Estimating heat energy requirements: The Heat Treatment Calculator (HTC) is a software program developed using Microsoft Visual Basic .NET (Subramanyam 2003) for calculating heat energy needed to heat a facility to the required (threshold) temperature. The HTC also calculates the amount of fuel and associated costs for a particular heat treatment. To calculate the energy requirements, HTC uses the U values for the building materials, the target temperature specified, and building parameters (e.g., walls and window dimensions, length and width of floors and roofs, etc.). Using these specifications, the HTC calculates the amount of heat dissipated through conduction, convection, radiation, and estimates heat loss from different rooms of a facility. All data entered into the HTC are stored in a database, and can be updated at any time. The user can modify the temperature data and see how a change in temperature can affect the cost of the heat treatment. Similarly, the user can also change the way a particular room is heated in the facility specifications and see corresponding changes in energy and fuel requirements. The HTC can also generate energy requirement data when a single variable is varied (e.g., starting ambient temperature or desired target temperature). The HTC was evaluated in 2006 in a pasta facility subjected to gas heat treatment. The heat energy used and the gas utilization costs reported by the facility were comparable to the HTC predictions (Table 1), which suggested that this program is a powerful tool to optimize heat treatments by providing information on the amount of heat energy needed for a given site and prevailing environmental conditions.

A 2005 MBT grant helped us develop a novel thermal death kinetic model (described in detail by Boina et al. (2008)) for predicting survival of insects during heat treatments. This model was also validated (see Fig. 5). The same model was also useful in describing survival of first instars, the most heat-tolerant stage of the red flour beetle (Mahroof et al. 2003). Heat-tolerant stages were used for model development and validation, because temperature-time combinations that control heat-tolerant stages should control all other stages.

Table 1. Comparison of estimated heat energy and costs of heat treatment of a pasta facility based on observed average temperature profile (Subramanyam, unpublished data).

Area	Heat requirements (in million BTU)			BTU/cubic foot/hour			Natural gas usage (in Therms)		
	Hourly Rise	Hold	Total	Rise	Hold	Total	Hourly Rise	Hold	Total
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 based on temperatures measured, 160.8 million BTU; estimated fuel cost: $ 2498. Natural gas used by facility during heat treatment: 2212 Therms. Cost of fuel used during heat treatment, $ 2411.Heat generated at 70% efficiency, 155 million BTU.

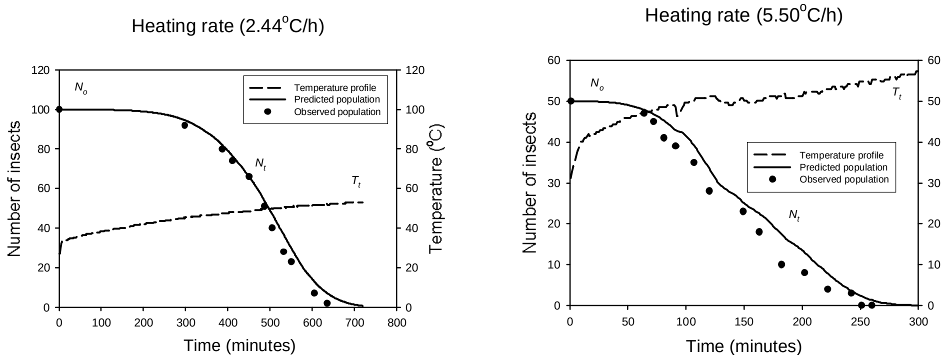

Fig. 5. Observed and predicted survival of mature larvae of confused flour beetles during heat treatment of Kansas State University feed mill (Boina et al. 2008).

Wireless sensor networks provide a powerful environment to transmit data from remote sites to a central base station. The MICA2 /MIB/MTS technology from Crossbow Technology, Inc. (San Jose, CA) can be used to acquire data (temperature/humidity) remotely from different locations on a real-time basis. The MICA2 mote is a radio board for enabling low power wireless sensor networks. The MIB510 serial interface and programming board allows the aggregation of sensor network data onto a PC. MTS sensor boards are weather sensor boards that offer five basic environmental sensing parameters. For instance, to get temperature readings during heat treatment of a facility, a MICA2 radio board along with a weather sensor board is placed at different locations. The weather sensor board acquires temperature and transmits this data to the base station using the radio board. The range of wireless sensor networks can be increased by placing intermediate radio boards for effective communication with the base station. The data aggregated by the base station can be stored in Postgre SQL server (database). Efficacy Assessment in Real-Time during Heat treatment (EARTH) is a software built using Java technology, providing the user with an interface to input and acquire heat treatment data. The data aggregated by the base station is used by the program to generate insect survival graphs in real time (Fig. 5) as an instantaneous function of time-dependent temperature profile. This information is extremely valuable in understanding which areas are being under-heated and which areas are being over-heated so corrective actions can be taken to improve heat treatment efficiency against insects. Some corrective actions for example may include placing an extra heater or moving a fan to redistribute heat or to eliminate cool spots. The software generates and archives a comprehensive report before, during, and after a heat treatment based on checklists provided in Dosland et al. (2006).

