ECONOMIC EVALUATION OF PHOSPHINE FUMIGANT MONITORING DEVICES USED IN OKLAHOMA COMMERCIAL GRAIN ELEVATORS

By

RONDA DANLEY

Bachelor of Science

Kansas State University

Manhattan, Kansas

2000

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
May, 2002

ECONOMIC EVALUATION OF PHOSPHINE FUMIGANT MONITORING DEVICES USED IN OKLAHOMA COMMERCIAL GRAIN ELEVATORS

Thesis Approved:

Brian Adam

Thesis Adviser

Thomas W. Phillips

Ronald T. Noyes

Kim B. Anderson

Jim T Criswell

Timothy J. Pettibone

Dean of the Graduate College

ACKNOWLEDGMENTS

I am grateful to my major adviser, Dr. Brian Adam. His encouragement and never-ending patience have made this research and my graduation possible. I also extend my appreciation to my other committee members Dr. Jim Criswell, Dr. Ron Noyes, Dr. Tom Phillips, and Dr. Kim Anderson whose guidance, assistance, and supervision were invaluable. In addition, I thank the Oklahoma State University Departments of Biosystems and Agriculture Engineering, Entomology and Plant Pathology, and Agricultural Economics for their physical and financial support.

I also thank the following people for allowing me to conduct phosphine field test monitoring at their elevator facilities: Mike Landis, Rick Williams, Kent Prickett, Lanie Hale, Mike Rosen, Glen Thorpe, Rick Weathers, Rodney Vogts, Mike Iverson, Rick Treeman, and Alan Terry. In addition, I would like to thank John Ayers and Jim Warner from Triangle Insurance Company, Chuck Estes from Midland Fumigant Inc., Michelle Hamlin from Industrial Fumigant, Inc., and Jeff Lavery from KC Supply.

Finally, I especially thank my family and friends for their love and support. I dedicate this degree to my mom, Janette. It is with her love that I find strength, courage, and inspiration to improve myself for my work in the world.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

ATI	Analytical Technologies, Inc.
EPA	Environmental Protection Agency
FMP	Fumigation Management Plan
MADM	Multiple Attribute Decision Making
MCDM	Multiple Criteria Decision Making
MSA	Mine Safety Appliances, Inc.
ppm	parts per million
PVIFA	Present Value Interest Factor Annuity
RED	Reregistration Eligibility Decision
RMM	Risk Mitigation Measure
SAW	Simple Additive Weighting
TOPSIS	Techniques for Order Preference by Similarity to Ideal Solution
TWA	Time-Weighted-Average

CHAPTER I

INTRODUCTION

Problem Statement

Aluminum and magnesium phosphide, both solid formulation phosphine gas producing fumigants, and methyl bromide are the only pesticides labeled for food use in the United States. However, "The use of methyl bromide will be banned in the United States by the year 2005 because it has been found to contribute to the destruction of earth's stratospheric ozone layer" (EPA-A, pp. 5-6). Moreover, aluminum and magnesium phosphide products, which are not ozone depletors and are non-flammable, are also being threatened because of a number of phosphine gas inhalation poisoning reports (Blondell and Spann).

On December 23, 1998, the Environmental Protection Agency (EPA) added fifteen new risk mitigation measures (RMMs) for all aluminum/magnesium phosphide products (EPA-B). Of the fifteen EPA recommendations, the grain and milling industries were mostly concerned with proposals that would prohibit phosphine fumigations within 500 feet of a residence and reduce the permissible level of exposure from 0.3 to 0.03 parts per million (ppm), a tenfold decrease (Paulsrud). By October of 2000, following intense phosphine manufacturer and commercial grain and milling industry lobbying, the EPA had dropped both proposed restrictions, but did enact other less stringent risk mitigation measures (RMMs).

These RMMs were developed to increase safety standards by implementing new requirements for users. Hundreds of people have been poisoned with phosphine in the United States. From 1982 – 1992, 179 illness cases were reported involving aluminum phosphide. Of those 179 cases, 24.9% involved fumigant applicators and 75.1% involved exposures to bystanders or workers (O'Malley, Kullman, and Cox-Ganser). During the phosphine reregistration process, the EPA also required that all aluminum/magnesium phosphide producers rewrite their phosphine labels to better inform users of the symptoms and health complications that may result from phosphine gas poisoning (Pestcon). The poisoning process starts when phosphine gas is inhaled. The gas irritates mucous membranes in the lungs and releases highly acidic phosphorus. The chemical is then absorbed throughout the entire body, damaging cells, and causing symptoms that are mild to serious depending on concentration and exposure length (Applicators Manual for Degesch Phostoxin). Extended exposure to low concentrations of phosphine gas, from 0.08 to 0.3 ppm, may cause headaches while higher concentrations for short durations (minutes), from 0.4 to 35 ppm, may cause diarrhea, nausea, abdominal pain, vomiting, tightness of chest, breathlessness, headache, dizziness, skin irritation or burns, staggering, palpitations, soreness or pain in the chest, unconsciousness, coma, and death (NIOSH Alert).

Because of the highly toxic nature of phosphine gas, the RMMs focus on a central theme—increased awareness (RED Facts). Many users are not aware of the dangers of phosphine gas and have not monitored gas levels in and around their facility to assess health risks even though it was previously required. Each grain elevator or milling facility is unique and must be monitored to determine if workers, bystanders, and residents are being exposed to harmful gas levels. To deter injuries linked with phosphine, the EPA is urging users to monitor gas levels frequently. EPA staff plans to conduct an experiment to develop additional monitoring studies and plans to work closely with registrants beginning with 2002 fumigations (Memorandum of Agreement). The purpose of this research will be to determine whether the maximum exposure rate should be lowered from the current 0.3 ppm.

A major question that has not been answered is how the monitoring should be conducted to give the most accurate and precise results. There are several phosphine gas-monitoring devices available to users. Some monitoring devices have simple operating procedures while others require a skilled worker. These devices also differ in cost, sampling time, accuracy, and reliability. Therefore, a cost feasibility study is needed to determine which monitoring device/s are best suited for grain and milling industry use.

Summary of Planned Field Work

A Multiple Criteria Decision Making (MCDM) model was used to determine the best phosphine monitoring device for Oklahoma grain elevator operators by weighing both costs and benefits of five different readily available monitoring devices: 1) MSA Kwik-Draw Pump and glass tube (MSA Tube); 2) Dräger Pac III; 3) Dräger MiniWarn; 4) ATI PortaSens II; 5) Lumidor MicroMax 1-JP (Lumidor MicroMax). For each device, a decision maker considers four cost and five benefit factors:

Initial equipment cost – How much does each device cost?

Additional equipment-related cost – How much additional equipment-related cost is incurred throughout a fumigation?

Recalibration cost – How often does each device need to be recalibrated and at what cost per recalibration?

Labor cost – How much time and cost in labor expense is required to properly use each device during fumigant sampling?

Benefit of worker safety perception – What is the likely contribution of each device to decrease the number of phosphine related illnesses?

Benefit of user-friendliness – How user-friendly (or easy to use) is each device during sampling?

Benefit of convenience – How convenient is each device during use?

Benefit of ruggedness – How rugged is each device during use – is it easily damaged?

Benefit of accuracy – What is initial accuracy of each device and how does the accuracy change (drift) during repeated sampling?

The best device was selected by weighting these costs and benefits according to individual grain elevator operator preferences. In addition, solutions were obtained for varying labor costs and lengths of fumigations.

The following were results for a MCDM model with grain elevator operator labor costs at eight dollars per hour for a 6-day fumigation. The model weighted costs at 80% (26.6% initial equipment cost, 26.6% additional equipment-related cost, and 26.6% labor cost) of the buying decision and benefits at 20% (4% on convenience, 4% on ruggedness, 4% on user-friendliness, 4% on worker safety perception, and 4% on accuracy). The ranking of devices from most-preferred to least-preferred was: 1) Dräger Pac III; 2) Lumidor MicroMax; 3) Dräger MiniWarn; 4) ATI PortaSens II; 5) MSA Tube.

Another MCDM model that used the same labor cost and fumigation length, weighted costs at 0% and benefits at 100% (20% on convenience, 20% on ruggedness, 20% on user-friendliness, 20% on worker safety perception, and 20% on accuracy). The ranking of devices was: 1) Dräger Pac III; 2) Dräger MiniWarn; 3) Lumidor MicroMax; 4) ATI PortaSens II; 5) MSA Tube.

These results illustrate that the rankings changed little when alternate weights were used in the evaluation scheme. The rankings did not change when wage rate was varied. Also, the rankings did not change when number of fumigations was varied. This suggests that economies of scale were not important within the ranges considered here. The only difference between these two scenarios was that the Dräger MiniWarn was preferred over the Lumidor MicroMax in the second scenario that weights benefits at 100%. The highest-ranking device in both situations was the Dräger Pac III and the lowest ranking device was the MSA Tube. Thus, all four electronic-type monitoring devices were preferred over the MSA Tube. However, it should be noted that it is not possible to assign statistical significance to differences among the devices in these rankings.

Each grain elevator operator needs to determine which phosphine gas-monitoring device fits the needs of their facility. Since all phosphine users are required to monitor their worker areas, this study may also be used by other industries that use aluminum/magnesium phosphide to fumigate.

Introduction

Phosphine is a colorless, odorless gas that is used to kill insects in stored food products. It is typically purchased in solid form as pellets or tablets and applied to grain in storage. The pellets or tablets react with moisture and form a highly toxic gas at a temperature dependent rate. The gas is a respiratory poison for insects. Insects breathe

the poison in, causing their internal organs to cease functioning. Phosphine has been the most used commercial grain fumigant for several decades.

Even though phosphine has been reregistered, it is still on the EPA's watch list. EPA is mandating new restrictions on phosphine by December 2002 through the RMMs. One of the new RMM process restrictions requires phosphine users to create a Fumigation Management Plan (FMP). See Appendix A.1 for a sample Fumigation Management Plan. Each FMP is facility-specific and includes a section about monitoring gas levels around the exterior of the fumigated facility during fumigation and during ventilation or aeration of all fumigated structures in the facility. The EPA requires data collection to determine the gas concentrations to which workers, bystanders, and nearby residents are being exposed at various leak or gas release points around the fumigated structures.

The data collection process is an important tool for the phosphine manufacturers and the grain and milling industries in determining the dangers of phosphine fumigants. EPA does not have sufficient data regarding gas levels in worker areas due to the wide variation in fumigated storage structures from site to site and is therefore unable to determine if risk is present. If gas levels at many facilities are found to be high, EPA may place further restrictions on the use of phosphine gas for grain and mill fumigation uses, such as increased sealing requirements. EPA has inserted a provision in the current regulations about monitoring. EPA has reserved the right to lower the current time-weighted average (TWA), the maximum concentration of gas that can be in the air where personnel are for an eight-hour period, from 0.3 if monitoring is not implemented

(Gordon). This RMM provision clearly implies the importance that the grain and milling industry should place on monitoring.

The choice of monitoring device used is left up to the applicator or grain manager. There are several options available. The two main types of portable devices are electronic and tube-type monitors. Tube-type models are relatively inexpensive (~\$200) and provide adequate reliability at the current exposure level standards. However, each reading requires a significant amount of time (several minutes/reading), so labor costs are high. The electronic models require minimal time (seconds) to operate, but are quite expensive (~\$1400) to purchase. In addition, several different brands of electronic monitoring devices are available. Each uses a unique operational technology, so each model has advantages and disadvantages.

This study determined which phosphine gas-monitoring device is the most cost-effective for grain storage facilities to use in protecting workers' safety by weighing costs and benefits for each device. Grain elevator operators need to know where leakage points are so that they can be sealed to decrease gas loss during fumigation. By using monitoring devices in worker areas and around each fumigated structure, the grain elevator operator can pinpoint the sources of the leaks so that they can be sealed. Leakage points are a function of the structural and maintenance characteristics of the facility, which includes the age of the facility, the type of storage structure, and the care given by the grain elevator operators to the facility. The other main variable is the number of fumigations per year per facility. With fewer fumigations per year at a small storage volume facility, the grain elevator operator is more likely to choose a device with lower fixed costs even though it has higher variable costs. Conversely, more fumigations or a facility with much larger storage volumes would encourage a grain elevator operator to choose a device with higher fixed costs and lower variable costs.

Because profit margins for grain elevator operators are typically low and the industry is highly competitive, identifying cost-effective management methods is important for grain elevator operators to make the necessary investment to protect applicators, workers, and bystanders.

It was assumed in this study that grain elevator operators want to comply with EPA's new restrictions, but that they need to know the most cost-effective way to do that. Therefore, Oklahoma grain elevator operators need to know which phosphine gas-monitoring device is best for their facilities and how to effectively implement the use of the device into their fumigation process.

Objectives

The general objective of this research is to help grain elevator operators achieve the greatest benefit from a given phosphine detection device while minimizing their cost of compliance with EPA regulations on phosphine.

The specific objective is to determine which phosphine gas-monitoring device is the most cost-effective for grain storage facilities to use in protecting workers' safety by weighing benefits for each device against the costs of each device.

Monitoring Devices

Tube and electronic monitoring devices accomplish the same general goal; however, their costs are different.

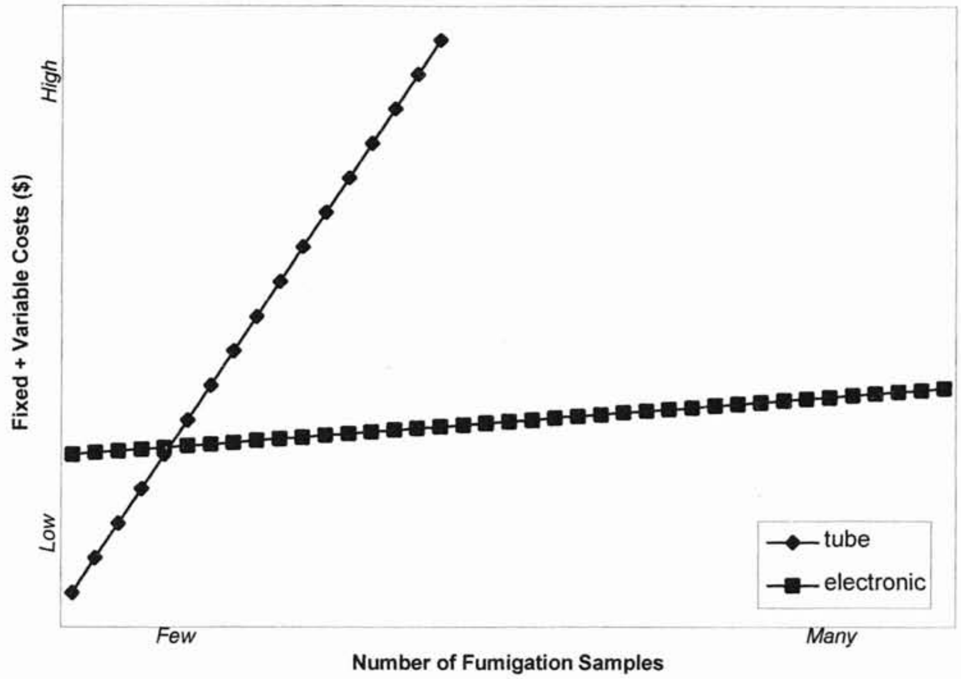


Figure 1. Cost of Tube-Type and Electronic-Type Monitoring Devices

Tube-type monitoring devices have low fixed costs and high variable costs while electronic-type monitoring devices have high fixed costs and low variable costs. As the number of fumigations increase, the average cost of the electronic-type monitoring devices decreases. Figure 1 shows the hypothetical costs of the two types of monitoring devices as the number of fumigations increases.

