A COMPARISON TO METHYL BROMIDE WITH TWO ALTERNATIVES TREATMENTS; SULFURYL FLUORIDE AND HEAT TO CONTROL STORED PRODUCTS INSECTS

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ABSTRACT

Environmental concerns are growing as new information is being discovered as to what is harmful to the environment. The desire to help the environment along with improving fumigations is a big concern and effects many people. Ongoing research to improve fumigations without harming the environment has shown great promise in advancing technology and lowering the cost in protecting commodities consumed by the consumer.

Methyl Bromide (MB) has been the major fumigant used to control stored-product insects for many commodities for many years. There has been a lot of concern surrounding MB because of health and environmental drawbacks. These concerns have caused MB to be reduced by 2005. With the total phase out of MB becoming critical, there is much anticipation as what will be the alternative(s). The research presented in this thesis describes two different and very effective methods of controlling stored product insects. Although there are many other methods of fumigating this thesis analyzes two forms; Sulfuryl Fluoride and Heat.

The first presented alternative in this paper will be heat treatments. It has the attraction that chemical forms of treatments do not have by having pesticide-free products. The total cost of heat fumigation depends on the complexity of the lay-out/structure and the cost heaters and electricity. This cost can range anywhere from $15,000-25,000.

The second alternative that will be discussed is sulfuryl fluoride. This fumigant has many positive aspects that counter act the negative aspects that have been a concern with methyl

bromide treatments. These positive aspects include environmentally safe and fast off-gassing. Sulfuryl fluoride is also very efficacious with stored product insects. The labor costs per job, ProFume shows a cost of about $216.00 less than that of a methyl bromide treatment.

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CHAPTER I: INTRODUCTION

1.1 Importance of Controlling Stored-Product Insects in Food Processing Facilities

The supply chain from the grower/packers to consumers is an integrated process in which there are many players involved. Maintaining quality is very important throughout this process as well as making it efficient to get the product to its final location in a timely manner. This is a detailed process that starts with the processors, growers, and shippers who fumigate their commodities while in the field or storage before they are shipped out. For instance, farmers sell their products to companies (packers, brokers, etc.) that process and package these products for export or for shipments to domestic consumers. As these products are shipped from one place to another, insect contamination may occur. This contamination can lead to infestation of other products in the facilities and warehouses (Highland, 1984; Mowery et al., 2004). Insect infestation in packaged products can occur through the seams, closures, or from ripping of packages (Mowery et al., 2004).

Fumigants are commonly used to control insects in food processing facilities (e.g., flour mills). A fumigant is a chemical that, at a required temperature and pressure, can exist in the gaseous state in sufficient concentration to be lethal to a given pest or organism. The major advantage of a fumigant is that it can penetrate to almost any area and be lethal to a wide variety of pests. This allows for better and quicker control with an end result of less need for other pesticides to be used in the area. There are limitations when using fumigants; some are extremely poisonous to mammals, some can corrode certain metals, and some are flammable or even explosive under certain conditions. Additionally, fumigants do not ensure long-term control, and insect infestation can occur after the gas dissipates from the treated facility.

There are many risk assessment challenges associated with the use of fumigants.

There are federal restrictions on how a fumigant should be applied, and these aspects are reported on a fumigant label. For instance, the site where the fumigant is to be applied should be characterized. This would include determining how the gas emissions from treated structures behave outdoors based on the prevailing environmental conditions and wind patterns. Fumigant management plans (FMPs) dictate that an effective plan be developed when using fumigants to protect bystanders. Proper sealing to contain gas within structures to provide maximum exposure time for effective insect kill is also a consideration. Under-dosing with fumigants may lead to the development of resistance in insect species (Subramanyam and Hagstrum, 1996). Reducing the amount of risk in treatments helps control the acute and ambient bystander exposure from fumigation (Gorham, 1991).

To protect commodities from reoccurring insect damage, companies fumigate on a regular basis. Typically, fumigations occur during major holidays, such as Labor Day, Independence Day, or Memorial Day. These calendar-based applications are made because many food-processing facilities operate 24 hours a day, 7 days a week. Stopping production to accommodate a whole facility treatment is not an economically viable option. In addition, food-processing facility managers rarely monitor insect pest populations, and these services are contracted to a pest management service provider. The pest management service providers do not place enough insect monitoring devices to accurately estimate populations of a major pest species to accurately time whole-plant interventions. Additionally, unlike field crops, action thresholds (pest density that requires intervention) have not been developed for industry insect pests. It would be better to fumigate using infestation thresholds rather than the calendar or just fumigating on major holidays (Toews et al., 2005b). In addition to periodic fumigations, managers control small scale infestation problems that occur within the facility by performing fogging and spot treatments.

It is hard to give an exact measure of how well a treatment works because it is difficult to ascertain whether insects survived in hidden spots, cracks, and crevices. Residual contact insecticides are often used on a regular basis in food-processing facilities to control infestation of the red flour beetle (Toews et al., 2005a). The effectiveness of residual applications to floor surfaces in a facility is influenced by food patches and the amount of area treated (Toews et al., 2005a). Insect mortality can be on average about 90% after treatment. However, the original insect population may reoccur within a month (Hagstrum and Flinn, 1992). There are measures that managers can take to address re-infestation. Toews et al. (2005b) indicated the importance of sealing the first floor by screening all open doors and windows when venting the fumigant and postponing fumigation until cool weather arrives in the autumn. Preventing insect entry from the outside is known as exclusion. Extra cleaning of the building and equipment before and after the fumigation and removing patches of product also prevents re-infestation (Toews et al., 2005b). These practices are known as sanitation. Sanitation and exclusion practices extend the degree and duration of insect intervention by preventing rapid reinfestation.