***(e) Role of stakeholders in problem identification and implementation of results*:** The food industry and NPMA stakeholders applying for CUN have cited several limitations for not fully utilizing MB alternatives. These include questionable efficacy of alternatives when compared with MB based on current data, lack of solid economic assessment to make alternatives viable, geographic location (related to temperature) that makes use of SF or heat unsuitable, lack of effectiveness against certain life stages of pests (SF and eggs), increased knowledge and skill required to use Fumiguide (SF), gas tightness of facilities (emissions and buffer zones), commodities stored that make using heat undesirable, extended treatment times (heat), and adverse effects on electronic equipment (phosphine [ECO_2FUME]). Over the last decade, food-processing facilities in the US have tried to reduce the number of MB fumigations by incorporating many of the alternatives identified by MBTOC, and there is now an increased emphasis on sanitation, insect monitoring, crack/crevice treatments with residual products, and fogging. These techniques do not disinfest a facility but are critical in providing site-specific management of pests. The food-processing industry and NAMA stakeholders have partnered with researchers to evaluate potential alternatives to MB. Researchers at Kansas State University, USDA-Grain Marketing and Production Research Center (GMPRC), and Purdue University have been working in partnership with companies such as ADM, Cargill, Con Agra, PepsiCo, New World Pasta, General Mills, pest management professionals, registrants of MB and SF, and heat service providers for generating valuable data on the effectiveness of MB, SF, and heat in commercial facilities. Our ongoing work with MB and MB alternatives and issues pertinent to adoption of MB alternatives were highlighted above. The food industry and NPMA stakeholders have clearly articulated their concerns and continue to be actively involved in seeking practical IPM solutions they can implement in their facilities. Therefore, this proposal addresses many, if not all, of the issues and concerns raised by the food industry and NPMA stakeholders in adopting MB alternatives. Letters of support for this proposal from food industry representatives, pesticide registrants, and fumigation/heat service providers are included in this proposal.

***(f) Stakeholder advisory group*:** As stated in the previous section, prior to development of this project and its objectives, we collaborated with a number of food-processing facility managers who provided valuable insights and feedback into the formulation of their needs and challenges, and confirming our proposed solution. Mr. Jim Bair, Vice President of NAMA has written a letter of support for this project on behalf of the U.S. flour milling industry. If this proposal is successful, we will work with Mr. Bair in forming an advisory group consisting of two university researchers, USDA representatives, two NAMA industry representatives, two FPC-IAOM members, two NPMA members. The advisory group will meet yearly to provide input and review progress of our work. The annual meeting could occur at the Methyl Bromide Alternatives Conference or during one of our planned fumigation/heat treatment training workshops and demonstrations at Kansas State University.

(2) Objectives

The overall goal of this project is to reduce the use of MB as a structural treatment for food- and feed-processing facilities and their associated warehouses by maximizing the efficacy of MB fumigation through precision fumigant delivery and monitoring, illustrating the efficacy and cost-effectiveness of SF, heat treatment, and other IPM approaches as compared to MB, and determining the effects of influencing factors such as structure air-tightness and weather conditions on fumigant emission from and dispersion around fumigated structures. Successful completion of this project will lead to continuing reduction and may eventually eliminate the need for MB use in food-processing facilities for which the US continues to request critical use exemptions for 2009 and beyond. To fulfill our goal, we propose to pursue the following objectives through integrated research, extension, and educational activities:

(1) Use bioassays and models to optimize and evaluate efficacy of MB compared to SF and heat on red flour beetle life stages in the K-State's Hal Ross flour mill.

(2) Verify optimization tactics in commercial food-processing facilities subjected to MB, SF, and heat and other IPM tactics and gauge its impact on red flour beetle populations.