Electronic-type monitoring devices have high fixed costs because the initial equipment purchase is ~$1400. On the other hand, variable costs are low. Because of quick monitoring times, labor costs are low. The only other variable cost of most electronic units is the recalibration cost (~$50) required at the beginning of the fumigation season (if fumigate less than three months/year) or every three months (if fumigate more than three months/year) (General Information Concerning Gas Detectors).

Tube-type monitoring devices have low fixed costs because the initial equipment cost is ~$200. However, the variable costs are high because, in addition to higher labor costs, a new tube must be used for each reading. Each box of 10 tubes costs between $40-$70 and tubes are used only once. For example, if a box of tubes costs $40 and gas readings at the facility are taken four times per hour for eight hours, the cost of tubes for one day of monitoring is 32 tubes at $4/tube = $128. This assumes that all employees are working in an area requiring four monitoring points and readings are taken; such as an office, scale, work floor, and belt tunnel. It also assumes that all employees work in this area for an entire 8-hour workday. This is a likely situation scenario that shows how quickly tube costs add up over the course of one fumigation in one location. If this example facility fumigation lasted five days, the cost of tubes would be $128 times five days = $640/fumigation.

Because of the cost relationships shown in Figure 1, it was expected that the electronic-type monitoring devices would be more economical for grain elevator operators that conduct more fumigations, and that tube devices would be more economical for grain elevator operators that conduct fewer fumigations.

A Multiple Criteria Decision Making (MCDM) model was used to identify the phosphine gas-monitoring devices that are best for Oklahoma grain elevator operators. Costs and benefits were calculated for several monitoring devices. The costs and benefits were entered into the MCDM model and weights were placed on each cost and benefit. The device with the number that was highest was the best device for that scenario. In this study, 19 scenarios were considered; varying length of fumigations, labor costs, and weights assigned to costs and benefits.

Overview of Thesis

Chapter 1 is an introduction to the thesis. The problem is presented along with an overview of the study.

Chapter 2 is a review of literature. It provides background information about phosphine fumigants, their role in grain quality, and alternatives to phosphine gas. The review also discusses several ways to monitor phosphine gas and lists previous research involving phosphine gas-monitoring devices.

Chapter 3 explains the model. A Multiple Criteria Decision Making (MCDM) Model was used to determine best phosphine gas-monitoring device. The specific form of MCDM used in this study was the Multiple Attribute Decision Making (MADM). This form has previously been used to explain, rationalize, or predict decision behavior.

Chapter 4 explains the study procedures and methods. It describes and compares the monitoring devices that were used in the study and discusses how they were chosen. Costs and benefits of each device and how they were calculated and used in the Multiple Criteria Decision Making model are discussed.

Chapter 5 presents and discusses the results of the study. Chapter 6 summarizes the results of the experiment, and provides important conclusions and policy implications of the study. Ways to extend and improve upon this research project are suggested.

CHAPTER II

REVIEW OF LITERATURE

Throughout the processing of any food product, there are safety procedures needed to keep employees safe and healthy. Safety standards are required to maintain quality and reduce risk to consumers who purchase and use the finished product.

Over the past few years, there has been controversy involving food safety standards. Insects are able to infest grain at any point from field to consumer. As insects reproduce and spread around processing plants, some of them end up in processed foods (Kenkel et al.). Insects feed on the grain or grain products, significantly reducing its value. However, there are ways to remove or neutralize storage insects before they decrease food quality. One way is through a process called fumigation. There are several physical and chemical ways to fumigate. Some of the most common methods are to insert aluminum/magnesium phosphide, hydrogen cyanide, and carbon dioxide into bulk grain masses in storage (Mueller). The most commonly used grain fumigant is a dry, solid formulation of aluminum/magnesium phosphide pellets or tablets.

This literature review discusses aluminum/magnesium phosphide fumigants and the fumigation process. Then, it compares and contrasts glass tube-type and electronic-type monitoring devices. Finally, previous monitoring studies are reviewed.

History of Aluminum/Magnesium Phosphide

The German company, Degesch, developed aluminum phosphide as a source of phosphine gas for fumigation. It was first used in the United States in 1958 by Hollywood Termite Control Company, Inc. to help control termites. There are currently 23 products containing aluminum phosphide as the active ingredient in the United States. Magnesium phosphide was first registered in the United States in 1979. There are currently four pesticide products containing magnesium phosphide as the active ingredient in the United States (RED Facts).

These products were not widely used when they were first put on the market and most people did not treat them a viable alternative to methyl bromide. Even as late as 1980, those who recognized aluminum or magnesium phosphide as an alternative thought it was not needed. Few thought it was needed because methyl bromide was cheap and faster acting. With the removal of methyl bromide from the market, phosphine gas products will be the only grain fumigant on the market (Wilson).

Since phosphine has become the most used fumigant, there are many questions that researchers ask regarding the chemical operations that take place. Phosphine has widespread use throughout the world, however there is little understanding of how it should be used to control insects (Newman).

Description of Aluminum/Magnesium Phosphide

Aluminum and magnesium phosphide are similar products - they both react with environmental moisture to form phosphine gas. However, there are specific circumstances in which one type is preferred over the other. For instance, aluminum phosphide is used more in commodity grains before processing while magnesium phosphide is used more in flour, meal, and other processed goods primarily because magnesium phosphide reacts faster than aluminum phosphide (Munzel). Magnesium phosphide can transform completely from solid form to gas in 48 hours at ambient temperatures while aluminum phosphide can take 72 or more hours (Munzel). Magnesium phosphide also leaves lower levels of unreacted phosphide than does aluminum phosphide. Magnesium phosphide leaves only about 0.2% unreacted phosphide while aluminum phosphide leaves 2% or more unreacted phosphide (Noyes, Kenkel, and Tate). This provides for shorter fumigations and increased product safety.

Aluminum phosphide is used in commodity grains, partially because it has a slower release rate, spreading out the dosage over longer periods. Commodities are usually fumigated and then stored for long periods of time; therefore, fumigation speed is not usually a concern. Also, the longer the gas is in the grain, the more effective the fumigation (Leesch et al.).

Both products are available in tablet, pellet, and sachet form. Each tablet weighs three grams and will release one gram of phosphine, each pellet weighs 0.6 grams and releases 0.2 grams of phosphine, and each sachet weighs 34 grams and releases 11 grams of phosphine (RED Facts). Aluminum phosphide is now also available in the gas form and is called ECO_2FUME^{TM}. Fumigating 1000 bushels of grain requires between 120-905 pellets, 25-180 tablets, or 12-16 bags, depending on type of storage (RED Facts). Another reason for the large range of recommended dosages is that different areas, climates, and insects require different doses (RED Facts). Even though the dosage and length of fumigation is location-specific, the process is uniform for most commodities.

The Fumigation Process

The fumigation process begins by sealing the storage facility to minimize leakage into work areas or to the outside of the facility. However, many times the facility has undetected leaks or is inadequately sealed. Aluminum/magnesium phosphide tablets, pellets, or bags are then placed inside the facility. The tablets, pellets, or bags generate a gas called phosphine (PH_3). The reaction or release time depends on the temperature of the grain and surrounding areas and the moisture content and air relative humidity in the commodity. The reaction may take one to three days, depending on reaction factors. The gas formed is odorless and colorless. However, impurities in phosphide come out during the gas formation and may be detectable. The detectable smell may resemble garlic, calcium carbide, or impure acetylene. Once the phosphine gas mixes with the grain and is absorbed, impurities and the smell disappear (Leesch et al.).

Phosphine gas disperses rapidly in the air due to its own partial vapor pressure and moves throughout the storage facility in the same manner as airborne smoke. The density of the resulting phosphine/air mixture is almost the same as that of air. Phosphine is only slightly heavier than air with a density or specific gravity of 1.24. At 1,000 ppm, the air/PH_3 density is about 1.00124.

Phosphine is slightly soluble in water and has low solubility in most solvents. It reacts with and may corrode silver, gold, copper, and alloys containing copper such as brass. Reaction time is increased by moisture in the air containing salt (RED Facts). The areas most prone to this reaction are seaside mills and elevators. All sensitive material should be sealed, greased, maintained in a positive pressure airflow, or removed before fumigation (RED Facts). The way the gas kills insects, or mode of action, is a respiratory poison. When an insect breathes the gas in, its organs absorb the poison and quit functioning.

There are many stored product insects that must be controlled to maintain quality in grain. However, they can be categorized based on their location in the bin and the damage that they cause. Insects may look different, but they all affect grain quality and purity. The damage done by insects directly reduces grain weight, nutritional value, and germination. Insect infestation can also cause contamination, odors, molds, and heat damage that reduces the market value of the grain and can make it unfit for processing into food for humans or livestock (Krischik and Burkholder). Once insects infest grain, grain buyers and manufacturers may refuse delivery of the grain. Moreover, buyers may reject grain in which insects are detected, even if no physical boring damage has occurred. Insect boring or chewing damage is called "insect damaged kernels" (IDK).

The three main categories of insects are surface feeders, internal feeders, and external feeders. The surface feeders and the external feeders feed on the fine materials, mold, and dust. They contribute to filth and infestation. The internal feeders are a bigger problem because they feed on the internal parts of the kernel. They not only contribute to filth and infestation, but also to the number of IDK and dry matter loss (Krischik and Burkholder).

All three categories of insects develop during a four-stage life cycle. The eggs hatch into larvae that change to immobile pupae, before finally becoming active adults. The eggs and pupae are "immobile" phases, while the larvae and adults are the only visible evidence of an infestation. From egg laying to adult stages, insect development is typically 30-40 days in warm grain (25-35 degrees C or 75-95 degrees F). In cool grain

(15-20 degrees C or 59-70 degrees F) an insect generation cycle may be 50-75 days or longer (Leesch et al.).

The mobile larvae and adults are easily killed by phosphine, in one to five days; however, insects in the immobile phases require more time due to low respiration. Because mobile larvae and adults are easily killed by phosphine, many people believe that a fast fumigation is sufficient. However, because the immobile phases (eggs and pupae) are much harder to kill, the infestation may become evident again within a month or two after fumigation.

An effective fumigation must aim at killing all life stages of insect growth. This requires that the phosphine dosage be retained over relatively long periods of time, such as 10-14 days in warm grain. This requires that phosphine be in all parts of the grain throughout the entire fumigation. High doses can cause insects to become comatose (shut down their respiration to dormant status) and absorb little or no phosphine during the fumigation. When the time of fumigation is long, the phosphine is able to kill all stages of insect life (Harein and Davis).

The objective of a phosphine fumigation is to maintain toxic concentrations of phosphine during a long enough period to kill all stages of all species that may be found. This process is called “concentration x time” or the “CxT” process. It is important to fumigate with correct CxT procedures. Failing to do this in the past has caused development of phosphine resistance in some insect strains. Further misuse of phosphine can have a long-term negative effect on future efficacy (Phillips and Burkholder).

Worker Safety

According to EPA, people should not enter an area being fumigated without a proper safety breathing apparatus until the gas concentrations are less than 0.3 ppm. To determine whether gas levels are low enough, air/gas levels must be monitored. Monitoring is a confusing subject to many phosphine users. Many users have stated that monitoring equipment was either too expensive or that they were unfamiliar with the monitoring equipment and operational procedures. The following section will explain the differences between two types of monitoring devices, tube-type and electronic-type, and give examples of each.

Glass Tube-Type Monitoring Devices

Glass tube-type (tube-type) monitoring devices have lower initial costs than the electronic-type devices, but they require more worker skill than electronic-type monitoring devices. The accuracy and precision of tube-type monitoring devices depends on the worker's skill level in reading the tube label, applying the correct number of pump strokes and reading the tube correctly. If the worker does not want to take measurements or does not care about the quality of the readings, then the readings may be inaccurate and the resulting data will not be useful to the company, and can be dangerous to other workers who depend on the gas level readings. Another disadvantage is that they require much more time to obtain readings than electronic-type monitoring devices.

Tube-type monitoring devices are a labor-intensive phosphine monitoring method. Glass tube-type monitoring involves drawing air through a glass tube containing particles of copper (II) sulfate, silver nitrate, o-phosphorus acid, and other chemical compounds (McCaslin). This is accomplished by breaking both tips off of the glass tube.

Then, based on the airflow direction arrow, one end of the glass tube is placed into an air pump and the other end of the glass tube is open to the air. An indicator chemical in the tube changes color with phosphine contact. The length of discolored indicator within the tube is a measure of the concentration of phosphine in the fumigated air space being sampled. The concentration can be read directly from a scale on the tube. Many tubes have two ranges. For each brand of detector, the concentrations and number of pump depressions vary. For most detectors, scale ranges and pump depressions are printed on the tube and each box of tubes has detail use instructions included.

Tube-type monitoring devices have been found, on average, to be about 80% to 90% accurate. These detectors are considered best for small-scale fumigations. Problems result, however, when using these tubes for larger fumigations. First, the large number of glass tubes required results in potentially high material variable costs, high labor costs, and lack of automation (Ducom and Bourges). Another possible disadvantage of glass tubes is grain contamination. When the glass tubes and tips are being used close to a storage facility, it is possible that some glass, or the entire tube, may fall into the grain mass. This is dangerous as glass fragments greatly affect the grading of grain and final product safety.

The major advantage with these devices is the low initial equipment cost. They do not require recalibration and are able to tolerate environmental condition changes without a drop in accuracy level. Another advantage is the ruggedness of the units. Tube pumps are generally made of steel or plastic and rubber materials that are able to withstand harsh treatment. The glass tubes are the only items that are not able to withstand harsh treatment.