One of the most common pests infesting food patches in food processing facilities is the red flour beetle, *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae) (Ziegler, 1976). There are many factors that influence the movement of insects to a patch of food including insect density (Naylor, 1961; Zyromska-Rudzka, 1966; Hagstrum and Gilbert, 1976; Ziegler, 1977), fitness consequences of dispersal (Ziegler, 1976; Lavie and Ritte, 1978), the heritability of dispersiveness (Ogden, 1970; Ritte and Lavie, 1977; Riddle and

Dawson, 1983; Korona, 1991), and the relationship between dispersal rates and life history traits (Lavie and Ritte 1978,1980; Lavie, 1981; Ben-Shlomo et al., 1991).

Methyl bromide has been the major fumigant used to control post-harvest insects for many years. There has been a lot of concern about methyl bromide because of its potential effects on human health and on the environment. The amount of methyl bromide that is currently used has declined significantly, dropping 11% since 1994. There are exemptions for which methyl bromide is used that include: quarantine and pre-shipments, critical use exemptions (CUE), and emergency use exemptions. Critical use exemptions can be given for the following reasons: not using methyl bromide would result in significant market disruption and there are no technically and economically feasible alternatives available.

In the critical use exception process, the U.S. government nominates uses and volumes on behalf of U.S. companies and then argues to the international committee overseeing the protocol that there is a critical need. Stakeholders in the U.S. have applied for critical use exceptions for certain volumes of methyl bromide every year since 2002, but the EPA has conveyed requests for much smaller amounts than those applied for (Federal Register, or www.epa.gov website). So far, 1.7 million ozone depleting substance tons of annual production and consumption have been phased out. Bromide accounts for approximately 25% of the decline in the troposphere since the phase out (Montzka, 2008).

The high cost of developing new chemicals to replace those withdrawn from use because of pest resistance and the imposition of regulations to prevent environmental damage or human health risks makes it prudent to explore non-chemical treatments (Gorham, 1991). Alternatives to methyl bromide include the use of other chemicals such as sulfuryl fluoride, which was registered as ProFume® by the U.S.-Environmental Protection Agency in January 2004, and heat treatment, a 100-year-old technology. The phase-out of methyl bromide because of its adverse effects on the stratospheric ozone has led to exploring alternatives to methyl bromide for management of stored-product insects associated with food-processing facilities.

1.2 Thesis Objectives

The primary objective of this thesis is to examine the costs of alternatives to the use of methyl bromide in flour mills. The two alternatives examined are sulfuryl fluoride and heat. Costs examined in the analysis include equipment costs, labor costs, and fumigation costs. It is difficult to obtain cost estimates. However, this thesis compares the cost-effectiveness of these treatments.

1.3 Thesis Organization

Chapter two will provide a discussion of related literature. Chapter three will discuss the survey and methods used. Chapter four will report the results. Chapter five will provide a summary and conclusions.

CHAPTER II: INSECT MANAGEMENT ISSUES IN FLOUR MILLS

2.1 Integrated Pest Management

Integrated pest management (IPM) is a decision making process in which all interventions (treatments, actions) are brought to bear on a pest problem with the goal of providing the most effective, economical, and safest remedy possible. IPM programs use current, comprehensive information on the life cycles of pests and their interaction with the environment. In combination with this information and available pest control methods, IPM is used to manage pest damage using most economical means, and with the least possible hazard to people, property, and the environment. The IPM approach is used in both agricultural and non-agricultural settings. IPM takes advantage of all appropriate pest management options including judicious use of pesticides. The goal of IPM is not to use like pesticide, but to reduce reliance of pesticides by using all available non-pesticide alternatives.

IPM involves pest management evaluations, decisions, and control, and conducts a cost/benefit and risk/benefit analyses. In practice, managers follow a four step approach. The first step is to set action thresholds. An action threshold is the point at which pest populations or environmental conditions suggest that the pest control action should be taken. The level at which pests become an economic threat is critical in guiding future pest control decisions. This requires developing sampling programs to assess pest density and damage. In cases where an action threshold is not available, experimental knowledge can be used to determine the action threshold. The second step is to monitor and identify pests. IPM programs monitor and identify pests so that appropriate control decisions can be made in conjunction with action thresholds. This monitoring and identification removes the possibility that pesticides will be used when they are not needed. The third step is prevention. IPM programs are used to prevent pests from becoming a threat. The fourth step is control. IPM programs evaluate the proper control method both for effectiveness and risk. Effective, less risky pest controls are used first, including highly selective chemicals such as pheromones, to disrupt pest mating. Mechanical control, such as trapping, can also be used. If further monitoring, identification, and action thresholds indicate that less risky controls are not effective, then additional pest control methods would be employed, such as targeted use of pesticides. IPM has dramatically reduced pesticide applications and the cost of pest control (EPA, pesticides fact sheet, 2008).