(3) Perform an economic analysis of structural treatments and physical control methods both in the Hal Ross (pilot) mill and commercial facilities.

(4) Disseminate science-based information to stakeholders through demonstration, hands-on training programs, and publications through various formats.

(3) Methods

***Objective 1: Use bioassays and models to optimize and evaluate efficacy of MB compared to SF and heat on red flour beetle life stages in the K-State's Hal Ross flour mill*:** The new Hal Ross flour mill of the Department of Grain Science and Industry, Kansas State University, opened on October 20th, 2006 (see http://www.grains.ksu.edu for pictures). It has five floors and a total volume of 35,136 m^3 (240,800 ft^3). This pilot mill provides a unique platform for performing comparisons of different treatments while critical experimental parameters, for example timing and duration of treatments, can be manipulated, which may be impossible in commercial facilities. Treatments will be performed by pest management professionals contracted to perform heat treatments (Temp-Air®, Burnsville, MN; see letter of support), and the MB and SF fumigations (Presto-X Company, Omaha, NE; see letter of support). Treatments with all three treatments (MB, SF, and heat) will be performed twice during the first year and once during the second year. Each of the three treatments will be performed within a four-week window of time to ensure treatments under similar environmental conditions. We estimate a period of approximately three days for preparation, treatment and breakdown for each treatment and approximately a week between treatments. Actual treatment time with each will be restricted to 24 hours. The order of treatments within each time period will be randomized with replications blocked by time. Environmental conditions within the mill will be monitored using HOBO® data loggers (Onset Computer Corporation, Bourne, MA) and wireless sensors (Crossbow technology, San Jose, CA). During each treatment we will collect information on the labor and time involved in preparation of the mill for treatment (e.g., sealing, sanitation) and getting the mill functional after the treatment (e.g., aeration for both fumigants and heat treatment). During heat treatment with natural gas heaters, temperature sensors (HOBO® data loggers, Onset

Computer Corp., Bourne, MA) that measure temperature and relative humidity will be placed throughout the mill, at least 10 per floor, to evaluate the pattern of heat distribution. During fumigations, environmental conditions will be monitored using data loggers, and fumigant monitoring lines will be placed throughout the mill, with at least one line per floor, to assess the pattern of fumigant distribution. Fumigant levels will be measured approximately hourly throughout the treatment to calculate Ct values to ensure that proper ct products were obtained for commercial insect kill. Pheromone trapping will be conducted daily before and after treatment for about a week; because these treatments are being applied so close together it is not really appropriate to look at population rebound levels directly. However, the capture of insects immediately after fumigation or heat treatment can indicate either a fumigation problem or rapid re-colonization. Ten commercial food-baited traps with red flour beetle/confused flour beetle pheromone (Trece, Adair, OK) will be placed on each floor and checked daily one week before and one week after a treatment. Ten traps will also be placed outside the mill, around the perimeter of the building using the methodology of Campbell and Arbogast (2004), and the traps outdoors will be checked biweekly to monitor insects outdoors from April through October each year.