Electronic-Type Monitoring Devices

The electronic-type monitoring devices have higher equipment costs than the tube-type devices but require far less labor time per reading and less worker skill. Small operations may not have the budget to cover the initial equipment cost of an electronic monitoring device. However, many grain elevator operators and scientists believe that the electronic devices are actually cheaper for a facility that fumigates often because of labor savings. Electronic monitors do not require additional equipment costs with each test, whereas tube-type monitors require a new tube for each test.

Most electronic monitors are highly automated and require little worker training to operate. By studying the facility for worker locations and known or potential leak points, a grain elevator operator can determine the number of samples needed and develop a monitoring plan. Electronic monitors are usually preferred in an emergency situation, because the instruments are generally hand-held devices with carrying straps or belt clips, and are compact and light.

One example of an electronic phosphine gas-monitoring device is the same as a carbon monoxide analyzer made by Herrmann Moritz Company in Portugal. The analyzer sensor was originally designed for carbon monoxide, but the sensitivity levels were adjusted and the scale was recalibrated to make the unit suitable for phosphine gas. This device pumps the air/phosphine mixture through an electro-chemical cell and the micro-electronic signal response is read on a digital meter. This instrument is more expensive than glass tubes, but it can provide continuous readings. It has also been adapted so that the sensor can be placed inside the stored grain facility. The sensor is connected to a digital meter through an electrical cable. The levels of phosphine gas are read remotely on the digital meter (Ducom and Bourges).

There are several other electronic-type monitoring devices available that work by methods similar to that of the carbon monoxide detector. Some available units in the United States are the ATI PortaSens II, Dräger MiniWarn, Dräger Pac III, and the Lumidor MicroMax. These devices work like the carbon-monoxide detector by pumping the gas level through an electro-chemical sensor that produces a reading on a digital meter display. The sensors in these devices can be changed to test for low or high gas readings. This is sometimes considered a disadvantage because changing sensors and waiting for the instrument to reboot takes time and the extra sensor(s) must be stored in a safe environment while not being used.

Some electronic monitoring devices are designed to read multiple gases, which may be a plus for some users, but a negative for others. Most electronic phosphine sampler users are only interested in phosphine levels. They often have no use for multiple sensors but may still have to pay extra for multiple sensors. However, these instruments can reduce equipment costs if users need to monitor multiple gases, such as phosphine, oxygen, and carbon monoxide. These are also much easier to use, as the user only has to carry one instrument. Two electronic-type devices that read multiple gases are the Dräger MiniWarn and the Lumidor MicroMax. They can handle up to four sensors, but can also be purchased with only the phosphine sensor.

Previous Research

There has not been much reported research involving phosphide fumigants. Many managers of stored products are still confused about parts of the gas generating process, residue formation, gas movement, and monitoring equipment. There is a need for increased understanding in all of these areas.

A 1993 research project evaluated electronic-type monitoring devices and identified a problem with the new electronic monitors (Winks, Waterford, and Russell). The sensors were found to detect carbon monoxide (CO) levels, causing phosphine level reading errors. Their research showed that when large amounts of carbon monoxide are in the air, the sensor produces high phosphine readings. The problem with this is that some grain masses can release carbon monoxide naturally when grain is stored over long periods of time (Winks, Waterford, and Russell). This could cause erroneous phosphine readings, leading to improper safety precautions.

The experiment was conducted in New South Wales, Australia using a Bedfont model EC80 phosphine gas monitor. The Bedfont sensor is sensitive to both phosphine and carbon monoxide gases. It was placed in a mass of stored grain that had been stored for over twelve months and had not been fumigated by phosphine gas. This monitor detected a level of 64 ppm of phosphine. A test was then conducted with a monitor that was only sensitive to phosphine (Dräger Hydrogen Phosphide 0.1); it found no level of phosphine gas. This experiment showed that some of the new electrochemical sensors have lower validity than originally thought (Whittle et al.).

Another study was conducted by Shlomo Navarro at the National Horticultural Crop Laboratory, Fresno, CA, in May of 1999. He compared three different electronic-type monitoring devices: ATI PortaSens I, Dräger MiniWarn, and the Bedfont. This study found that the Dräger MiniWarn was accurate when measuring low levels of phosphine, but as dosage levels increased, it became less accurate. He also found it difficult to separate the audible alarm deriving from the presence of phosphine in the air from the low battery alarm. The ATI PortaSens I responded quickly and he found it to be handy and field-friendly. However, the readings were fairly inaccurate. The Bedfont gave the most accurate results, when compared to the other two. Navarro recommended the ATI PortaSens I and the Bedfont over the Dräger MiniWarn (Navarro).

Another study was conducted by Lorillard Tobacco Co. in 1999 to measure gas levels around a fumigated structure. They used a gas chromatograph and a Dräger Pac III to determine gas levels. At the end of the study, they validated the Dräger Pac III accuracy, stating that the accuracy level of the Dräger Pac III was similar to that of the gas chromatograph (Thorn et al.).

With the exception of these experiments, there has been little research on monitoring equipment. There is a need for research on monitoring methods to identify cost-effective ways to ensure the safety of workers, bystanders, and residents.

Research Needed

It appears that aluminum/magnesium phosphide products may be regulated more tightly unless research shows that tighter restrictions are not needed. A large amount of the phosphine applied to a commodity is typically lost due to leaks in the storage facility. Some have claimed that the loss can be as much as 90% of the gas generated. The gas can then leak into the workspace and may filter into residences located close to the fumigated structure (Winks, Waterford, and Russell). Monitoring seems to be the only way to avoid more strict regulations on aluminum/magnesium phosphide. Firms need to be able to conduct monitoring accurately but without a large commitment of resources.

Conclusion

Phosphine gas is an important tool for the grain industry. There are many advantages that it provides to help maintain grain and bulk product quality. It is a widely used grain fumigant and to maintain it for the future, it must be better understood. There are proper procedures that must be followed when applying phosphine and monitoring dosage levels.

By conducting a cost feasibility study, the best phosphine gas-monitoring device(s) can be determined. Oklahoma grain elevator operators will have more information to evaluate when they select a phosphine gas-monitoring device. If phosphine users start monitoring their worker areas and documenting their results, it may help prevent future EPA restrictions on aluminum/magnesium phosphide.

CHAPTER III

MODEL

Chapters 1 and 2 discussed the importance of using a phosphine gas-monitoring device. They also indicated that there is minimal use of phosphine gas-monitoring devices used by Oklahoma grain elevator operators and few published studies to indicate the best device. Therefore, this cost-benefit analysis was conducted to help Oklahoma grain elevator operators determine the best monitoring device(s) for their elevators.

Some grain elevator operators and scientists believe cost/benefit analyses are controversial when applied to tube-type versus electronic-type phosphine monitoring devices because monitoring devices can also provide much better worker safety. Worker safety should be the most important factor in selecting a device because one cannot place value on human life. However, Jeffreys argues that cost-benefit analysis compares and helps to select the best device(s). This technique was first used with public infrastructure projects but has grown to include laws and regulations to protect health, safety, and environmental values (Moore).

Multiple Criteria Decision Making

People have faced multiple criteria decision-making problems (MCDM) since the beginning of time. We may pick the largest orange from a grocery rack or the highest salary offer from several companies. But, often we wonder if the largest orange is the best tasting or if the highest salary offer provides the best professional opportunity. Although the analysis of multiple criteria problems has been used frequently, adapting this type of analysis into a formal mathematical equation format is relatively new (Yu). However, it is the fastest growing area of decision analysis in the last twenty years (Yu).

Ballestero and Romero state that MCDM is widely acknowledged as a logically sound and well-corroborated decisional paradigm applied in many fields of study. This kind of decision-making problem is not dealt with in classical mathematics, and it is not purely a maximizing or minimizing problem (Tabucanon). Rather, it exists as a new brand of mathematical programming in the mixed objective and subjective modes (Tabucanon).

MCDM deals with multiple, conflicting objectives. For example, "minimize cost" and "maximize worker safety" are two main concerns of decision makers. If a decision maker is primarily concerned with one objective, then another important objective may be overlooked. A decision maker's job is to resolve the dilemma of simultaneously analyzing several conflicting objectives. MCDM problems have four common characteristics: multiple objectives or attributes; conflict among criteria (for example, a cheap phosphine gas-monitoring device could compromise worker safety); incommensurable units (different units of measurement for each attribute); and design selection (deals with the selection of the best one among a finite number of alternatives) (Yoon and Hwang).

An optimal solution in the classical sense is one that has a maximum value of all the objectives or attributes simultaneously. A MCDM process achieves an efficient or Pareto optimal solution. Such a solution is one in which no increase can be obtained in any of the objectives or attributes without causing a simultaneous decrease in at least one of the objectives (Tabucanon). A specific kind of MCDM, Multiple Attribute Decision Making (MADM) is used here.

Multiple Attribute Decision Making

To use MADM in selecting the best phosphine-monitoring device, the decision maker must first choose the important attributes. The important attributes may be objective traits or subjective traits. Although they cannot be separated from the decision maker's values and model of reality, they must be identified and measured without the decision maker's desires (Zeleny). These selected attributes must accurately represent the desired research objective or mission.

One way to ensure that the most important attributes or objective traits are selected is to derive the attributes hierarchically. Yoon and Hwang suggest making a list of attributes that is complete and exhaustive. These attributes should be restricted to performance attributes of the highest degree of importance. "These attributes are assumed to be measurable and can usually be expressed as a mathematical function f (x) of the decisional variables" (Romero, p.1). The number of attributes depends on the nature of the problem. The attributes selected for this study were: initial equipment cost, additional equipment-related cost, recalibration cost, labor cost, worker safety perception, ruggedness of device, user-friendliness of device, accuracy of device, and convenience of device.

Second, the decision maker must determine the objectives of the problem. At this point, the decision maker's desires enter the picture. Objectives are not attributes, but they derive from attributes. Objectives are minimized or maximized attributes (Romero). The objectives take the form: "Max f (x) or Min f (x), f (x) being the mathematical expression of the attributes" (Romero, p.1). For example, a car buyer considering two attributes, price and features, might seek to minimize price and maximize features. For this study, the objectives were to minimize initial equipment cost, additional equipment-related cost, recalibration cost, and labor cost, and to maximize ruggedness of device, convenience of device, user-friendliness of device, accuracy of device, and worker safety perception.

Third, the decision maker must determine the goals. Goals can be precise or they can be fuzzy and vague. A goal is defined in terms of both attributes and objectives. Goals are designed to limit and restrict the alternative set. "If the goals are quantifiable, then f (x) = b where b represents the target value. This contrasts with a constraint problem, in which the right-hand side must be satisfied to avoid infeasible solutions" (Romero, p.2). The goal here was to rank the devices to determine the best monitoring device.

After normalizing the attributes, they are put on a scale so that all fuzzy attributes are quantified. Here, the fuzzy attributes were four of the benefits (worker safety perception, ruggedness of device, convenience of device, and user-friendliness of device). A Likert-type range scale is used. This scale is an interval scale; comparisons of the intervals between statements are important but the ratios have no meaning (Yoon and Hwang) The Likert-type range scale used here is as follows:

Benefit attributes
  1.0 – very low
  2.0 – low
  3.0 – average
  4.0 – high
  5.0 – very high

After four benefit attributes were placed on this scale, there were still incommensurable units because the costs were in dollars, and the accuracy level benefit was a percentage. Step four in MADM problems is needed because of the incommensurable units that often result, like in this study.

Vector Normalization

The fourth step of the MADM process is to normalize the cost/benefit attributes, putting the units from the different attributes on the same scale. This is done to obtain a comparable scale among different attributes. Normalized ratings have dimensionless units and are found by first classifying attributes into three groups (Yoon and Hwang):

1) Benefit attributes: offer increasing monotonic utility – the greater the attribute value the more it is preferred (Yoon and Hwang).
2) Cost attributes: offer decreasing monotonic utility – the greater the attribute value the less it is preferred (Yoon and Hwang).
3) Nonmonotonic attributes: offer nonmonotonic utility – the maximum utility is located somewhere in the middle of an attribute range (Yoon and Hwang).

Nonmonotonic attributes were not used in this study. The second part in normalization is to select a normalization method. Vector normalization was chosen in this study because of its widespread use in selection problems.

Vector normalization is a procedure that divides the rating of each attribute by its norm to get normalized matrix elements, R_{ij}, such that:

$$(1) \qquad R_{ij} = X_{ij} / \sqrt{\ } (\sum_{i=1}^{m} X_{ij}^2),$$

where X_{ij} = the numerical outcome of the i^{th} alternative with respect to the j^{th} criterion (or attribute) and R_{ij} are the elements of the normalized decision matrix

Simple Additive Weighting

The fifth MADM process step is to weight the normalized decision matrix. There are many ways to do this. The Simple Additive Weighting (SAW) Method was chosen here because it is probably the most popular and most widely used MADM model (Yoon and Hwang). Elements of the decision matrix are assigned relative importance weights that become the coefficients of the variables. The weighted decision matrix then provides a total score for each alternative simply by multiplying the scale rating for each attribute value by the importance weight assigned to the attribute and then summing these products over all attributes using equation (2). The weights can be changed if costs/benefits are important at different levels for different grain elevator operators.

$$(2) \qquad W = (W_1, W_2, \ldots W_n), \ \sum_{j=1}^{n} W_j = 1$$

$$V = [W_1 * r_{11} \quad W_2 * r_{12} \ldots . W_n r_{1n}$$

$$W_1 * r_{m1} \quad W_2 * r_{m2} \ldots . W_n r_{mn}],$$

where W = 1 (weights placed on the attributes sum to one) and V = sum of all weights x normalized decision matrix numbers

The SAW method assumes that attributes are preferentially independent. This means that a contribution of an individual attribute to the total score is independent of other attribute values (Yoon and Hwang). Therefore, the decision maker's preference of one attribute is not influenced by the values of the other attributes (Yoon and Hwang).

Techniques for Order Preference by Similarity to Ideal Solution

Steps six through nine are developed through a type of MCDM theory called TOPSIS (Techniques for Order Preference by Similarity to Ideal Solution). An ideal solution is defined as a collection of ideal levels in all attributes considered. However, the ideal solution is usually unattainable or infeasible. "It is assumed that there is an ideal level of attributes and that the decision maker's utilities decrease monotonically when an alternative moves away from this ideal (utopia) point" (Yoon and Hwang). The ideal solution is composed of all best attribute values attainable and the negative-ideal solution is composed of all of the worst attribute values attainable. The best alternative chosen is the one that has the (weighted) minimum distance to the ideal solution and that is farthest from the negative-ideal solution (Yoon and Hwang, p.38).