Cost effectiveness is a major consideration in IPM program development and must be assessed in the long term as well as the short term. Economic evaluation relies on understanding and measuring the physical, chemical, and biological effects of treatments (i.e., rates of mortality of the interventions). Economic evaluation is generally the last step in the analysis.

The IPM systems approach considers all reasonable methods to avoid pest problems and combines the control or suppression procedures that best suit the particular need at a particular time. As situations change, the combination of methods can change, and this is often the case. A lot of care is needed in selecting and implementing control measures under the following circumstances: larger facilities, complex facilities, and facilities that are poor from physical and maintenance standpoints, as they are more likely to allow insect populations to become established (Gorham, 1991). Consumer and regulatory expectations must also be considered since these vary with the commodity, facility, and the government entities involved. Users consider the cost of fumigating and how well the fumigant penetrates and kills the target insects.

2.2 Sanitation Issues

Fumigating can control most insect damage because it can penetrate most areas and is lethal to a wide spectrum of pests in a processing facility. It is hard to know all locations where insect infestations exist within a processing facility. These infestations exist because of product accumulation in cracks and crevices or on ledges within pores of equipment or floors, or floor-wall junctions. Thus, estimating the absolute insect population or understanding the age structure of insects within facilities is difficult. Consequently, when a fumigant or a whole facility intervention is employed, determining effectiveness against resident insect populations cannot be determined accurately. One method to ensure that insects in unsanitary locations are removed is through thorough sanitation. Thorough sanitation is accomplished only if the facility manager recognizes unsanitary zones that contribute to insect infestations. Good sanitation helps to reduce re-infestation.

The FDA and USDA have developed a strategy to lower the risk of food borne illnesses that occurs because of pathogenic microbial contamination. This plan requires food industries to write Standard Operating Procedures (SOP) for sanitation that address maintenance, procedures, and handling of the product and the cleanliness of the establishment. These procedures must be monitored by a designated employee and maintained on a daily basis. Tests are performed to ensure microbial counts do not exceed the FDA and USDA's tolerances. These tests consist of microbial sampling and organoleptic monitoring. If test results exceed the required tolerances then management needs to take corrective action to address the problem. This can include cleaning the plant again or re-training employees.

Good manufacturing practices (GMPs) are guidelines that the FDA established in the Federal Food, Drug and Cosmetic Act of 1938. This Act covers most direct and indirect aspects of food processing. Food is required to be free of adulteration. Good manufacturing practices help prevent microbial contamination before a corrective action needs to be performed.

The most common spots in which adult insects are found are in doorways and outside the facility (Throne and Cline, 1989, 1991; Fields et al., 1993; Dowdy and McGaughey, 1994; Doud and Phillips, 2000; Campbell and Mullen, 2004). As discussed above, determining the absolute populations of insects within a facility is difficult. Therefore, devices have been developed to sample a particular stage of insects, usually adults. Traps are used as a means of monitoring the pest population. However, insects caught in traps are not always representative of the actual or absolute pest population in the facility. Traps should be used several weeks prior to a treatment and should be used several weeks after a treatment to determine the reduction in trap catch immediately after an intervention, and the rate of rebound following an intervention. However, there are a lot of other factors to consider when using traps, e.g. the type of trap (Levinson and Hoppe, 1983; Ahmad, 1987; Barak et al., 1990; Mullen, 1992; Quartey and Coaker, 1992; Hussain et al., 1994; Mullen, 1992; Mullen et al., 1998; Mullen and Dowdy, 2001; Nansen et al., 2003; Nansen et al., 2004a; Nansen et al. 2008), the type of pheromone used and the dosage (Phelan and Baker, 1986; Vick et al., 1986; Hussain et al., 1994; Zhu et al., 1999; Nansen et al., 2006), and the location of the traps (Vick et al. 1986; Nansen et al., 2003; Nansen et al. 2004b; Nansen et al. 2008). A study by Campbell et al. (2002) reported that red flour beetle traps placed along the walls of a facility collected more insects than traps placed next to poles. There are a lot of variables when addressing the issue of distance including the amount of air movement, barriers to dispersal, and the number and distribution of food patches inside and outside facilities (Campbell and Mullen, 2004). Campbell and Arogast (2004) reported that male warehouse beetles were captured more than 500 meters from the facility and male Indian meal moth were captured at a distance slightly less than 500 meters (Doud and Phillps, 2000).

Another method to measure population involves using bioassays. To achieve a more accurate count of pest infestation, pre-counted insects, confined in vials with food, should be placed in various spots of the facility and counted after the treatment. Empty facilities have patches of food product that vary in size, quality, and persistence that are an attractive environment for infestation of stored-product insects (Campbell and Hagstrum, 2002).

Another method to assess insect populations involves sampling spilled products (food patches) or examining product during its processing. Food patches vary by the amount of infestation, the species, and when they occur at an opening have more infestation (Campbell and Hagstrum, 2004). There have been many studies on the direct correlation of adults found in the traps and the actual adult infestation in empty warehouses compared to those that have food patches (Toews et al., 2005b) and the correlation of trap capture and product infestation in flour mills (Campbell and Arbogast, 2004). Sanitation in a warehouse is very important when addressing the issue of infestation of food patches in warehouses.