Evaluation of MB, SF, or heat treatment will be conducted using life stages of red flour beetles placed in test chambers in pre-selected mill locations. Red flour beetles used for these experiments will come from a colony started with individuals obtained within the past year from commercial flour mill locations. Beetles will be reared in flour (5% by weight of brewer’s yeast sieved through a 60 mesh (250 μm sieve)). Different life stages and habitat patch sizes will be used to simulate different levels of sanitation. Ten monitoring locations, with each location containing the complete set of the treatments described in more detail below, will be placed within the mill – at least two per floor. Chambers holding insects will be made from 10.2 cm diameter white PVC pipe cut to 35 cm lengths with end caps attached at both ends. The top end cap will have a 4-cm hole cut through it and a disk of metal screen attached using glue. Tubes will receive flour (5% brewer’s yeast added and sieved through a 60 mesh (250 μm sieve) to a depth of 0 (control), 3, 30 or 300 mm; representing the different patch size/sanitation level conditions. For the direct assessment of mortality, tubes will be set up with 100 eggs, small larvae (first instars), large larvae (22-d-old), pupae (mixed sexes) and adults (2-wk-old, mixed sexes), respectively. Extraction of each of the life stages in large numbers has been previously reported by our group (Mahroof et al. 2003). At each of the 10 locations in the mill, all combinations of life stages and flour depth will be setup in separate tubes. A total of 1,000 individuals of each stage will be exposed for each mill treatment; this should enable us to detect even low survival rates. An additional three chambers, with similar infestation levels, will be placed in the control location and not exposed to the treatments. After each treatment, tubes will be brought to the laboratory and placed in growth chambers at 28°C and 65% RH. Mortality of adults in the tubes will be assessed after 24 hours of recovery in the growth chamber. Mortality of eggs will be assessed after passing the flour through a 60 and 80 μm mesh size sieves to separate live larvae from the flour. Young and old larval mortality will be determined by counting live larvae after one week in the growth chamber. Pupal mortality will be based on number of adults that failed to emerge from pupae. For analysis, we will compare the percent survival of the different life stages among the different treatments using ANOVA, by combining data from all the chamber locations within either the mill or the control location. Variation in level of mortality within the mill during a treatment will be assessed by plotting the percent mortality as a function of location, and when appropriate, examining for correlations between mortality and flour depth, environmental conditions and fumigant concentration or temperature measured (for heat treatment) in the vicinity of the location. Survival of insects subjected to various treatments will be incorporated into a population model being developed by one of the proposal co-investigator, Dr Paul Flinn (see below) to simulate how infestation level, sanitation and rates of immigration would impact rebound rate after treatment. Information on the treatment costs and efficacy will be included in the economic analysis described in Objective 3.

The 3D computational fluid dynamics (CFD) model, that was developed and validated in commercial facilities (Chayaprasert et al. 2008), described in detail above, will be used to determine the performance of MB and SF fumigation. This will also allow the fumigator to better understand influences of environmental conditions on fumigant behavior in different types of food-processing facilities.

The building parameters will be entered into the HTC to estimate heat energy requirements and costs associated with the gas heat treatment. The HTC predictions will be refined after the heat treatment from temperature profile data obtained from 10 HOBO® data-loggers placed on each of the pilot mill floors (see Table 1) and later compared with observed heat energy determined from the amount of fuel (natural gas in Therms) consumed and the output and efficiency of the gas heaters used by Temp-Air (Burnsville, MN). The EARTH software will be tested extensively in the pilot mill to predict survival of first instars of the red flour beetle (the most heat tolerant of all stages and species of insects evaluated so far) in real time as a function of time-dependent temperature profile prior to practical use and additional verification in commercial facilities. We plan to use five wireless sensors on each of the five pilot mill floors for evaluating and refining the EARTH software predictions. First instars of red flour beetles, placed in test cages will be exposed throughout the heat treatment and sampled at specific time intervals so that the model predictions can be compared with observed insect survival in cages. The methods used for validating model predictions will be similar to those described in our previous papers (Mahroof et al. 2003, Boina et al. 2008).

An existing model which is being developed for the red flour beetle in flour mills in another project will be used to predict the effects of MB, SF, and heat on population dynamics. The model uses a distributed delay to simulate variation in developmental time, manage survivorship, and move insects through stages (Manetsch 1976), and has been used previously to predict insect population dynamics in farm bins and in commercial grain elevators (Flinn et al. 1997, 2004). We will add compartments for different floors of the flour mill. This will increase accuracy because heat treatment temperatures are often much lower in the basement compared to other floors, or fumigation concentration may vary by floor. Several studies have investigated factors affecting red flour beetle dispersal (Ogden 1970, Naylor 1961, Campbell and Hagstrum 2002, Campbell and Runnion 2003). The model will include mortality factors for fumigation, heat treatment, residual insecticides, and sanitation. Based on studies by Mahroof et al. (2005), the effects of sub-lethal heat treatment on fecundity will be added to the model. We will validate the model based on data collected from intensive monitoring of insect populations in commercial food-processing facilities. Following model validation, we will conduct simulation studies with the model. These studies will allow us to develop optimal IPM strategies for managing red flour beetles in food-processing facilities. The model can be used to evaluate the economics of various IPM strategies as well.

Expected outcomes and deliverables for Objective 1: The collected data, findings, and experience gained in the pilot mill will be utilized for (1) improvement of the automatic monitoring and decision support system, (2) refinement of the modeling methodology and/or the proposed models (3) verification of the success and/or efficacy (i.e., insect mortality) of the treatments performed, (4) economic analyses of cost and benefits of MB fumigation as compared to SF fumigation and heat treatments.