Sometimes an alternative will have an attribute with a shorter distance to the ideal solution and another attribute that is closer to the negative-ideal solution than other alternatives (Yoon and Hwang). Then, it is difficult to justify the selection of one alternative over another. This is why the application of TOPSIS is necessary. "It considers the distances to both the ideal and negative-ideal solutions simultaneously by calculating the relative closeness to the ideal solution. TOPSIS assumes that each attribute takes either monotonically increasing or monotonically decreasing utility. That is, the larger the attribute outcome, the greater the preference for benefit attributes and the less the preference for cost attributes" (Yoon and Hwang, p.39). This method is simple and yields an indisputable preference order of solution.

Step six determines the ideal and negative-ideal solutions. The alternatives are examined and placed in order from largest to smallest and the largest and smallest alternatives for each attribute are recorded using equation (3).

$$A^* = \text{Max}\ \{V_1^*, V_2^* \ldots\ldots V_n^*\} \quad (3)$$

$$A- = \text{Min}\ \{V_1^-, V_2^- \ldots\ldots V_n^-\},$$

where A^* = the maximum alternative for each attribute and A^- = the minimum alternative for each attribute

Step seven calculates the separation measure from the ideal and negative-ideal solution using equation (4).

$$(4) \qquad S_{i*} = \sqrt{\sum_{j=1}^{n} (V_{ij} - V_j*)^2}$$

$$S_{i-} = \sqrt{\sum_{j=1}^{n} (V_{ij} - V_j-)^2}$$

$i = 1,2, \ldots m$

Step eight calculates the relative closeness to the ideal solution. In this step, the negative-ideal solution from step seven is divided by the sum of the negative-ideal and ideal solutions using equation (5).

(5) $C_{i*} = S_{i-}/(S_{i*} + S_{i-})$,

where $0 < C_{i*} < 1$, $i = 1,2,\ldots m$

Step nine ranks the C_{i*} preference order. The number closest to one is the best alternative and the number closest to zero is the least-best alternative. The alternatives are written in descending using equation (6).

(6) Alternative 1>Alternative 2>Alternative 3>Alternative 4

Summary of MADM

In summary, there are nine steps in creating a Multiple Attribute Decision Making model. The first three steps determine the attributes, objectives, and goals. The fourth step uses vector normalization to get the costs and benefits on the same scale. The fifth step is to weight each of the attributes. The last four steps are used (TOPSIS) to determine the ranking of the alternatives. All formulas used were obtained from Yoon and Hwang.

CHAPTER IV

PROCEDURES

Chapter four describes the procedures used in the analysis. Seven steps were necessary to complete the procedures: selecting monitoring devices, selecting elevators to monitor phosphine gas levels, determining phosphine monitoring device costs, determining device benefits, calculating device accuracy levels, determining if phosphine reading discrepancies exist, and calculating phosphine gas-monitoring device rankings with a MADM model.

Selecting Monitoring Devices

The first step was to select the monitoring devices that are available in the United States for Oklahoma grain elevators operators to purchase. The devices were selected by price and method – the price has to be low enough so that grain elevator operators can afford them and the method has to be easy enough to understand so that training does not take a significant amount of time (there are more devices available than the five chosen). The devices selected were divided into two categories: glass tube-type or electronic-type monitoring devices.

Glass Tube-Type Monitoring Devices

Glass tube-type devices are nearly identical in operation, accuracy, and price. Therefore, only one was selected because of the similarities between devices. The device selected was the Mine Safety Appliances (MSA) Kwik-Draw Pump (MSA Tube). The Kwik-Draw Pump was used with MSA Detector Tube Part Number 497101. Each tube measures two different scale ranges. The high scale measures from 0.1 ppm to 3.0 ppm phosphine gas in increments of 0.5 ppm and the low scale measures from 0.05 ppm to 1.5

ppm phosphine gas in increments of 0.02 ppm. The accuracy of the MSA Tube is stated to be up to ±15% for the low scale and up to ±25% for the high scale. The MSA Tube is able to read different gases and gas levels by selecting different tubes than the phosphine gas tubes that were used in this study.

To use the pump, the operator first checks the detector tube pump for leakage. Then, s/he breaks off the tube tips, and inserts the tube into the pump (the arrow on the tube must point toward the pump), squeezes the pump 10 or 20 times (10 times for the high scale and 20 times for the low scale), allowing full expansion of the pump bellows between each squeeze. The operator reads the gas concentration at the end of the color zone within two minutes after sampling. Each squeeze of the pump takes 45 seconds, so the sampling time would be 7.5 minutes or 15 minutes per gas sample (MSA Tube Instructions).

Electronic-Type Monitoring Devices

The other devices selected were electronic-type monitoring devices. These devices differ from one another in operation, primary function, accuracy, and price. The devices chosen were the Lumidor MicroMax 1-JP (Lumidor MicroMax), Dräger Pac III, Dräger MiniWarn, and ATI PortaSens II.

The Lumidor MicroMax is capable of measuring four different gasses (from among thirty available) at one time. It is only capable of reading phosphine gas between 0.0 ppm and 20.0 ppm. If a manager is interested in purchasing a device that will measure high concentrations as well, (for example, to measure gas levels inside a structure under fumigation) this device will not be an option. The Lumidor MicroMax has a NiCad battery that should be kept fully charged when not in use, so it is ready for a full days use at any time. When the device is fully charged, it can be operated for eight hours. It has an On/Off button and goes through a forty-five second self-check after being turned on. After this check, the device is ready for use. The accuracy level is ±5% of the actual value (Lumidor MicroMax Operator's Manual).

The Dräger Pac III is capable of measuring only one gas at a time. However, there are 25 sensors for other gasses that can be purchased and used individually in the Dräger Pac III. The Dräger Pac III also is capable of reading high range phosphine (0-500 or 0-1000 ppm). This device operates on a 9-Volt non-rechargeable battery that must be periodically replaced. The device has a large "On" button and two small "Off" buttons. The Dräger Pac III goes through a 10-12 second self-check similar to the Lumidor MicroMax, and is then ready for use. The accuracy level is ±2% of the actual value (Dräger Pac III Operator's Manual).

The Dräger MiniWarn is capable of measuring four gases at one time. It uses the same sensors as the Dräger Pac III; all sensors can be interchanged. This device has a NiCad battery that should be kept fully charged when not in use. When the device is fully charged, it can be used for nine to ten hours. The device has a large "On" button and two small "Off" buttons. The Dräger MiniWarn goes through a 10-12 second self-check similar to the other devices, then it is ready for use. The accuracy level is ±2% of the actual value (Dräger MiniWarn Operator's Manual).

The ATI PortaSens II is capable of measuring only one gas at a time. However, there are 33 optional sensors that can be purchased and used in the ATI PortaSens II. The ATI PortaSens II is also capable of reading high range phosphine (0-200 or 200-2000 ppm) with other sensors. This device has a NiCad battery with a replaceable dry cell battery back up. The NiCad battery should be kept fully charged when not in use. When the device is fully charged, it can be used six hours. The dry cell battery back up has a 75-hour life. The device has an On/Off button and goes through a self-check after being turned on. After this, the device is ready for use. The accuracy level is ±5% of the actual value (ATI PortaSens II Operation and Maintenance Manual).

Determining Monitoring Device Costs

Four categories of monitoring device costs were considered: initial equipment costs, recalibration costs, additional equipment-related costs, and labor costs. The initial equipment costs were determined by comparing purchase prices from different companies. The costs used were the lowest costs supplied by any company for the selected device.

Recalibration costs were only applicable for the electronic-type devices.

The Net Present Value (NPV) of the combined initial equipment costs (for the electronic devices) and the recurring recalibration costs was computed for each device using equation (7).

$$\text{Initial Cost} + \text{Recalibration Cost}\,(1 - i) + \text{Recalibration Cost}\,(1 - i)^2 + \text{Recalibration Cost}\,(1 - i)^3 + \text{Recalibration Cost}\,(1 - i)^4], \tag{7}$$

where i = interest rate, the cost of capital to the firm.

This value was converted to an annual amortized cost for each device by dividing it by a Present Value Interest Factor Annuity (PVIFA), where:

$$\text{PVIFA} = [1 - (1 / (1 + i)^n] / I, \tag{8}$$

where n = life of the device, in years.

Dividing the result from (7) by PVIFA expresses the costs for each device in the form of an annual payment as if the grain elevator operator borrowed money to cover all five years of expense associated with the device and paid it back in n equal installments.

The additional equipment-related costs were only applicable for the tube-type devices. The replaceable back-up battery of the ATI PortaSens II was considered a negligible cost. These were assumed to be the same for each year. When using a tube-type device, new tubes must be purchased to take additional readings and each tube can be used only once.

The labor costs were calculated by determining the average wage and benefit rate provided by the grain elevator operators. Since labor costs likely vary by facility, though, the effect of alternative labor costs was considered in several scenarios.

Determining Benefits on Selected Monitoring Devices

Five monitoring device benefits were considered: convenience, ruggedness, user-friendliness, worker safety perception, and accuracy. These benefits are subjective and were valued differently by different users. Convenience, ruggedness, user-friendliness, and worker safety perception were measured using surveys given to 28 Oklahoma grain elevator operators. These 28 grain elevator operators were trained to use all five monitoring devices and were then given a survey asking their opinions. Accuracy was measured by regular laboratory testing during the 31-day fumigation study. Accuracy for the tube-type monitoring device was also calculated by giving the 28 grain elevator operators five tubes that were subjected to phosphine gas to evaluate reading discrepancies.

A copy of the survey with results is provided in Appendix B.1 and the Institutional Review Board (IRB) form is provided in Appendix D.1. The surveys requested that grain elevator operators rate the devices according to these benefits, and also asked them other questions about phosphine gas-monitoring devices.

The data were used to calculate the mean, high, low, mode, and standard deviation. A test was then used to test differences between each of the devices of the survey questions. The test compares populations with unequal variances. The test is from Dixon and Massey, p. 126.

$$z = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{((\sigma_1^2 \div \mathrm{N}_1) + (\sigma_2^2 \div \mathrm{N}_2))}} \tag{9}$$

The null hypothesis is that the mean answer to the survey question is the same for two different devices. The alternative hypothesis is that the means are not the same. When z is larger than 2.0 (from a t distribution with 54 degrees of freedom), the difference between the two devices is significant at the 5% (0.05) level (Dixon and Massey). Therefore, if $z < 2.0$ then fail to reject H_o and if $z > 2.0$ then reject H_o. If the null hypothesis is rejected, there is a statistical difference in the means.

Convenience is a benefit that deals with how much attention is required before the device is ready for use. The electronic-type monitoring devices require batteries, chargers, and/or plug-ins. The tube-type monitoring devices require tubes that must be available for use and must be within the use date (not expired) when needed. A cost factor was placed on the inconvenience associated with these requirements. The MSA Tube uses one tube for each phosphine gas reading. The tubes take four to six days to ship from the supplier after the order is placed. The Lumidor MicroMax, Dräger MiniWarn, and ATI PortaSens II must be charged four to five hours before they can be used. The Lumidor MicroMax and the Dräger MiniWarn will not operate while on the charger. The ATI PortaSens II will operate while on the charger but can only be moved the length of the charger cord (four feet) from the plug-in without an extension cord. The Dräger Pac III operates with a 9-Volt battery. The battery can be changed out anytime for a new battery; a new battery is ~$2. The 28 grain elevator operators had different opinions about the relative convenience of these devices.

Ruggedness is a benefit that deals with how well each device can withstand day-to-day use. Each device is unique; some of them have protective covers while others are made of more breakable materials. The MSA Tube is plastic but the tubes are made of glass. The Lumidor MicroMax has a rubber cover surrounding the device that keeps it protected, but it is heavy and sometimes does not stay attached by the belt loop attachment, and falls. The Dräger Pac III is lightweight and is small enough to be carried in a pocket or on a belt loop, but it does not have a protective cover. The Dräger MiniWarn is top heavy and does not have a protective cover. The ATI PortaSens II is large and has a sampling wand attachment that is 10 inches long and bulky. Each user was asked to express an opinion on ruggedness of each instrument.

User-friendliness is a benefit dealing with the mode of operation of each of the devices. The operation of some of the devices may be confusing to grain elevator operators. This benefit was also based on how easy the operator's manual is to read and which devices seemed intimidating to the grain elevator operators (multiple languages, etc.). The tube-type monitoring devices are owned by most of the grain elevator operators but the electronic-type monitoring devices are relatively new to operators.

Worker safety perception is a benefit dealing with how safe the workers are if they are using the monitoring devices. The electronic-type monitoring devices read continuously, can be attached to the grain elevator operators clothing, and issue a noise if the gas levels are unsafe. They read a new gas level every second whereas the tube-type monitoring devices take a reading only during one time period. Also, obtaining a reading with the tube-type monitoring devices takes much longer (7.5 to 15 minutes/reading). This means that workers can be in an unsafe environment without knowing it for several minutes.

Accuracy Levels of Electronic-Type Monitoring Devices

Accuracy levels of the devices were tested to determine whether or not accuracy levels changed over time when being used during fumigation. The four electronic devices were factory calibrated immediately prior to the study. Then, all five monitoring devices were used for 31 days to monitor phosphine gas levels in Oklahoma grain elevators that were under fumigation. Phosphine gas was monitored at six concrete storage facilities, three steel storage facilities, and one flat storage facility. The grain elevators that were chosen were all older facilities that have been using phosphine gas to fumigate for many years.

The accuracy levels were checked sixteen times during the 31 day monitoring study using a known calibration-gas sample, or CAL-gas. The Lumidor MicroMax, Dräger Pac III, and Dräger MiniWarn were placed in 3,778.2 ml glass jars and sealed. The devices were then placed under a laboratory hood. Ten ml of air was taken out with a syringe and 10 ml of phosphine gas at 189 ppm in Nitrogen of phosphine gas was then syringed back into the jar. The 10 ml is equivalent to 0.5 ppm.

After the addition of the gas, gas readings were taken every fifteen seconds. Readings were taken until the monitor's reading of the gas level stabilized. A reading was considered stabilized after showing the same concentration for one minute without change. Accuracy was computed by dividing the reading by 0.5 ppm and then multiplying by 100 to give percent accuracy.

The time to stabilization was also recorded. This is important so that workers know how long that they can be subjected to a high level before they get the proper reading on the device. This was an ideal situation because most locations have gas readings that change whereas in the OSU Entomology Lab situation the gas level is constant. The ATI PortaSens II is larger than the glass jar so the wand was inserted into the jar septum after 10 ml of phosphine gas was syringed in and readings were taken.

The tube-type monitoring devices were also checked for accuracy in this study. The same 3,778.2 ml glass jar was sealed and 10 ml of air was syringed out. Then, 10 ml of phosphine gas was syringed in and a tube was inserted into the jar septum and readings were taken. The tube was read and accuracy was computed by dividing the reading by 0.5 ppm and then multiplying by 100 to give percent accuracy.