2.3 Chemical Treatments and Alternatives

There have been many estimates that indicate between 15 and 40% of the world's food supply is destroyed before consumption (USDA website, 2005). Pests such as insects, mites, rodents, and birds are a threat to producing safe and wholesome food. Of these pests, stored-product insects are present in almost every food-processing facility and pest management programs are targeted to manage these insects. Treatments such as post-harvest and quarantine treatments are necessary to protect commodities from pest damage. Typical pest management programs for stored-product insects include sanitation, stock rotation, crack/crevice treatment with residual insecticides, sanitary design of equipment, inspection of facilities, and use of fumigants or heat treatment of the entire structure. Although all of the tactics are generally used, most food-processing companies rely on whole structure treatments, applied once or twice a year, because of continuous production. The discussion below provides a brief overview of the use of methyl bromide, sulfuryl fluoride, and heat.

2.3.1 Methyl Bromide

Approximately 85% of the methyl bromide used in the U.S. is used for soil fumigation to kill soil-borne pathogens, nematodes, insects, and weeds during pre-plant preparation of crops (USDA website, 2005). Methyl bromide has also been an important tool for the food industry for several decades for managing stored-product insects. The amount of methyl bromide used for commodity applications represents approximately 20% of the total methyl bromide usage worldwide. Of this amount, more than 10,000 metric tons are consumed for postharvest commodity applications in developing countries. The United States, Italy, Japan, Australia, and South Africa are the largest users of methyl bromide for postharvest applications. Depending on the dosage, temperature, structure, gas-tightness, and insect life stage, methyl bromide fumigation may take as little as four hours using a vacuum fumigation. However, for whole structure treatments, the fumigation time is usually 24 hours to kill insects. Methyl bromide is also the fumigant of choice for quarantine and pre-shipment because of its effectiveness (Armstrong et al., 1998). The major advantage of methyl bromide is the ease and the high rate of efficacy (Gorham, 1991).

Methyl bromide is an odorless, colorless, toxic gas which is used as a broad-spectrum pesticide and is controlled under the CAA as a Class I ozone-depleting substance (ODS). It is also regulated by the EPA under the 1947 Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) and other statutes and regulatory authority. Under FIFRA, methyl bromide is a restricted use pesticide. Restricted use pesticides are subject to certain Federal and State requirements governing their sale, distribution, and use (EPA, 10 CFR Part 82, 2009). Methyl bromide emerges from ocean emissions, from burning biomass, agriculture applications, structural fumigation combustion, and leaded gasoline (Bell et al., 1996). Methyl bromide was not an environmental concern until 1974 when it was discovered that MB could affect the balance of the ozone layer (Bell et al., 1996). Methyl bromide is one of the primary sources of bromide that diminishes the ozone layer (Salawitch et al., 1988; Schauffler et al., 1993; Bell et al., 1996).

The Montreal Protocol is an international agreement aimed at reducing and eliminating the production and consumption of stratospheric ozone-depleting substances. The U.S was one of the countries to sign the 1987 Montreal Protocol and ratified the Protocol on April 12, 1988. It was the signed into law by the Clean Air Act Amendment of 1990 (EPA, 10 CFR Part 82, 2009). The Clean Air Act of 1998 states that “to the extent consistent with Montreal Protocol’s quarantine and pre-shipment provisions, the Administrator shall exempt the production, importation, and consumption of methyl bromide to fumigate commodities entering or leaving the United States or any State (or political subdivision thereof) for purposes of compliance with Animal and Plant Health Inspection Services requirements or with any international, Federal, State, or local sanitation or food protection standard" (Aegerter and Folwell, 2001).

Over a period of time, methyl bromide use has been reduced from several benchmark levels. The amount of methyl bromide currently used has been declining significantly. The use of methyl bromide was reduced to 75% of 1991 baseline levels in 1999. In 2001, the use dropped to 50% of the 1991 level, and in 2003, it fell to 30%. Developing countries, such as Mexico and Chile, were given until 2015 to ban methyl bromide use. In North America, the production and use has been phased out except for some critical uses. So far a phase out of 1.7 million ozone depleting substance tons of annual production and consumption has occurred. The phase out of methyl bromide and reduction in amounts of methyl bromide granted for critical uses requires that effective alternatives be sought to replace methyl bromide.

2.3.2 Sulfuryl Fluoride

Dow AgroSciences has been developing the gas fumigant ProFume (99.8% sulfuryl fluoride) for over 7 years to control stored-product pests in milling, food processing, and food storage facilities. It has excellent penetration qualities, low reactivity potentials, low residues, and rapid aeration (ProFume website, 2009). ProFume is inorganic, non-combustible, and stable under most fumigation environments. It is packaged in cylinders as a liquid under pressure. It converts to a gas upon release from an introduction hose due to its high vapor pressure and low boiling point (ProFume website, 2009). It is non-flammable and non-corrosive as a gas and odorless. Sulfuryl fluoride is the active ingredient in ProFume. ProFume contains no chlorine or bromine and, thus is a non-ozone-depleting substance.