***Objective 2: Verify optimization tactics in commercial food-processing facilities subjected to MB, SF, and heat and other IPM tactics and gauge its impact on red flour beetle populations*:** The CFD model, HTC, EARTH, and red flour beetle population model will be extensively evaluated in commercial food-processing facilities to predict (1) gas emissions during structural fumigation, (2) heat energy requirements, (3) minimum time required to kill all heat-tolerant stage of red flour beetles, and (4) evaluate impact of treatments on population rebounds, respectively. A total of 15 commercial facilities comprising of rice mills, wheat flour mills, corn mills, pasta plants, breakfast cereal manufacturing facilities, and feed manufacturing facilities will be identified through cooperative arrangements to conduct our proposed work. Cooperating facilities will be using either MB, SF or use heat treatment during the 2009-2011 study period, and every effort will be made to select five facilities receiving each of the treatments. A CFD fumigation model (i.e., combination of one internal and one external flow model) will be constructed for each facility. The flow domain of each external flow model will include the facility itself and also a portion of the surroundings. The internal flow domain will incorporate interior details of the facility such as building plans, locations of major equipment, partitions and ducting. Structural bodies and interior objects will be represented using combinations of simple geometric shapes (e.g., rectangular or cylindrical volumes). The dimensions and layouts of these geometric shapes will be estimated based on construction drawings, satellite images, and field measurements of the actual structures and objects. The models will be validated using the experimental data collected during the fumigation trials in the pilot mill. We will perform grid independence analyses to ensure that the simulation domains are meshed with enough resolution for accurate simulation results while they are not excessively demanding in terms of computing time. The study of gas dispersion around fumigated structures will be done with the use of modified external flow models. The external flow model for each reference facility will be modified by incorporating species transport calculations into the governing equations. Additional surrounding structures might be added in the domain for evaluating gas dispersion in different assumed urban settings. Fumigant emissions from the fumigated structure will be modeled as uniform species sources on the external surfaces (i.e., walls and/or roof) of the structure. The release rate (i.e., emission rate) of this species source will be implemented via UDF. Given a HLT value and the structure’s volume, the fumigant emission rate in terms of unit weight per unit time (e.g., kg/s) can be calculated using the first order-derivative equations (see Chayaprasert et al. 2008). The HLT value can be either a result of fitting first-order derivative equations to concentration decay curves that are generated from fumigation simulations or an assumed value. As fumigant dispersion is dominated by air movement around the structure, wind speed and direction will be two primary input parameters of the simulation. Wind speed and direction are specified at the perimeter boundaries of the simulation domain. The refined CFD model predictions with respect to HLT and fumigant emissions will be compared with observed gas readings measured inside and outside commercial facilities. Gas will be measured as shown in Fig. 4.

To refine and document performance of the HTC, building and temperature data from five commercial facilities will be entered into the HTC to estimate heat loss by floor and room, and also estimate cost of the heat treatment by selecting the fuel (gas, steam, or electric) used for conducting the heat treatment. The estimated heat energy required will be compared with actual heat energy by examining fuel consumption records provided by the company, and by determining heat energy from average temperature profiles obtained from HOBO® data loggers placed within the heated structure (see Table 1). We will place 50 data loggers in predetermined locations of each facility in consultation with the facility manager. The HTC uses the observed temperature profile (because what the actual desired temperature will be can only be verified after a heat treatment) and breaks it down into two phases, rise phase (duration from ambient to desired temperature) and hold phase (duration from desired until end of heat treatment). These validations in commercial facilities are important because heat treatments can become more cost-competitive with MB and SF if the correct amount of heat energy is used for maximum effectiveness against insects.

In the same facilities, during each of the heat treatments, we will use the wireless sensors to remotely acquire data to invoke the thermal death kinetic model for first instars of the red flour beetle, the most heat tolerant of all stages and species we have evaluated so far (Mahroof et al. 2003, Boina and Subramanyam 2004, Mahroof and Subramanyam 2006). The EARTH software will be used to predict in real-time, time-dependent survival of first instars as a function of temperature. This information will be valuable for managers to observe and gauge the success of the heat treatment. Heat treatment can be stopped or extended by an hour or two when predictions based on temperature data from all sensors show that all first instars have died. This verification will help managers optimize heat treatments and prevent damage due from prolonged high temperatures.