Reading Discrepancies of Tube-Type Monitoring Devices

Although the electronic-type devices provide a digital display of the gas reading, the tube-type monitors are read like a thermometer. Thus, data collectors might not read the numbers consistently. In this study, the same 28 Oklahoma grain elevator operators that learned how to use the devices and fill out the surveys were given five tubes that had been exposed to different lab-determined levels of phosphine gas. They were asked to record their readings of the gas level.

An empty glass jar was sealed and 10 ml of air was syringed out. Then, 4 ml of phosphine gas was syringed in and a tube was inserted into the jar septum and readings were taken. Then, another empty glass jar was sealed and the process was repeated with 8 ml, 4 ml, again with 8 ml, and 30 ml of gas added. The tubes were then attached to white paper so that the concentrations could be easily read. Then, grain elevator operators were given the samples to determine the gas concentration level. The true gas concentrations are shown in Table I.

TABLE I

CONCENTRATION OF FIVE MSA TUBES

Sample Number	Concentration
Sample 1	0.2 ppm
Sample 2	0.4 ppm
Sample 3	0.2 ppm
Sample 4	0.4 ppm
Sample 5	1.5 ppm

Model

All costs and benefits were put in a Multiple Criteria Decision Making model and the best monitoring device was chosen. The first step was to create a table with costs ($ format) and benefits (1-10 format). See Appendix C.1 for a copy of Table XL. The second step was to normalize, which means that the costs and benefits were put on the same scale. See Appendix C.2 for a copy of Table XLI. This table used equation (1):

For example, the normalized number for the MSA Tube labor cost was calculated by dividing the MSA labor cost from Table XL by the square root of the squared sum of labor costs of each device. If labor costs for four monitoring devices are 10, 15, 7, and

25, then the normalized decision matrix element for the MSA Tube equals $10/(10^2+15^2+7^2+25^2)^{0.5} = 0.3164$.

The third step was to weight the normalized decision matrix. The weighting process was necessary because grain elevator operators may think that different attributes are important. The weighting method chosen was Simple Additive Weighting (SAW). This table was a matrix and each entry was the number from the normalized decision matrix (from Table XLI in Appendix C.2) multiplied by the weight for that attribute. The weights were changed for different scenarios so that grain elevator operators can pick the best weighting for them. See Appendix C.3 for a copy of Table XLII. Equation (2) was used in this step.

For example, the weighted normalized decision matrix for labor cost for the MSA Tube was calculated by multiplying the normalized decision matrix element for labor cost by the weight assigned to initial equipment cost for any specific scenario. If 0.3164 is the normalized decision matrix number for the MSA Tube and the weight is 4% then the weighted matrix element is 0.3164 * 0.04 = 0.0127.

The fourth step was to determine the ideal and negative-ideal solutions. The ideal solution was the one with the lowest values for the cost attributes and the highest values for the benefit attributes. The negative-ideal solution was the one with the highest values for the cost attributes and the lowest values for the benefit attributes using equation (3). See Appendix C.4. for a copy of Table XLIII.

For a cost example, if the normalized labor costs from step three are 0.0127, 0.0190, 0.0089, and 0.0316, then the ideal solution is 0.0089 and the negative-ideal solution is 0.0316. For a benefit example, if the normalized worker safety perception benefits are 0.1081, 0.1946, 0.1513, and 0.0216, then the ideal solution is 0.1946 and the negative-ideal solution is 0.0216.

The fifth step was to determine the separation measure from the ideal and negative-ideal solutions using equation (4). See Appendix C.5 for a copy of XLIV.

For example, the separation measure of the ideal solution for the i^{th} device was calculated by subtracting the ideal solution for the j^{th} attribute from the weighted normalized decision matrix element for the i^{th} device and j^{th} attribute. These differences were squared and summed over all attributes. The square root of their result was the separation measure of the i^{th} device from the ideal solution. If the weighted normalized decision matrix numbers for the MSA Tube are 0.0127, 0.0233, 0.1055, 0.0366, 0.0429, 0.0458, and 0.1081 and the ideal solutions are 0.0316, 0.0233, 0.1677, 0.1098, 0.0773, and 0.0458, then the formula to find the ideal solution for the MSA Tube is equal to $[(0.0127-0.0316)^2+(0.0233-0.0233)^2+(0.1055-0.1677)^2+(0.0366-0.1098)^2+(0.0429-0.0773)^2+(0.0458-0.0458)^2+(0.1081-0.1946)^2)^{1/2}=0.1351$. The ideal separation measure for the MSA Tube is 0.1351.

The sixth step was to determine the relative closeness to the ideal solution. The separation measure from the negative-ideal solution was divided by the separation measure from the negative-ideal solution, plus the separation measure from the ideal solution as in equation (5). A copy is in Appendix C.6 in Table XLV.

For example, if the MSA Tube has a separation measure from ideal solution of 0.1351 and the separation measure from the negative-ideal solution is 0.1149, then the relative closeness to the ideal solution is $0.1109/(0.1109+0.1351) = 0.4508$.

The seventh step was to rank the devices. Table XLV was used to figure Table XLVI. The data from Table XLV in Appendix C.6 placed the devices in order from the largest relative closeness measure to the smallest relative closeness measure. The best device was the one that has a relative closeness to the ideal solution closest to one. A copy of Table XLVI is in Appendix C.7.

For example, if the devices have the following relative closeness to ideal solutions of 0.4508 (MSA Tube), 0.7196 (Lumidor), 0.7055 (Dräger), and 0.2289 (ATI) then the top device is the Lumidor, then Dräger, MSA Tube, and ATI.

Here, the MADM model was used to rank the devices under several criteria scenarios using alternative weighting schemes. The weighting schemes used were as follows: 80% cost and 20% benefit, 35% cost and 65% benefit, 50% cost and 50% benefit, 20% cost and 80% benefit, 65% cost and 35% benefit, 100% cost and 0% benefit, and 0% cost and 100% benefit. The fumigation length scenarios were one day, six days, 12 days, 24 days, and 30 days. The labor cost scenarios was \$6/hour, \$8/hour, \$12/hour, \$15/hour, and \$30/hour.

Summary

The procedures used in the analysis were time consuming and required data collection. Seven different steps were used to select monitoring devices, selecting elevators to monitor phosphine gas levels, determining costs, determining benefits, calculating accuracy levels, determining if reading discrepancies exist, and calculating rankings. Some of these steps were subjective and required many opinions. This was difficult because the opinions had to be from operators who are skilled in all of the monitoring devices. They must also be operators who are interested in monitoring.

CHAPTER V

RESULTS

Chapter five explains the results obtained from following the procedures discussed in the previous chapter. This chapter lists the cost calculation, the survey results used to determine benefits of each of the devices and the qualitative "costs", and the results of the tests for accuracy. Then, it discusses the results obtained from the model based on alternative weighting schemes for costs and benefits, fumigation length, and labor costs.

Costs

Initial equipment costs are listed in Table II.

TABLE II

LOWEST QUOTE ON INITIAL EQUIPMENT COSTS

Device	Company	Price ($)
MSA Tube	KC Supply	215
Dräger MiniWarn	Industrial Fumigant, Inc.	1,810
Dräger Pac III	Industrial Fumigant, Inc.	779
ATI PortaSens II	Analytical Technologies, Inc.	1,500
Lumidor MicroMax	Industrial Fumigant, Inc.	1,482

Recalibration costs are listed in Table III.

TABLE III

LOWEST QUOTE ON RECALIBRATION COSTS

(ELECTRONIC-TYPE MONITORING DEVICES ONLY)

Device	Company	Price
Dräger MiniWarn	Industrial Fumigant, Inc.	$50
Dräger Pac III	Industrial Fumigant, Inc.	$50
ATI PortaSens II	Analytical Technologies, Inc.	$150
Lumidor MicroMax	Industrial Fumigant, Inc.	$50

Industrial Fumigant, Inc. charges $50 to recalibrate any number of devices the grain elevator operator would send for recalibration at any one time. The amortized (annual) initial equipment and recalibration costs are shown in Table IV. It was assumed that grain elevator operators fumigate less than three months each year and would not need to have the instrument recalibrated more than once each year.

TABLE IV

YEARLY INITIAL EQUIPMENT COST AND RECALIBRATION COST

(ASSUMING FIVE-YEAR EQUIPMENT LIFE AND 10% INTEREST RATE)

Device	Equipment Cost ($)/year (for five years)
MSA Tube	56.72
Dräger MiniWarn	518.40
Dräger Pac III	246.32
ATI PortaSens II	518.17
Lumidor MicroMax	431.77

The additional equipment-related costs were only applicable for the tube-type monitoring devices. The MSA Tubes that measure from 0.1-3.0 ppm and 0.05-1.5 ppm were $40 per box of ten tubes. These were purchased from KC Supply. Other brands of tubes may cost slightly more or less. The quotes from other companies for MSA Tubes ranged from $40 to $70 per box of 10.

The labor costs used in the model were $6/hour, $8/hour, $12/hour, $15/hour, and $30/hour. The average wage rate given by the 28 grain elevator operators was $8/hour. Also, several values were considered for number of fumigation monitoring days: 1, 6, 12, 24, and 30 day/s.

Benefits

When asked the question "This device is easy to set up/turn on for use", to ask about convenience, grain elevator operators responded with the results shown in Table V.

TABLE V

SURVEY RESULTS

CONVENIENCE

Device	Mean	High	Low	Mode	Standard Deviation
MSA Tube	7.9	10	1	10	2.63
Dräger MiniWarn	7.1	10	3	8	2.29
Dräger Pac III	7.0	10	2	8	2.52
ATI PortaSens II	6.9	10	3	8	2.18
Lumidor MicroMax	6.8	10	1	8	2.77

Number of Observations = 28

Convenience means and modes were all similar when comparing the monitoring devices.

The grain elevator operators were also asked an additional question regarding convenience. They were asked if they think that the electronic monitoring devices are more convenient than the tube-type monitoring device. Their average response was 8.9 so they strongly felt that the electronic-type monitoring devices were more convenient than the tube-type monitoring device. This question indicates that there were changes in survey responses when asked a question in a different format.

When asked the question "This devices seems to be rugged enough that it could last for years to come without replacement" to ask about ruggedness, grain elevator operators responded with the results shown in Table VI.

TABLE VI

SURVEY RESULTS

RUGGEDNESS

Device	Mean	High	Low	Mode	Standard Deviation
MSA Tube	6.0	10	1	8	3.11
Dräger MiniWarn	6.4	10	2	7	2.28
Dräger Pac III	6.3	10	2	7	2.55
ATI PortaSens II	5.9	10	2	5	2.37
Lumidor MicroMax	6.1	10	1	5	2.64

Number of Observations = 28

Ruggedness means were similar for all electronic-type and tube-type monitoring devices.

When asked the question "I believe that this device is user-friendly" to ask about user-friendliness, grain elevator operators responded with the results shown in Table VII.

TABLE VII

SURVEY RESULTS

USER FRIENDLINESS

Device	Mean	High	Low	Mode	Standard Deviation
MSA Tube	6.1	10	1	5	3.04
Dräger MiniWarn	6.6	10	1	5	2.47
Dräger Pac III	7.1	10	2	10	2.61
ATI PortaSens II	5.7	10	2	5	2.40
Lumidor MicroMax	6.0	10	1	10	2.98

Number of Observations = 28

The MSA Tube mean was in the middle of the electronic-type monitoring devices for user-friendliness. The modes were unique in that the Dräger Pac III and the Lumidor MicroMax were 10 and all other monitoring devices were five.

When asked the question "I would feel safe working near a fumigated area if I had this device with me" to ask about worker safety perception, grain elevator operators responded with the results shown in Table VIII.

TABLE VIII

SURVEY RESULTS

WORKER SAFETY PERCEPTION

Device	Mean	High	Low	Mode	Standard Deviation
MSA Tube	5.3*	10	1	5	2.90
Dräger MiniWarn	7.8	10	1	9	2.25
Dräger Pac III	8.2	10	1	10	2.51
ATI PortaSens II	7.5	10	1	8	2.30
Lumidor MicroMax	7.9	10	1	10	2.31

Number of Observations = 28

* Indicates that the MSA Tube was different from all other devices at the 5% level

Worker safety perception means were similar for all electronic-type monitoring devices but were almost three points lower for the MSA Tube. There was a significant pairwise difference when the MSA Tube was compared against each of the electronic-type monitoring devices. This is the only benefit in which there was a significant difference in the means. Therefore, there is not a statistical difference in the mean responses for convenience, ruggedness, and user-friendliness.

Other Survey Results

There were other questions asked in the survey regarding the importance of safety to the grain elevator operators, whether operators think the device will interfere with their daily tasks, whether they prefer an electronic-type monitoring device or a tube-type monitoring device, if they think the devices are intimidating, if they think the training

When asked the question "I would feel safe working near a fumigated area if I had this device with me" to ask about worker safety perception, grain elevator operators responded with the results shown in Table VIII.

TABLE VIII

SURVEY RESULTS

WORKER SAFETY PERCEPTION

Device	Mean	High	Low	Mode	Standard Deviation
MSA Tube	5.3*	10	1	5	2.90
Dräger MiniWarn	7.8	10	1	9	2.25
Dräger Pac III	8.2	10	1	10	2.51
ATI PortaSens II	7.5	10	1	8	2.30
Lumidor MicroMax	7.9	10	1	10	2.31

Number of Observations = 28

* Indicates that the MSA Tube was different from all other devices at the 5% level

Worker safety perception means were similar for all electronic-type monitoring devices but were almost three points lower for the MSA Tube. There was a significant pairwise difference when the MSA Tube was compared against each of the electronic-type monitoring devices. This is the only benefit in which there was a significant difference in the means. Therefore, there is not a statistical difference in the mean responses for convenience, ruggedness, and user-friendliness.

Other Survey Results

There were other questions asked in the survey regarding the importance of safety to the grain elevator operators, whether operators think the device will interfere with their daily tasks, whether they prefer an electronic-type monitoring device or a tube-type monitoring device, if they think the devices are intimidating, if they think the training time to learn how to use the devices is too lengthy or too brief, and how they rank the devices.

The grain elevator operators believe that safety is very important. They rated the question "I feel that safety is the most important part of my job" with a mean of 9.3 (strongly agree).

Grain elevator operators wanted an electronic-type monitoring device. They rated the question "I think my facility should invest in some type of electronic-type monitoring device" with a mean of 9.3 (strongly agree).