SF and MB are approximately three and a half times heavier than air. SF has approximately 35% higher heat capacity and thermal conductivity than that of MB (Yaws 2001). Both SF and MB have almost the same fluid viscosities and mass diffusivities (Cryer 2008). Even with these similarities in the physical properties, SF is different from MB in many aspects. SF is an excellent penetrator thus making it more effective at reaching insects that reside deep in cracks and crevices, treated commodities, or residual flour than MB (Subramanyam, 2008). SF penetrates through nylon and polyethylene sheeting more slowly than MB, which makes it is easier to confine SF with plastic tarps commonly used in structural fumigation (EPA 2009). A study by 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 to no residues on treated commodities when compared with MB (Subramanyam, 2008).

Several studies, and results from more than 400 commercial fumigations, have documented the effectiveness of SF for stored-product insect pests (Bell and Savvidou 1999, Bell et al. 1999, 2003, 2004; Reichmuth et al. 1999, Schneider and Hartsell 1999, Wontner-Smith 2005, Small 2007). Laboratory and field research confirms that ProFume is effective on all life stages of postharvest insect pests (EPA grant performed by DFA, 2004). ProFume fumigations have shown positive results on insect control comparable to methyl bromide fumigations. Larvae, pupae, and adult insects are highly susceptible to ProFume, while eggs are more tolerant. Lower dosages can be used at higher temperatures because of increased insect metabolism. ProFume dissipates the process of the glycolysis and fatty acid cycles, thus preventing insects from metabolizing the stored fats they need to maintain a sufficient source of energy for survival (USDA-ProFume website, 2004).

The Fumiguide is a computer based program that calculates the dosages needed to customize fumigations. The Fumiguide calculates the amount of ProFume to use depending on the temperature, size of the structure, targeted insect(s), and commodity and gas loss from enclosures on fumigation efficacy. This type of precision fumigation can also be applied to MB fumigation. In the case of sulfuryl fluoride, residue levels are very low in commodities (dried fruit and tree nuts) and only after repeated fumigations are low levels of residues found in nuts. The fluoride ion is the residue that is usually of concern and generally higher amounts are found in the edible parts of the product.

ProFume fumigations are not damaging to sensitive equipment or electronic controls (i.e., fans). It can be used for short or long fumigations to meet the time constraints of the fumigator and customer (ProFume website, 2008). ProFume effectiveness, like methyl bromide, is CT (concentration x time) product dependent. This means that when fumigating, the CT product must be achieved in order to get the best results from the fumigation. Vacuum fumigations can have exposures ranging from 2 to 4 hours, depending on the CT product they are targeting. ProFume off-gases very fast and allows for the aeration period to be shorter than most other fumigations, which is around 24 hours.

2.3.3 Heat

The use of thermal energy has a long history just like many other conventional technologies for stored-product insect control. Many food- and feed-processing companies such as General Mills, ConAgra, Cargill Inc., Kraft Foods, Quaker Oats (PepsiCo), and

Nestle Purina, among others, are using heat treatment as an alternative to MB (Subramanyam, 2008). Heat treatments involve raising the ambient temperature of the treatment area of the facility to 50 to 60°C using gas, electric, or steam heaters and maintaining these high temperatures for 24-36 hours (Imholte and Imholte-Tauscher 1999, Dowdy and Fields 2002, Wright et al. 2002, Subramanyam, 2008). Different parts of a facility heat up at different rates. With heat treatments, gas, electric, or steam heaters are used to slowly heat the surrounding air. Long heat treatments of 24-36 hours are necessary to penetrate wall voids and equipment to kill the insects inside the structures (Mahroof et al., 2004). Products within the structure should be cleaned or removed because they are poor conductors and can serve as places for the insects to harbor (Subramanyam, 2008).

The first industrial-scale heat disinfectors were developed in Australia between 1915 and 1919 (Beckett et al., 2007). These early machines heated grain by conduction up to 600^{o}C as the grain fell by gravity through a bank of steam-heated pipes. The units stood 6 meters high and could treat 25 tons (1,000 bushels) per hour. Of the 12 units built over this period, six processed over `10,000,000 bags of wheat’ or 816,000 tons (Beckett et al., 2007).

There are many factors that need to be addressed when using thermal disinfestations to control stored-grain insects. Issues that need to be addressed include throughput rate, thermodynamic design, energy costs, safety, and versatility for a range of commodities (Beckett et al., 2007). Another important factor in using heat treatments is not only to control insects but treating without damaging equipment or structures. The current practice in heat treatments is to warm the building up by 5^{o}C per hour to a target temperature of 50-60^oC, hold this temperature for 24-36 hours, and then cool the building at 5-10^oC per hour (Beckett et al., 2007).

Temperature control and aeration are important considerations when conducting a heat treatment. During heat treatments, the temperature is not uniform throughout the structure and some areas may be under heated (<50^oC), while others may be overheated (>50^oC) (Mahroof et al., 2004). Stored product insect mortality of all stages can be achieved rapidly by high temperatures of 65^oC within a few seconds of exposure. However, treatments with temperatures above 60^oC are not recommended because of possible damage to heat-sensitive equipment in food-processing facility (Mahroof et al., 2004). As the temperature is lowered, the time required to achieve high levels of insect mortality become longer. A temperature of 50^oC requires a couple hours whereas a temperature of 42^oC requires days. Below 42^oC, some insects can survive and continue to produce progeny, even though reproduction is not as rapid as it would be in their normal optimum environment temperature ranges. When the rate in which the facility is heated is slow, the insects may have time to equilibrate to the temperature, thus resulting in increased thermal tolerance (Waddell et al., 2000). Most insects have optimum temperatures in the range of 26.7-32^oC (Banks, 2000).