The red flour population model being developed by Dr. Paul Flinn (USDA-GMPRC) we will be validated in all 15 commercial facilities by investigating the effects of different levels of sanitation (outside building, inside building, and inside equipment), length of heat treatment, maximum temperature of heat treatment, time of year heat treatment occurs, fumigant concentration, number of fumigations per year, and time of year when fumigation occurs on populations of the red flour beetles. The model can be used to evaluate the economics of various IPM strategies as well. Costs will be compared for various levels of sanitation, number of fumigations per year, high and low rates of MB or SF fumigation.

In order to determine the degree and duration of red flour beetle populations in each of the 15 commercial facilities subjected to MB, SF, or heat, we will place 30 commercial food-baited traps with a red flour beetle/confused flour beetle lures (Trece, Adair, OK) inside and five outside the facility. These traps will be replaced with new ones biweekly to enumerate the number of red flour beetles captured. Trapping will be conducted on four occasions before and four occasions after an intervention with MB, SF, or heat to evaluate treatment effectiveness (Roesli et al. 2003, Campbell and Arbogast 2004, Toews et al. 2006, Cryer 2008). Temperature throughout the trapping period will be measured by placing five HOBO® data loggers in each facility. Where possible, insect levels inside facilities will be monitored by collecting product samples from different locations in the equipment and product stream, from material sieved from the product stream (i.e., tailings), and/or from spillage. Collected samples will be converted to number of insects per gram. Information on structural treatments (e.g., timing and dosage of MB or SF fumigation) and other IPM practices (e.g., timing and specific location of aerosol pesticide application, and sanitation schedules) of the facilities during monitoring period will be obtained to interpret population rebound data and evaluate treatment performance. Changes in number of flour beetles captured and proportion of traps with insects before and after treatment (or other IPM practices) will be compared using paired *t*-tests, and the rate of rebound will be determined using regression techniques. Other calculated values will include time to reach pre-treatment capture levels and average action threshold for treatment, and these will be compared among treatments using general linear models procedure. To assess spatial variation due to the impact of treatments (or other IPM practices), trap captures or product samples will be combined into different spatial scale groupings, such as inside versus outside facility, by floor or building, by individual trap locations, or by product sample. Relationships between insect levels at these different scales will be compared over time using Spearman rank correlation analysis. Principal component analysis, stepwise linear regression, and/or analysis of covariance will be used to quantify the effects of MB, SF, and heat (or other IPM practices), environmental conditions, initial insect levels, outside trap captures, etc. on insect population reduction and rebound.

Expected outcomes and deliverables for Objective 2: The multi-year treatment simulations will allow for conducting sensitivity analysis of treatment performance and/or cost variability due to measured weather conditions. A predictive function of emission rates as affected by weather conditions will be established based on the fumigation simulation results. The HTC and EARTH software results will be valuable in optimizing heat treatments by indicating the minimum heat energy needed to attain and hold target temperatures and minimum time needed for complete control of exposed insects. The red flour beetle population dynamics model coupled with the trap capture data provides an additional measure of treatment performance. Quantifying the effects of the various influencing factors on insect population reduction and rebound will enable us to custom-design best IPM programs for food processing facilities. The insect monitoring and record of structural treatments and other IPM practices will be used in cost and benefit analyses discussed below.

***Objective 3: Perform an economic analysis of structural treatments and physical control methods both in the Hal Ross (pilot) mill and commercial facilities*:** Cost budgets and capital budgeting techniques will be used to compute the cost per cwt of flour produced for each red flour beetle control strategy (Mansfield et al. 2002, Kay et al. 2004). Control strategies in the Hall Ross pilot mill and commercial facilities include the following: MB, SF, and heat treatment. The cost of insecticides, energy costs, the cost of discarding infested product, labor used for each control strategy, the opportunity cost associated with shutting the plant down when implementing each control strategy, the cost associated with installing equipment, and equipment cost will be included in the analysis. The investment cost associated with installing equipment as well as the cost of the equipment will be annualized using the useful life of each piece of equipment and interest rates reported by the Federal Reserve Bank of Kansas City. The total cost of each control strategy will be expressed on a per cwt of flour produced. Standard operating procedures will be used for each control strategy. These procedures do not necessarily assure 100% insect mortality. This makes it necessary to examine the tradeoff between control strategy cost and insect mortality in addition to estimating the cost of each control strategy as explained above. Optimization models are commonly used to examine tradeoffs between key variables (Yu et al. 2002, Ragsdale 2004). The model developed by Tilley et al. (2007) will be used to examine the tradeoff between insect mortality and cost across control strategies. This model examines the tradeoff between cost and total deviations below a target insect mortality rate. Deviations for each control strategy replication will be measured using a target mortality goal of 100%. As the model allows for more total deviations below this target, cost decreases. By varying the total deviations allowed, the tradeoff between cost and total deviations below the target insect mortality rate can be measured.