Grain elevator operators were asked, "The operation of this device would interfere with my daily tasks." They were relatively indifferent on this issue. The MSA Tube had a mean of 6.7, ATI PortaSens II with 4.9, Dräger MiniWarn with 4.4, Dräger Pac III with 4.4, and Lumidor MicroMax with 5.5. There was a significant difference at the 5% level when comparing the electronic-type devices against the MSA Tube. There was also a significant difference at the 5% level when comparing the Lumidor MicroMax against the Dräger MiniWarn and when comparing the Lumidor MicroMax against the Dräger Pac III.

The devices all have a different method of operation and operators were asked, "Do you think the devices are intimidating". The mean response was 3.8 for the MSA Tube, 4.1 for the ATI PortaSens II, 4.3 for the Dräger MiniWarn, 4.4 for the Dräger Pac III, and 4.7 for the Dräger Pac III.

When asked, "Do you think the training time for the devices is too long?" the operators disagreed. The mean was 3.4 for the MSA Tube, 4.0 for the ATI PortaSens II, 3.8 for the Dräger MiniWarn, 3.5 for the Dräger Pac III, and 4.4 on the Lumidor MicroMax.

Another question asked "Could you remember how to use each device in one month?" The following responses showed that they think they can remember how to use the device after the initial training lesson. The mean was 7.4 for the MSA Tube, 6.8 for the ATI PortaSens II, 7.1 for the Dräger MiniWarn, 7.5 for the Dräger Pac III, and 6.8 for the Lumidor MicroMax. In the last three questions, there were no significant differences when comparing the mean of two populations with unequal variances.

The last question on the survey was the ranking of the devices by operator preference. The ranking shown in Table IX is the most representative of the results.

TABLE IX

PREFERENCE RANKING OF DEVICES BYOKLAHOMA GRAIN ELEVATOR OPERATORS

Device	Mean	Standard Deviation	Rank
Dräger Pac III	1.667*	0.96	1
Dräger MiniWarn	2.852*	1.08	2
Lumidor MicroMax	3.259*	1.15	3
ATI PortaSens II	3.444*	1.16	4
MSA Tube	4.333*	1.42	5

Number of Observations = 28

* Indicates significant difference of 5%

The means were placed in order from smallest to largest to determine rank. There was a significant difference to the 5% level when devices were compared against each other except when the ATI PortaSens II was compared against the Lumidor MicroMax. In that situation, there was not a statistical difference.

Accuracy of Electronic-Type Monitoring Devices

The Dräger MiniWarn's sensor reads from 0.0-1.0 ppm. The sensor reads in hundredths. Figure 2 shows the accuracy levels.

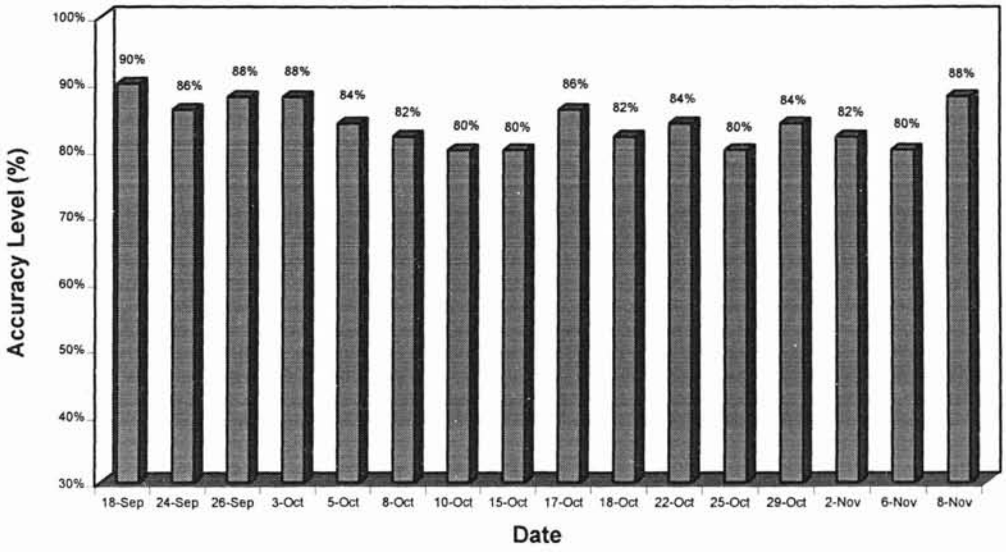


Figure 2. Dräger MiniWarn Accuracy Levels During 31-Day Study

The accuracy levels ranged from 80% to 90%. The accuracy level was relatively stable throughout the study. The accuracy level did not, however, get above 90% at any time. The 80% accuracy levels resulted when the phosphine level was 0.5 ppm and the device read 0.4 ppm.

The Dräger Pac III's sensor reads from 0.0-20.0 ppm. The sensor reads in hundredths. Figure 3 shows the accuracy levels.

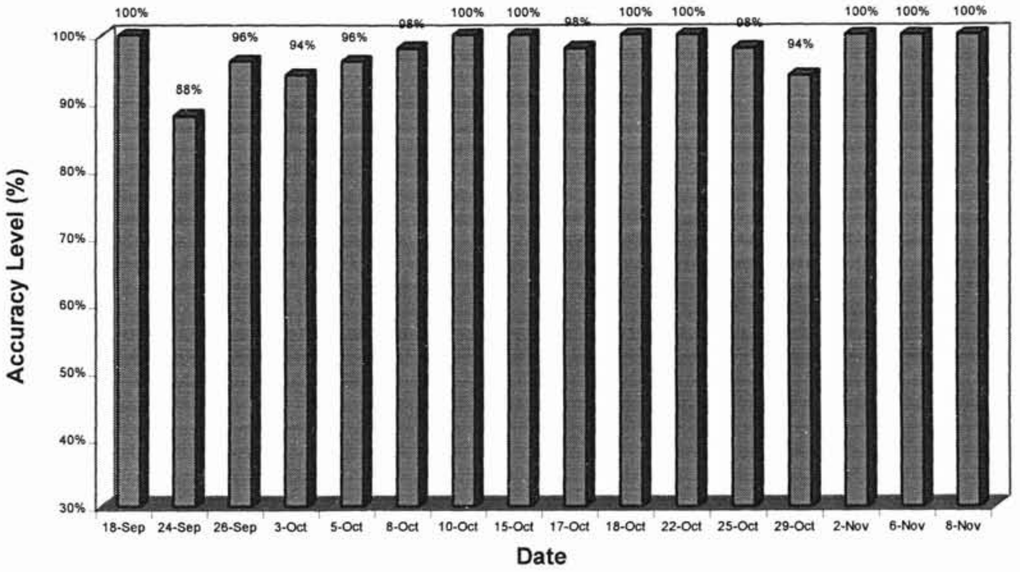


Figure 3. Dräger Pac III Accuracy Levels During 31-Day Study

The accuracy levels ranged from 88% to 100%. The accuracy levels were relatively stable throughout the study. The levels were high. The 88% accuracy levels resulted when the phosphine level was 0.5 ppm and the device was reading 0.44 ppm.

The ATI PortaSens II uses two sensors to measure worker safety perception. The low range sensor reads from 0.0-2000 ppb or 0.0-2.0 ppm. This sensor reads in hundredths. Figure 4 shows the accuracy levels.

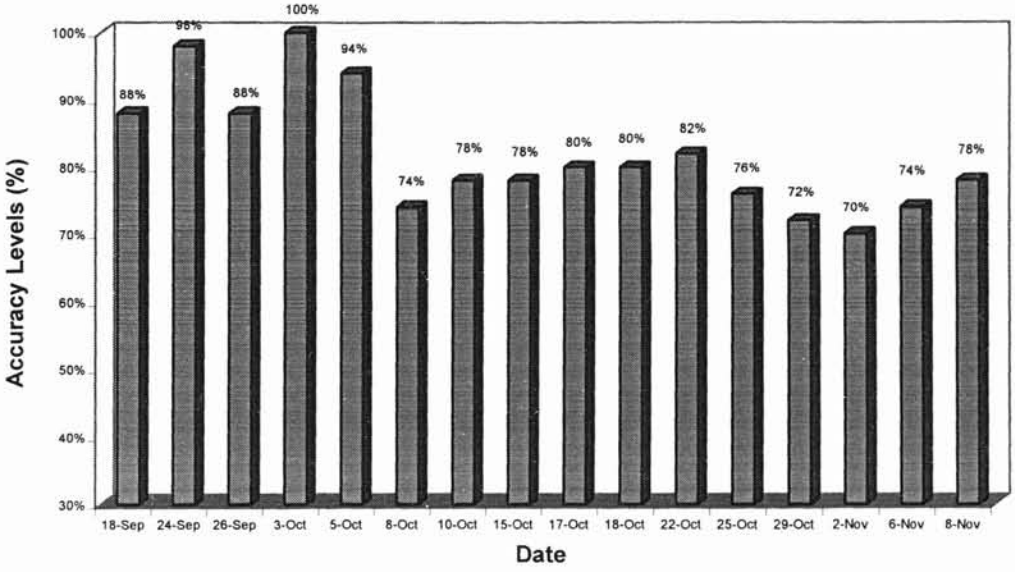


Figure 4. ATI PortaSens II Low-Range Accuracy Levels During 31-Day Study

The accuracy levels ranged from 70% to 100%. The accuracy level decreased as time progressed. The 70% accuracy levels resulted when the phosphine level was 0.5 ppm and the device read 0.35 ppm.

The ATI PortaSens II high range sensor reads from 0-20 ppm. This sensor reads in tenths. Figure 5 shows the accuracy levels.

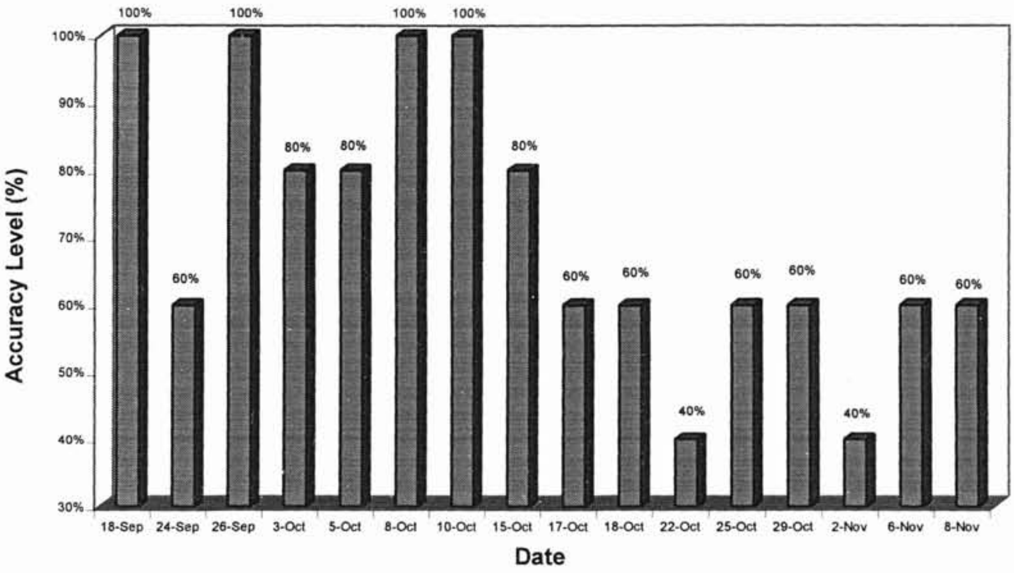


Figure 5. ATI PortaSens II High-Range Accuracy Levels During 31-Day Study

The accuracy levels ranged from 40% to 100%. The accuracy level decreased as time progressed. The levels for this device may have been low because of the sensors ability to only read in tenths. The 40% accuracy levels resulted when the phosphine level was 0.5 ppm and the device read 0.2 ppm.

The Lumidor MicroMax's sensor reads from 0.0-20.0 ppm. The sensor reads in tenths. Figure 6 shows the accuracy levels.

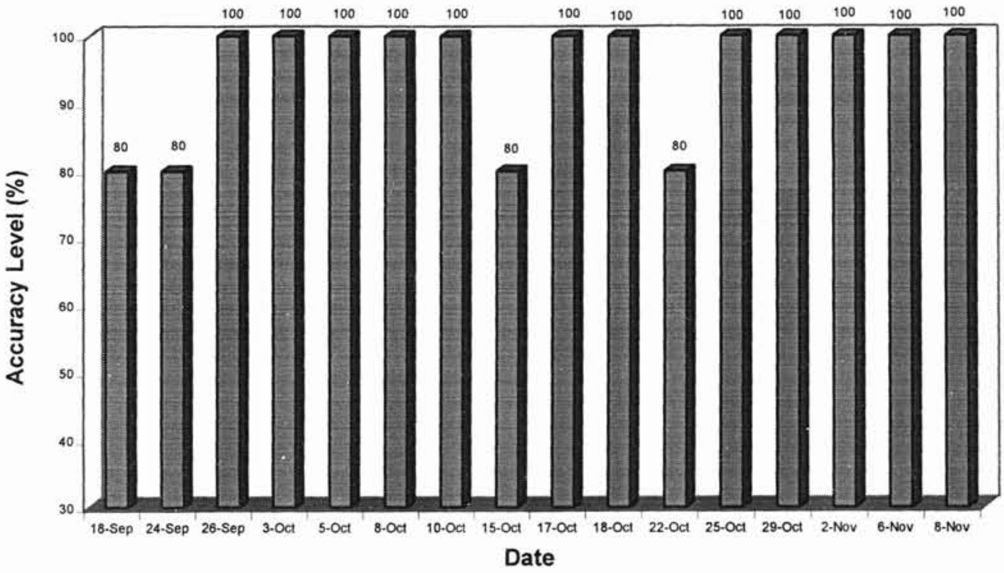


Figure 6. Lumidor MicroMax Accuracy Levels During 31-Day Study

The accuracy levels ranged from 80% to 100%. The accuracy level was relatively stable throughout the study. The 80% accuracy levels resulted when the phosphine level was 0.5 ppm and the device read 0.4 ppm or 0.6 ppm. The reason that the only accuracy levels were only 80% or100% was because the MicroMax only reads in tenths. This is the only device that could read above 0.5-ppm concentration.

The accuracy level at the end of the study for all devices is shown in Figure 7. This shows which devices stayed in calibration the best throughout the study.