Mahroof et al. (2004) showed that young larvae, when compared to all other stages of the red flour beetle, were the most tolerant at 50^oC. The authors concluded that heat treatments that target young larvae should control all other stages (Mahroof et al., 2004). Studies by Bijok (1996) and Emekci et al. (2002) reported that newly hatched red flour beetle larvae had greater oxygen consumption per unit weight compared with eggs, old larvae, and pupae. Bijok (1996) also states that the higher respiration rates in insects may be caused from their higher metabolic rates which are connected with a reaction to stress, and may enhance survival under unfavorable environmental conditions. Tolerance to high temperatures could be caused by the synthesis of stress proteins and other metabolites in many organisms (Currie and Tufts, 1997).

Additional cost savings can be accrued by decreasing the target temperature and increasing the treatment period. A paper by Beckett and Morton (2003) discusses treatment cost at various temperatures. In their study, they show that at the most rapid rate of heating, it required 0.73 minutes to reach 60^{o}C. Insect mortality was 99.9% and the cost was $2.72 per ton at this heating rate. At the next rate of heating, it required 23.62 minutes to reach 55^{o}C. Insect mortality was the same as at the high rate of heating while the cost was $1.87 per ton. At 50^{o}C, 22 hours were required to achieve a high level of insect mortality, but the cost was reduced to $1.25 per ton. However, such schedules have not been established for structures. The heating of grain is far different from the heating of structures. In the former, it is high temperature short time heating whereas in the latter it is high temperature long time heating.

CHAPTER III: METHODS

Assessing the economic viability of existing and proposed alternatives to methyl bromide is one of the key elements in this thesis. To compare costs of different alternatives, an informal survey was conducted from individuals in the commercial pest management industry who routinely treat commercial grain facilities. The results of the survey were compared to the benchmark values established by the EPA, *Methyl Bromide Critical Use Renomination for Post-Harvest Treatment of Structures, 2011*.

Since treatment cost varies with the size of a facility, the informal survey asked respondents to indicate the approximate facility size treated. The survey allowed the respondent to indicate whether the facility was small – 1 Million (M) ft^3, medium – 1-2 M ft^3, or large – >2 M ft^3.

Another important factor influencing treatment cost is half loss time which determines how long a treatment will take. Half loss time is influenced by how well the facility is sealed. A well sealed facility reduces the required amount of time for heat or fumigation. When fumigating with sulfuryl fluoride or methyl bromide, concentration readings are used to indicate whether to add more fumigant or to extend or shorten the duration of treatment.

The survey instrument also addressed the number of days a facility was shut down. There are a couple of factors that affect the amount of days a facility is shut down such as the amount of time it takes to set-up for fumigation and the duration of treatment which in turn is influenced by how well or poorly the facility is sealed. The more time a facility is shut down, the more money is lost in production. As discussed above, most treatments occur during holidays when the facilities are already closed. The final question on the survey asked the respondent to provide the estimated cost to treat the facility.

The survey was sent to individuals that used methyl bromide, sulfuryl fluoride, and heat treatments. All of the individuals receiving the survey were involved in conducting commercial fumigation or heat treatments. Some of these people conducted treatments on their own facilities and some conducted treatments all over the U.S. Some conducted 5-7 fumigations while others performed around 2 per year. Participants were asked to fill out the survey form which was e-mailed to them. The survey was sent out at the end of February, 2010 and the last response was received in the middle of April. Table 3.1 presents the survey instrument.

The survey was sent to 12 individuals of which four responded. This gave a 25% response rate. The low response rate can be explained by several factors, but most likely is due to work schedules or an unwillingness to share proprietary information.

Table 3.1: Methyl Bromide and Alternatives Survey.

	Size of the facility			½ Loss Time			Days shut down			Est. cost for the facility ($K)		
Treatment	<1 Mft^3	1-2M ft^3	>2M ft^3	<1M ft^3	1-2M ft^3	>2M ft^3	<1 Mft^3	1-2M ft^3	>2M ft^3	<1M ft^3	1-2M ft^3	>2 M ft^3
Methyl Bromide												
Bld-1												
Bld-2												
Bld-3												

	Size of the facility			½ Loss Time			Days shut down			Est. cost for the facility ($K)		
Treatment	<1 Mft^3	1-2M ft^3	>2M ft^3	<1M ft^3	1-2M ft^3	>2M ft^3	<1 Mft^3	1-2M ft^3	>2M ft^3	<1M ft^3	1-2M ft^3	>2 M ft^3
ProFume												
Bld-1												
Bld-2												
Bld-3												

	Size of the facility			½ Loss Time			Days shut down			Est. cost for the facility ($K)		
Treatment	<1 Mft^3	1-2M ft^3	>2M ft^3	<1M ft^3	1-2*M ft^3	>2M ft^3	<1 Mft^3	1-2M ft^3	>2M ft^3	<1M ft^3	1-2M ft^3	>2 M ft^3
Heat												
Bld-1												
Bld-2												
Bld-3												

CHAPTER IV: RESULTS

The results from the survey came from four industry members that performed several sulfuryl fluoride, methyl bromide and heat treatments. The results are presented in Table 4.1.