***Objective 4: Disseminate science-based information to stakeholders through demonstration, hands-on training programs, and publications through various formats*:** The results from this proposed work will be transferred to food industry and NPMA stakeholder groups, through seminars held at association meetings, extension publications, and technology-transfer activities. Results will be presented at the International Association of Operative Millers Annual Technical Meeting and Trade Show, Methyl Bromide Alternatives Annual Meeting, Grain Elevator and Processing Society Annual Meeting, and other relevant professional meetings, and through publications in trade journals such as the Milling Journal, World Grain, and International Association of Operative Millers Bulletin. This information will also be published electronically at our web sites (http://www.oznet.ksu.edu/grsc_subi and http://www.GrainQuality.org) and subsequently as articles in scientific peer-reviewed journals such as the Journal of Stored Products Research, Journal of Economic Entomology, Transactions of ASABE, and Applied Engineering in Agriculture. In addition, fumigation and heat treatment training workshops will be organized at various locations (e.g., Kansas State University and Purdue University). These workshops will include classroom type lectures and hands-on training on status of MB and alternatives in the food industry, proposed research results and outcomes, training in using various models described in the proposal, and training on application technology of MB and alternatives, with ample time for questions/answers and interaction between industry stakeholders, researchers, regulators, service providers, and pesticide registrants. The number of hits to websites, number of requests for information, and/or the number of participants attending the various workshop/conference presentations and changes in practices of these participants to implement best IPM practices (through surveys/phone interviews) will be used to evaluate extension and education program success.

Dr. Subramanyam has an active research program in the management of stored-product insect using alternatives to pesticides, and he is a member of the Food Protection Committee of the International Association of Operative Millers that is represented by members from various food and feed industries. He has a dedicated column in the Milling Journal. Dr. Subramanyam has hosted several pest management and heat treatment workshops in the US and he has trained over 300 people at six heat treatment workshops organized between 1999 and 2004. Dr. Maier maintains an active research program on stored-product protection, as well as is engaged in educational training and extension outreach activities to the grain, feed, food and allied industries. His outreach activities will facilitate the quick transfer of this technology to the industry. Dr. Mason annually trains hundreds of professionals attending her fumigation certification workshops in Illinois, Indiana, Ohio, and Michigan. Other project personnel also will be intimately involved in the extension and educational activities, with additional assistance from the food industry stakeholders, pesticide registrants, and food industry service providers.

Expected outcomes and deliverables for Objectives 3 and 4: We expect our proposed research to clearly document the challenges and issues and realistic costs/benefits involved in using MB and MB alternatives under field conditions. The extension and educational activities should improve adoption of MB alternatives and optimize utilization of MB and MB alternatives. The LOGIC model showing inputs, outputs, and outcomes for our project is submitted separately as ancillary information.

Timelines for proposed research: The table below shows timelines for various aspects under the four objectives by month and year.

Objective/Activity	**Yr**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1/Planning[a]	08							🟥	🟥	🟥	🟥	🟥	🟥
1/Mill preparation and treatments[b]	09	🟦	🟦	🟦						🟦			
	10					🟦	🟦						
1/Data analysis/modeling	09				🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
	10	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
	11	🟨	🟨	🟨	🟨			🟧	🟧	🟧	🟧	🟧	🟧
2/Identify/travel to commercial sites	09						🟩	🟩					
2/Verification of models at commercial sites	09								🟪	🟪	🟪	🟪	🟪
	10	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪			
	11	🟪	🟪	🟪	🟪								
3/Economic analysis	09						🟦						
	10						🟦						
	11						🟦						
4/Stakeholder group formation	08								▨	▨			
4/Meeting with stakeholders	09	🟦											
	10	🟦											
	11	🟦											
4/Create web site	09												
4/Hands-on workshops[c]	09			🟪						🟪			
	10						🟪						
4/Survey workshop participants	10	🟧											
	11	🟧											
4/MB Alternatives meeting	08										🟦	🟦	
	09										🟦	🟦	
	10										🟦	🟦	
4/Peer-reviewed and extension publications	09										🟪	🟪	🟪
	10								🟪	🟪	🟪		
	11					🟪	🟪						
4/Final report	11					🟨	🟨						

[a] Planning includes meetings with project investigators, ordering supplies, mass culturing test insects, developing data sheets, and promoting hands-on workshop to be held in 09 and 10.