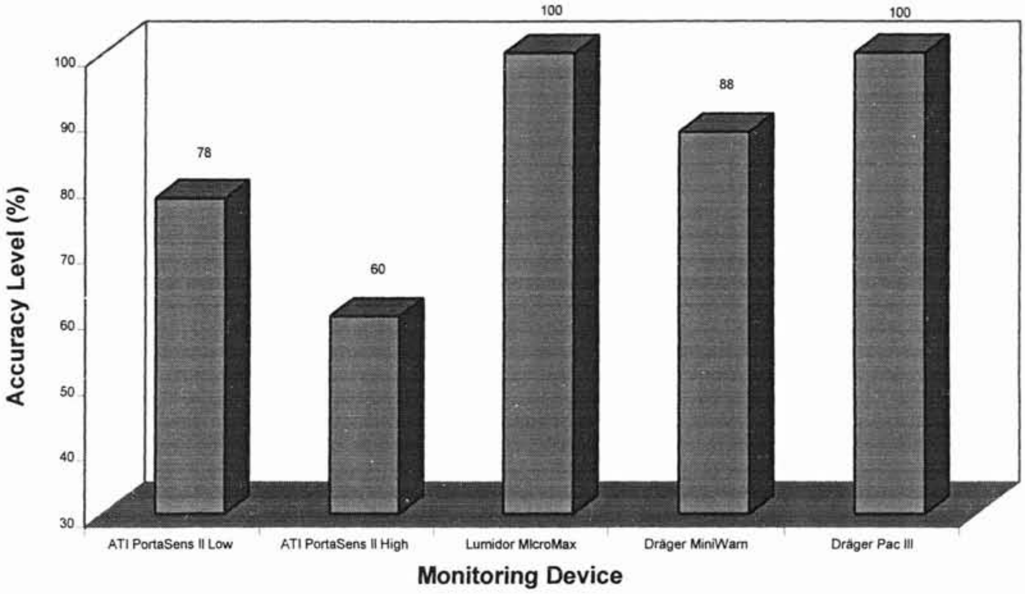


Figure 7. Accuracy Level of All Devices On Day 31

The ATI PortaSens II had the lowest accuracy with 60% and 78% for the high and low sensors, respectively. The Dräger MiniWarn was third with 88% accuracy and the Lumidor MicroMax and Dräger Pac III both had 100% accuracy at the end of the study.

The average accuracy level for all devices is shown in Figure 8. This shows which devices were the most accurate throughout the study.

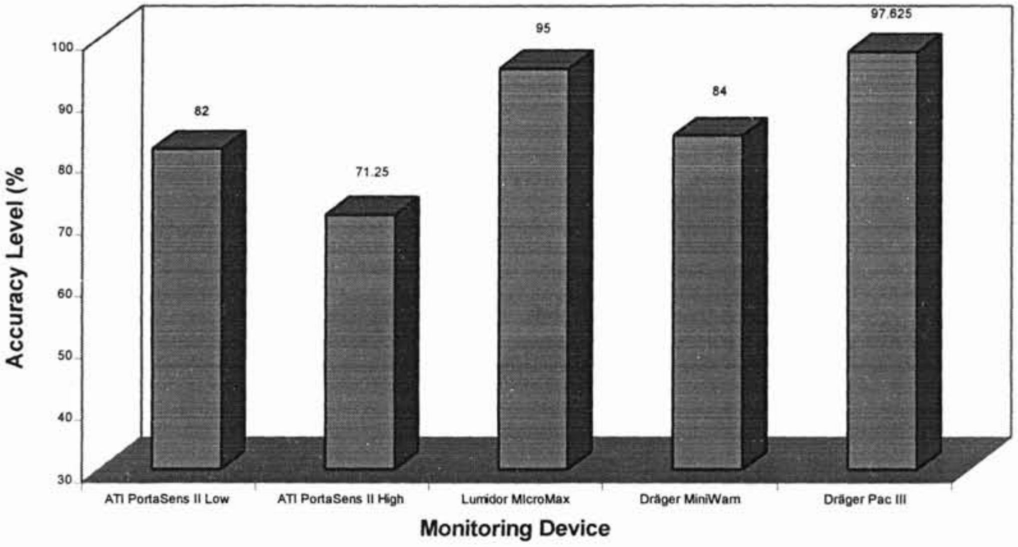


Figure 8. Average Accuracy Level of All Devices During 31-Day Study

The ATI PortaSens II had the lowest accuracy with 71.25% and 82% for the high and low sensors respectively. The Dräger MiniWarn was third with 84% accuracy. The Lumidor MicroMax was second with 95% accuracy and the Dräger Pac III was first with 97.63% accuracy. These numbers were used as accuracy levels in the model for the electronic-type monitoring devices. The ATI low and high sensors were averaged together and that number, 76.63%, was used in the model.

Each device took a different amount of time to stabilize. Figure 9 shows how much time each of the devices take to stabilize.

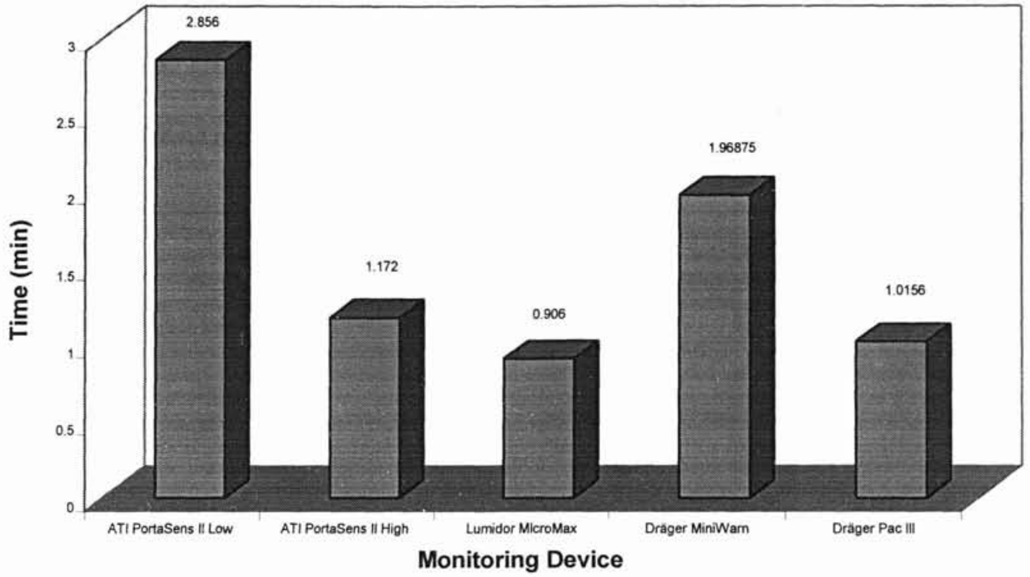


Figure 9. Time for Each Monitoring Device to Reach a Stable Level

The ATI PortaSens II took the longest time to stabilize at 2.86 minutes and 1.17 minutes for the low and high sensors, respectively. The Dräger MiniWarn took 1.97 minutes, the Dräger Pac III took 1.02 minutes and the Lumidor MicroMax was the fastest with 0.91 minutes. It should be noted that only one of each device was available for this study. This, the accuracy results may not be representative of the other devices of the same model.

Accuracy of Tube-Type Monitoring Devices

Table X shows the results of the five MSA tube samples given to the 28 grain elevator operators.

TABLE X

TUBE-TYPE MONITORING DEVICE SAMPLES

ACTUAL CONCENTRATION VS CONCENTRATION READ BY OKLAHOMA GRAIN ELEVATOR OPERATORS

Sample Number	Actual Concentration (ppm)	Average Concentration Read by Operator (ppm)
1	1.5	1.64
2	0.2	0.18
3	0.4	0.36
4	0.2	0.23
5	0.4	0.38

The average concentration read by operators was close to the actual concentration. The mode, high and low concentrations, and average percent accuracy from the 28 surveys is shown in Table XI.

TABLE XI

MODE, HIGH, LOW, AND % ACCURACY FROM

PHOSPHINE CONCENTRATION SAMPLES

Sample Number	Mode	High	Low	Avg. % Accuracy
1	1.5	3	0.65	90.6
2	0.2	0.2	0.01	90
3	0.4	0.4	0.02	90
4	0.2	0.4	0.01	85
5	0.4	0.6	0.02	95

The mode was exactly the same as the actual concentration. The high was similar except with sample 1, but the low was not close to the actual concentration. The lows were very low and indicate that gas levels were safe when they were not. This may indicate a problem for tube-type monitoring devices. The average of the five accuracy measures was 90.12%. This number was multiplied by 100% accuracy (from the laboratory testing) to get the accuracy number used in the model for the MSA Tube, 90.12%.

Multiple Criteria Decision Making Results

This section discusses which device was best under various scenarios. The weighting of costs and benefits, number of fumigations, and labor cost were varied in the model. Several scenarios were considered to reflect different user preferences.

80% Weighting on Costs, 20% Weighting on Benefits

The first scenario used an 80% weighting on costs (26.6% on equipment costs, 26.6% on additional equipment-related costs, and 26.6% on labor costs) and 20% weighting on benefits (4% for user-friendly benefit, 4% for convenience, 4% for ruggedness, 4% for worker safety perception, and 4% for accuracy). Table XII shows the results.

TABLE XII

RANKING OF DEVICES, SCENARIO 1

Rank	Device	MADM Number
1	Dräger Pac III	.8675
2	Lumidor MicroMax	.7640
3	Dräger MiniWarn	.7241
4	ATI PortaSens II	.7170
5	MSA Tube	.2759

The score for the Dräger Pac III was more than three times higher than that for the MSA Tube, although it should be noted that there are no measures of statistical significance available with this model. The other electronic devices were between the MSA Tube and the Dräger Pac III but closer to the Pac III.

The second scenario used an 80% weighting on costs (26.6% on equipment costs, 26.6% on additional equipment-related costs, and 26.6% on labor costs) and 20% weighting on benefits (2.5% for user-friendly benefit, 2.5% for convenience, 2.5% for ruggedness, 10% for worker safety perception, and 2.5% for accuracy). Table XIII shows the results.

TABLE XIII

RANKING OF DEVICES, SCENARIO 2

Rank	Device	MADM Number
1	Dräger Pac III	.8677
2	Lumidor MicroMax	.7642
3	Dräger MiniWarn	.7243
4	ATI PortaSens II	.7171
5	MSA Tube	.2757

The score for the Dräger Pac III was more than three times higher than that of the MSA Tube, although it should be noted that there are no measures of statistical significance available with this model. All other devices were between the MSA Tube and the Dräger Pac III but closer to the Pac III. The numbers in this scenario were almost exactly the same as those in the first scenario.

The third scenario used an 80% weighting on costs (26.6% on equipment costs, 26.6% on additional equipment-related costs, and 26.6% on labor costs) and 20% weighting on benefits (2.5% for user-friendly benefit, 2.5% for convenience, 2.5% for ruggedness, 2.5% for worker safety perception, and 10% for accuracy). Table XIV shows the results.

TABLE XIV

RANKING OF DEVICES, SCENARIO 3

Rank	Device	MADM Number
1	Dräger Pac III	.8676
2	Lumidor MicroMax	.7641
3	Dräger MiniWarn	.7239
4	ATI PortaSens II	.7165
5	MSA Tube	.2751

35% Weighting on Costs, 65% Weighting on Benefits

The fourth scenario used a 35% weighting on costs (11.6% on equipment costs, 11.6% on additional equipment-related costs, and 11.6% on labor costs) and 65% weighting on benefits (13% for user-friendly benefit, 13% for convenience, 13% for ruggedness, 13% for worker safety perception, and 13% for accuracy). Table XV shows the results.

TABLE XV

RANKING OF DEVICES, SCENARIO 4

Rank	Device	MADM Number
1	Dräger Pac III	.8645
2	Lumidor MicroMax	.7589
3	Dräger MiniWarn	.7220
4	ATI PortaSens II	.7063
5	MSA Tube	.2779

The fifth scenario used a 35% weighting on costs (11.6% on equipment costs, 11.6% on additional equipment-related costs, and 11.6% on labor costs) and 65% weighting on benefits (10% for user-friendly benefit, 10% for convenience, 10% for ruggedness, 25% for worker safety perception, and 10% for accuracy). Table XVI shows the results.

TABLE XVI

RANKING OF DEVICES, SCENARIO 5

Rank	Device	MADM Number
1	Dräger Pac III	.8691
2	Lumidor MicroMax	.7648
3	Dräger MiniWarn	.7266
4	ATI PortaSens II	.7121
5	MSA Tube	.2710

The sixth scenario used a 35% weighting on costs (11.6% on equipment costs, 11.6% on additional equipment-related costs, and 11.6% on labor costs) and 65% weighting on benefits (20% for user-friendly benefit, 15% for convenience, 15% for ruggedness, 5% for worker safety perception, and 10% for accuracy). Table XVII shows the results.

TABLE XVII

RANKING OF DEVICES, SCENARIO 6

Rank	Device	MADM Number
1	Dräger Pac III	.8624
2	Lumidor MicroMax	.7519
3	Dräger MiniWarn	.7210
4	ATI PortaSens II	.7014
5	MSA Tube	.2796

50% Weighting on Costs, 50% Weighting on Benefits

The seventh scenario used a 50% weighting on costs (16.6% on equipment costs, 16.6% on additional equipment-related costs, and 16.6% on labor costs) and 50% weighting on benefits (10% for user-friendly benefit, 10% for convenience, 10% for ruggedness, 10% for worker safety perception, and 10% for accuracy). Table XVIII shows the results.

TABLE XVIII

RANKING OF DEVICES, SCENARIO 7

Rank	Device	MADM Number
1	Dräger Pac III	.8667
2	Lumidor MicroMax	.7626
3	Dräger MiniWarn	.7235
4	ATI PortaSens II	.7139
5	MSA Tube	.2765

The eighth scenario used a 50% weighting on costs (16.6% on equipment costs, 16.6% on additional equipment-related costs, and 16.6% on labor costs) and 50% weighting on benefits (5% for user-friendly benefit, 5% for convenience, 20% for ruggedness, 15% for worker safety perception, and 5% for accuracy). Table XIX shows the results.

TABLE XIX

RANKING OF DEVICES, SCENARIO 8

Rank	Device	MADM Number
1	Dräger Pac III	.8679
2	Lumidor MicroMax	.7641
3	Dräger MiniWarn	.7248
4	ATI PortaSens II	.7162
5	MSA Tube	.2748

The ninth scenario used a 50% weighting on costs (16.6% on equipment costs, 16.6% on additional equipment-related costs, and 16.6% on labor costs) and 50% weighting on benefits (15% for user-friendly benefit, 5% for convenience, 5% for ruggedness, 5% for worker safety perception, and 20% for accuracy). Table XX shows the results.