Methyl bromide treatments with facility sizes of <1 M ft^3 (buildings 1-3) had half loss times ranging from 10 to 36 hours. Buildings 1-3 were shut down for 48 hours. The cost to fumigate these facilities ranged from $7 to $26/cu ft. There were four treatments with facility sizes of 1-2 M ft^3 (buildings 4-7). The half loss times for buildings 4-7 were similar and averaged 35 hours. On average, the facilities were shut down for 48 hours. The costs to fumigate were similar averaging $41/cu ft Building 8 had a facility size of >2 M ft^3. The half loss time was 91 hours and the building was shut down for 48 hours. The cost to fumigate building 8 was $68/cu ft.

Fumigation information for sulfuryl fluoride treatments from eleven different buildings were obtained from the survey respondents. Buildings 1-4 had a facility size of <1 M ft^3. The treatments for these buildings ranged in half loss time from 10 to 36 hours. The buildings were shut down from 24 to 72 hours. The cost to fumigate buildings 1-4 were: $7; $11; $11; and $50/cu ft, respectively. Buildings 5- 9 had a facility size of 1-2 M ft^3. The half loss times for these buildings averaged 35 hours. Buildings 5 and 7 were shut down 120 hours, building 6 was shut down for 96 hours, and building 8 was shut down for 48 hours. The costs to fumigate these buildings ranged from $17 to $80/cu ft. Buildings 10 and 11 were >2 M ft^3 in size. Building 10 had a half loss time of 91 hours with a total shut down time of 120 hours and cost less to fumigate ($24/cu ft). Building 11 had the lowest half loss time and was shut down for 24 hours. The cost for this fumigation ranged from \$80 to \$100/cu ft.

Heat information obtained from the survey showed a building facility with a size of <1Mft^3 had an estimated cost of \$19/cu ft. Estimated cost for building 2, with a facility size of 1-2Mft^3 had a cost of \$28/cu ft. The third building with a facility size of >2Mft^3, had an estimated cost of \$36/cu ft. Half loss time is not an issue with heat treatments therefore "not applicable" for this survey.

Comparing all three treatments at the smaller facility of <1Mft^3 per cubic foot; \$17, \$20, and \$19 for methyl bromide, sulfuryl fluoride and heat, respectively, all are very comparable to one another in price. As the facility size gets larger, the price per cubic foot for heat averages about \$10 more for each treatment. However, this isn't the case for methyl bromide and sulfuryl fluoride treatments with an average of about \$20 more for each treatment.

Table 4.2 shows the annual economic impact of methyl bromide alternatives for the North American Millers Association. Rice millers and North American millers are major users of methyl bromide with use of approximately 16 and 68% annually, respectively, of the nominated amount for stored-product pest management (Subramanyam, 2008). This data comes from the EPA *Methyl Bromide Critical Use Renomination for Post-Harvest Treatment of Structures, 2011*. The total fumigation cost for sulfuryl fluoride is approximately double the cost of total fumigation cost for methyl bromide. The cost of using heat in Table 4.2 is greater than 10 times the total cost of methyl bromide fumigation. The majority of the cost for methyl bromide and sulfuryl fluoride fumigations is the fumigant cost. When using a heat treatment only one day is lost. Sulfuryl fluoride and methyl bromide fumigations do not require any days lost when fumigating. When comparing the total annual loss to methyl bromide treatment, sulfuryl fluoride has a loss of $13,931 whereas heat has a loss of $137,000. The average facility loss per kg of methyl bromide when compared to sulfuryl fluoride treatments is $25, while for heat treatments it is $148.

When comparing survey results of the three treatments and averaging their cost per cubic foot for all three size facilities; methyl bromide averaged $42/cu ft, sulfuryl fluoride averaged $38/cu ft and heat averaged $28/cu ft. Comparing these results to the Millers Association cost analysis with these three treatments; methyl bromide was about three times less, sulfuryl fluoride was about 1.5 times less and heat was about 5 times less, Table 4.3.

All of the costs were calculated into per cubic foot to show a 1:1:1 comparison. There are many different variables that could have changed the cost with these three treatments. For example, set-up cost (i.e., sealing the building), the location of the facility, and how many employees it took to fumigate the facility. In both cases, heat treatments were based off of propane which could increase significantly with the cost of fuel. Heat only covered cases where heat treatment may potentially be technically feasible, and does not cover situations where heat would degrade the commodity being processed (those with fats and edible oils).