[b]Prepare mills for conducting MB, SF, and heat treatment.
[c]Conduct hands-on workshops. Only a single technology will be demonstrated in-depth at a workshop. Therefore, three workshops are scheduled for all three technologies (MB, SF, and heat).

(4) Cooperation and institutional units involved

This project is a cooperative effort between the Department of Grain Science and Industry and Agricultural Economics at Kansas State University, Purdue University, and the USDA's Grain Marketing and Product Research Center. The table below shows responsibilities of project personnel.

Name	Institution	Responsibilities
Bhadriraju Subramanyam	Kansas State University	Project co-director: Overall coordination and management of project; red flour beetle bioassays; conduct heat treatment research with HTC and EARTH; co-supervise a postdoc and graduate student
Dirk Maier	Kansas State University	Project co-director: Supervise a postdoc in the refinement and evaluation of MB, SF, and heat treatments in pilot and commercial facilities using the CFD model
Wat Chayaprasert	Kansas State University (now at Purdue University)	Postdoc; plan and execute experiments in pilot and commercial mills for optimizing the CFD model
Michael Langemeier	Kansas State University	Conduct cost-benefit analysis of MB, SF, and heat treatments in pilot and commercial mills
James Campbell	USDA-GMPRC	Evaluate impact of sanitation and IPM intervention on life stages of the red flour beetle in pilot and commercial mills, and interpret effectiveness of IPM intervention based on trap captures; co-supervise a graduate student
Paul Flinn	USDA-GMPRC	Develop, validate, and refine red flour beetle population data and conduct simulations to determine effects on beetle populations at various manipulated environmental conditions; co-supervise a graduate student
Linda Mason	Purdue University	Supervise a graduate student in evaluating effectiveness of MB, SF, and heat in commercial facilities
Xingwei Hou	Kansas State University	Postdoc; plan and conduct research with the HTC and EARTH in pilot and commercial facilities

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Bibliography

Logic Model for Proposal on:
“Critical Evaluation of Methyl Bromide, Sulfuryl Fluoride and Heat Treatment for Disinfesting Food-processing Facilities”

Goals

(1) Analyze cost-effectiveness of MB, SF, and heat in food-processing facilities through research in pilot-scale and commercial facilities
(2) Promote and implement MB transition strategies through extension and educational programs

Situation

(1) Consistent decrease in MB CUE amount over time versus slow adoption of MB transition strategies
(2) Inappropriate comparisons on cost-effectiveness of MB, SF, and heat in commercial facilities
(3) Urgent need for science-based extension and educational programs to promote adoption of MB alternatives

Input

People

- Investigators, research associates, graduate students
- Food industry stakeholders
- Pest management service providers
- Fumigant registrants

Facilities

- Hal Ross (pilot) flour mill
- Commercial food-processing facilities
- Workshop facilities

Materials

- Heaters
- Fumigants
- Gas monitoring devices
- Environmental condition sensors
- Insect monitoring devices
- Bioassay tools

Finances

- Support for all project activities

Output

Activities

Research

- Apply MB, SF, and heat treatments in Hal Ross (pilot) mill
- Monitor gas and environmental conditions
- Assess efficacy against red flour beetle life stages
- Determine costs
- Use precision fumigation, computational fluid dynamics, heat energy, and insect survival models
- Refine and implement models in commercial facilities

Extension

- Hands-on demonstrations during pilot mill treatments

Education

- Seminars, websites, distance education, publications

Participation

- Pest management professionals
- Food processing facility managers
- Researchers
- Regulators

Outcome

Short-term

- Increased stakeholder knowledge of MB and alternatives
- Familiarity with models for optimizing treatment effectiveness
- Understand fumigant and heat distribution and effectiveness in mills

Medium-term

- Optimize cost-effectiveness of pest management practices
- Reduce MB use and emissions

Long-term

- Adopt environmentally viable IPM technologies
- Produce wholesome and unadulterated food and feed products using MB alternatives