Table 4.1: Results from the Cost Benefit Analysis of Methyl Bromide, Sulfuryl Fluoride and Heat Treatment Survey

	Size of the facility			½ Loss Time			Days shut down			Est. cost for the facility (per Cu ft)		
Treatment	**<1 Mft^3**	**1-2M ft^3**	**>2M ft^3**	**<1M ft^3**	**1-2M ft^3**	**>2M ft^3**	**<1 Mft^3**	**1-2M ft^3**	**>2M ft^3**	**<1M ft^3**	**1-2M ft^3**	**>2M ft^3**
Methyl Bromide												
Bld-1	X			10hr			48hr			$7		
Bld-2	X			24hr			48hr			$20		
Bld-3	X			36hr			48hr			$24		
Bld-4		X			36hr			48hr			$39	
Bld-5		X			35hr			48hr			$44	
Bld-6		X			44hr			48hr			$44	
Bld-7		X			25hr			48hr			$36	
Bld-8			X			91hr			48hr			$68

	Size of the facility			½ Loss Time			Days shut down			Est. cost for the facility (per Cu ft)		
Treatment	**<1 Mft^3**	**1-2M ft^3**	**>2M ft^3**	**<1M ft^3**	**1-2M ft^3**	**>2M ft^3**	**<1 Mft^3**	**1-2M ft^3**	**>2M ft^3**	**<1M ft^3**	**1-2M ft^3**	**>2M ft^3**
ProFume												
Bld-1	X			10hr			72hr			$7		
Bld-2	X			24hr			72hr			$11		
Bld-3	X			36hr			72hr			$11		
Bld-4	X			10-12hr			24hr			$50		
Bld-5		X			36hr			120hr			$17	
Bld-6		X			35hr			96hr			$30	
Bld-7		X			43hr			120hr			$30	
Bld-8		X			25hr			48hr			$36	
Bld-9		X			10-12hr			24hr			$50-80	

Bld-10	X	91hr	120hr	$24
Bld-11	X	10-12hr	24hr	$80-100

	Size of the facility			**½ Loss Time**			**Days shut down**			**Est. cost for the facility (per Cu ft)**		
Treatment	**<1 Mft^3**	**1-2M ft^3**	**>2M ft^3**	**<1M ft^3**	**1-2M ft^3**	**>2M ft^3**	**<1 Mft^3**	**1-2M ft^3**	**>2M ft^3**	**<1M ft^3**	**1-2M ft^3**	**>2M ft^3**
Heat												
Bld-1	X			NA			1			$19		
Bld-2		X			NA			1			$28	
Bld-3			X			NA			1			$36

Table 4.2: Annual Economic Impacts of Methyl Bromide Alternatives for North American Miller's Association

NAMA[a]	Units[b]	Methyl Bromide[b]	Sulfuryl Fluoride	Heat:29C
Total Fumigation/Heat Cost	**$/year**	**$13,000**	**$26,933**	**$150,000**
Quantity of Fumigant	**$/year**	**567**	**1,588**	**Na**
Fumigation Costs (i.e., gas)	**kgs/facility**	**$7,500**	**$21,000**	**Na**
Other fumigation costs(i.e., labor, equip., etc.)	**$/year**	**$5,500**	**$5,933**	**$150,000**
Time lost	**Days**	**0**	**0**	**1**
Total Annual Loss (MB to alt)	**$/year**	**-**	**$13,931**	**$137,000**
Average Facility Loss per Kg MB Requested	**$/kg** requested	**-**	**$25**	**$148**

[a] Analysis for a 28,317 cubic meter (1,000,000 cubic foot) facility

[b] Temperature at 29.44 degrees C

Table 4.3: Comparing Survey and Miller's Association Results at all Three Treatments and Averaging Their Cost Per Cubic Foot for all Three Size Facilities (per Cu ft); Methyl Bromide, Sulfuryl Fluoride and Heat.

	Methyl Bromide	Sulfuryl Fluoride	Heat
Survey	$42	$38	$28
Miller's Association	$13	$27	$150

CHAPTER V: SUMMARY AND CONCLUSIONS

Research shows that the negative environmental aspects outweigh the positive aspects when fumigating with methyl bromide. Alternatives to methyl bromide are the future for fumigation. Estimates presented in this thesis and those presented by the Miller's Association are dependent on each situation. Heat and sulfuryl fluoride are very effective with stored product insects with minimal harm to the environment compared to methyl bromide.

Using the survey and cost estimates from the Miller's Association, a comparison of the economic costs of using methyl bromide, sulfuryl fluoride, and heat treatments was conducted. Survey information was obtained for methyl bromide, sulfuryl fluoride and heat treatments. These results were compared to numbers developed by the Miller's Association. In most cases, when comparing the industry survey methyl bromide cost to the Miller's Association cost, the industry cost was much higher, about three times as much. When comparing sulfuryl fluoride costs, they were slightly higher by 1.5 times than the cost the Miller's Association fumigation cost. Heat treatment costs were just the opposite showing fumigation cost of almost six times less than the Miller's Association cost. The ranges in cost with each of these fumigations could have been due to different conditions such as: set-up cost (i.e., sealing the building), the location of the facility and how many employees it took to fumigate the facility.

The comparison between the survey results and the Miller's Association numbers would have been enhanced with a higher survey response rate. Heat treatment costs are considerably higher than the cost associated with methyl bromide fumigations. Spot treatments are very effective and used on a much smaller scale could cut down the cost of using heat.

In summary, the costs when using sulfuryl fluoride and heat as an alternative is comparable to methyl bromide when comparing the survey results. Methyl bromide has been the most effective fumigant for several decades. The alternatives discussed in this thesis, though with limited data, may be viable alternatives to methyl bromide. However, tangible data is needed on the cost-effectiveness of these three technologies.

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