TABLE XX

RANKING OF DEVICES, SCENARIO 9

Rank	Device	MADM Number
1	Dräger Pac III	.8680
2	Lumidor MicroMax	.7620
3	Dräger MiniWarn	.7216
4	ATI PortaSens II	.7084
5	MSA Tube	.2782

20% Weighting on Costs, 80% Weighting on Benefits

The tenth scenario used a 20% weighting on costs (6.6% on equipment costs, 6.6% on additional equipment-related costs, and 6.6% on labor costs) and 80% weighting on benefits (16% for user-friendly benefit, 16% for convenience, 16% for ruggedness, 16% for worker safety perception, and 16% for accuracy). Table XXI shows the results.

TABLE XXI

RANKING OF DEVICES, SCENARIO 10

Rank	Device	MADM Number
1	Dräger Pac III	.8555
2	Lumidor MicroMax	.7430
3	Dräger MiniWarn	.7150
4	ATI PortaSens II	.6742
5	MSA Tube	.2845

The eleventh scenario used a 20% weighting on costs (6.6% on equipment costs, 6.6% on additional equipment-related costs, and 6.6% on labor costs) and 80% weighting on benefits (10% for user-friendly benefit, 15% for convenience, 20% for ruggedness, 20% for worker safety perception, and 15% for accuracy). Table XXII shows the results.

TABLE XXII

RANKING OF DEVICES, SCENARIO 11

Rank	Device	MADM Number
1	Dräger Pac III	.8590
2	Lumidor MicroMax	.7553
3	Dräger MiniWarn	.7204
4	ATI PortaSens II	.6872
5	MSA Tube	.2776

The twelfth scenario used a 20% weighting on costs (6.6% on equipment costs, 6.6% on additional equipment-related costs, and 6.6% on labor costs) and 80% weighting on benefits (10% for user-friendly benefit, 10% for convenience, 10% for ruggedness, 25% for worker safety perception, and 25% for accuracy). Table XXIII shows the results.

TABLE XXIII

RANKING OF DEVICES, SCENARIO 12

Rank	Device	MADM Number
1	Dräger Pac III	.8746
2	Lumidor MicroMax	.7692
3	Dräger MiniWarn	.7145
4	ATI PortaSens II	.6690
5	MSA Tube	.2788

65% Weighting on Costs, 35% Weighting on Benefits

The thirteenth scenario used a 65% weighting on costs (21.6% on equipment costs, 21.6% on additional equipment-related costs, and 21.6% on labor costs) and 35% weighting on benefits (7% for user-friendly benefit, 7% for convenience, 7% for ruggedness, 7% for worker safety perception, and 7% for accuracy). Table XXIV shows the results.

TABLE XXIV

RANKING OF DEVICES, SCENARIO 13

Rank	Device	MADM Number
1	Dräger Pac III	.8673
2	Lumidor MicroMax	.7637
3	Dräger MiniWarn	.7239
4	ATI PortaSens II	.7162
5	MSA Tube	.2750

The fourteenth scenario used a 65% weighting on costs (21.6% on equipment costs, 21.6% on additional equipment-related costs, and 21.6% on labor costs) and 35% weighting on benefits (5% for user-friendly benefit, 5% for convenience, 5% for ruggedness, 5% for worker safety perception, and 15% for accuracy). Table XXV shows the results.

TABLE XXV

RANKING OF DEVICES, SCENARIO 14

Rank	Device	MADM Number
1	Dräger Pac III	.8678
2	Lumidor MicroMax	.7643
3	Dräger MiniWarn	.7245
4	ATI PortaSens II	.7168
5	MSA Tube	.2753

The fifteenth scenario used a 65% weighting on costs (21.6% on equipment costs, 21.6% on additional equipment-related costs, and 21.6% on labor costs) and 35% weighting on benefits (5% for user-friendly benefit, 5% for convenience, 5% for ruggedness, 5% for worker safety perception, and 15% for accuracy). Table XXVI shows the results.

TABLE XXVI

RANKING OF DEVICES, SCENARIO 15

Rank	Device	MADM Number
1	Dräger Pac III	.8676
2	Lumidor MicroMax	.7640
3	Dräger MiniWarn	.7233
4	ATI PortaSens II	.7149
5	MSA Tube	.2766

100% Weighting on Costs, 0% Weighting on Benefits

The sixteenth scenario used a 100% weighting on costs (33.3% on equipment costs, 33.3% on additional equipment-related costs, and 33.3% on labor costs) and 0% weighting on benefits. Table XXVII shows the results.

TABLE XXVII

RANKING OF DEVICES, SCENARIO 16

Rank	Device	MADM Number
1	Dräger Pac III	.8676
2	Lumidor MicroMax	.7641
3	Dräger MiniWarn	.7241
4	ATI PortaSens II	.7172
5	MSA Tube	.2759

In all of the scenarios, the score for the Dräger Pac III was more than three times that of the MSA Tube. The electronic-type devices all had similar MADM numbers and the MSA Tube was ranked last.

0% Weighting on Costs, 100% Weighting on Benefits

The seventeenth scenario used 0% weighting on costs and 100% weighting on benefits (20% for user-friendly benefit, 20% for convenience, 20% for ruggedness, 20% for worker safety perception, and 20% for accuracy). Table XXVIII shows the results.

TABLE XXVIII

RANKING OF DEVICES, SCENARIO 17

Rank	Device	MADM Number
1	Dräger Pac III	.8010
2	Dräger MiniWarn	.6433
3	Lumidor MicroMax	.6283
4	ATI PortaSens II	.4448
5	MSA Tube	.3439

For this scenario, the score for the Dräger Pac III was more than two times that of the MSA Tube. The electronic-type devices all had similar MADM numbers and the tube-type device ranked lower than all other devices. Unlike previous scenarios, the Dräger MiniWarn ranked above the Lumidor MicroMax. Also, the score for the MSA Tube was closer to that of the electronic-type monitoring devices than in previous scenarios.

The eighteenth scenario used 0% weighting on costs and 100% weighting on benefits (16.6% for user-friendly benefit, 16.6% for convenience, 16.6% for ruggedness, 30% for worker safety perception, and 20% for accuracy). Table XXIX shows the results.

TABLE XXIX

RANKING OF DEVICES, SCENARIO 18

Rank	Device	MADM Number
1	Dräger Pac III	.8624
2	Dräger MiniWarn	.7312
3	Lumidor MicroMax	.7189
4	ATI PortaSens II	.5565
5	MSA Tube	.2517

The score for the Dräger Pac III was more than three times that of the MSA Tube. The electronic-type devices all had similar MADM numbers and the tube-type device ranked lower than all other devices. Again, the Dräger MiniWarn ranked above the Lumidor MicroMax.

The nineteenth scenario used 0% weighting on costs and 100% weighting on benefits (15% for user-friendly benefit, 15% for convenience, 15% for ruggedness, 40% for worker safety perception, and 15% for accuracy). Table XXX shows the results.

TABLE XXX

RANKING OF DEVICES, SCENARIO 19

Rank	Device	MADM Number
1	Dräger Pac III	.8960
2	Dräger MiniWarn	.7853
3	Lumidor MicroMax	.7852
4	ATI PortaSens II	.6437
5	MSA Tube	.1751

The score for the Dräger Pac III was more than five times that of the MSA Tube. The electronic-type devices all had similar MADM numbers and the MSA Tube was ranked lower than all other devices. Again, the Dräger MiniWarn ranked above the Lumidor MicroMax. This scenario was the only one in which the score for the MSA Tube was below 0.2.

Each of the 19 scenarios was then altered using fumigation monitoring lengths of 1 day, 6 days, 12 days, 24 days, and 30 days. Each of these was then altered by using labor costs of \$6/hour, \$8/hour, \$12/hour, \$15/hour, and \$30/hour. There were no differences in rankings when any of these changes were made. Thus, neither variations in labor costs nor economies of size with respect to number of days of monitoring affected the relative rankings of the devices.

The scenarios to this point were based on a mean of all responses but the standard deviations suggested that there was not a statistical difference in convenience, ruggedness, user-friendliness, or worker safety perception. Because of this, the devices were then ranked for each of the 28 grain elevator operators individually. Each of the 9 costs and benefits were weighted evenly at 11.1%. The results for the 28 grain elevator operators were as follows:

TABLE XXXI

15 GRAIN ELEVATOR OPERATORS – RANKING OF DEVICES

Rank	Device
1	Dräger Pac III
2	Lumidor MicroMax
3	Dräger MiniWarn
4	ATI PortaSens II
5	MSA Tube

TABLE XXXII

THREE GRAIN ELEVATOR OPERATORS – RANKING OF DEVICES

Rank	Device
1	Dräger Pac III
2	Dräger MiniWarn
3	Lumidor MicroMax
4	ATI PortaSens II
5	MSA Tube

TABLE XXXIII

THREE GRAIN ELEVATOR OPERATORS – RANKING OF DEVICES

Rank	Device
1	Dräger Pac III
2	Lumidor MicroMax
3	ATI PortaSens II
4	Dräger MiniWarn
5	MSA Tube

TABLE XXXIV

TWO GRAIN ELEVATOR OPERATORS – RANKING OF DEVICES

Rank	Device
1	ATI PortaSens II
2	Dräger MiniWarn
3	Dräger Pac III
4	Lumidor MicroMax
5	MSA Tube

TABLE XXXV

ONE GRAIN ELEVATOR OPERATOR – RANKING OF DEVICES

Rank	Device
1	Lumidor MicroMax
2	Dräger Pac III
3	Dräger MiniWarn
4	ATI PortaSens II
5	MSA Tube

TABLE XXXVI

ONE GRAIN ELEVATOR OPERATOR – RANKING OF DEVICES

Rank	Device
1	Dräger Pac III
2	ATI PortaSens II
3	Lumidor MicroMax
4	Dräger MiniWarn
5	MSA Tube

TABLE XXXVII

ONE GRAIN ELEVATOR OPERATOR – RANKING OF DEVICES

Rank	Device
1	Dräger MiniWarn
2	ATI PortaSens II
3	Dräger Pac III
4	Lumidor MicroMax
5	MSA Tube

TABLE XXXVIII

ONE GRAIN ELEVATOR OPERATOR – RANKING OF DEVICES

Rank	Device
1	Dräger Pac III
2	Dräger MiniWarn
3	ATI PortaSens II
4	Lumidor MicroMax
5	MSA Tube

TABLE XXXIX

ONE GRAIN ELEVATOR OPERATOR – RANKING OF DEVICES

Rank	Device
1	Dräger Pac III
2	ATI PortaSens II
3	Dräger MiniWarn
4	Lumidor MicroMax
5	MSA Tube

CHAPTER VI

SUMMARY AND CONCLUSIONS

Summary

Aluminum/magnesium phosphide is an important tool in keeping commodity grain free of insects. This fumigant is important to all Oklahoma grain elevator operators. However, EPA requires elevator operators to monitor phosphine levels in the area around bins that are under fumigation. The intent is to ensure that neighbors and workers are not exposed to unsafe levels of escaping gas.

A phosphine gas-monitoring device is needed to comply with EPA regulations. These devices are expensive and require training so it is important for each facility to select a device that is the best suited for them. There are several tube-type and electronic-type monitoring devices available in the United States. Five phosphine gas-monitoring devices are evaluated in this study. They represent only some of the devices that are available. Also, only one device of each brand was used. A different device of the same brand may perform differently in another study. This study evaluated their performance in measuring phosphine gas only, and only for measuring in worker areas. If a device is being selected for other uses as well, the rankings may vary.

This study listed the costs and benefits for five phosphine gas-monitoring devices. When considering costs, the shipping costs for the devices and for the recalibrated sensors were not included. Also, the initial equipment prices may or may not be the same in the future and/or may be dependent on who is purchasing the equipment and where it is being purchased.

Convenience results showed similar means for the electronic-type and tube-type monitoring devices. However, when asked the question in a different way, the 28 grain elevator operators answered that the electronic-type monitoring devices were more convenient than the tube-type monitoring device.

Ruggedness and user-friendliness means were similar for all devices. Worker safety perception means for the electronic-type monitoring devices were more than twice that of the tube-type monitoring devices. The mean answer when asked about safety being the most important part of work was a 9.3. This indicates that many of these grain elevator operators place a high value on safety. Although differences in answers to survey questions between devices could be tested, it should be noted that in the MADM model rankings, statistical tests are not possible.

The accuracy levels were only tested one time on each date. If tested more than once, it would have been possible to determine standard error. It may have also made the average accuracy levels lower or higher. The accuracy levels for the ATI PortaSens II and the Dräger MiniWarn were lower than the manual stated. However, the sensors in the Dräger MiniWarn and Dräger Pac III are interchangeable. The accuracy levels in the Dräger Pac III were higher than in the Dräger MiniWarn. The accuracy differences in the two devices could have been because of the sensor and not because of the device itself. Also, only one of each device was available for this study. The accuracy levels calculated here do not necessarily reflect those of a representative sample of all devices of the same model. Additional studies should test a larger number of each device.

MADM Model

A MADM model was used to weight each of the costs and benefits in order of importance. The devices were then ranked according to scenarios that change the weights of costs and benefits, number of days of monitoring, and labor costs.

The hypothesis stated that as the number of fumigations increase, the average cost of the electronic-type monitoring devices decrease. Because of the cost relationships shown in Figure 1, it was expected that electronic-type monitoring devices are more economical for grain elevators operators that conduct more fumigations, and that tube-type monitoring devices are more economical for grain elevator operators that conduct fewer fumigations. It was found that this is not true. The electronic-type monitoring devices were preferred over the tube-type monitoring device in all scenarios. This is because the variable costs of the MSA Tube quickly exceeded the fixed costs of the electronic-type monitoring devices.

The most common result found in the scenarios ranked the devices as: 1) Dräger Pac III; 2) Lumidor MicroMax; 3) Dräger MiniWarn; 4) ATI PortaSens II; 5) MSA Tube. This shows that the tube-type device ranked below all electronic-type devices.

The only difference in the results occurred when costs were not given any weight and benefits were weighted 100%. The ranking of the devices in those situations was: 1) Dräger Pac III; 2) Dräger MiniWarn; 3) Lumidor MicroMax; 4) ATI PortaSens II; 5) MSA Tube. This shows that the tube-type device was still ranked below the electronic-type devices but that the Dräger MiniWarn was ranked above the Lumidor MicroMax. In these situations, the Dräger MiniWarn ranked almost as high as the Dräger Pac III. The reason that the Dräger MiniWarn was ranked above the Lumidor MicroMax was because the 28 grain elevator operators that filled out the surveys ranked the Dräger MiniWarn higher than the Lumidor MicroMax. They may have felt this way because some of the operators had previously used the Dräger MiniWarn.

In all situations, the Dräger Pac III ranked highest and the MSA tube ranked lowest. Therefore, a Dräger Pac III is the best device to purchase based on this study.

Need for Further Research

There is a need for further research to support the results found in this study because little current research exists in this area. This study was based only on Oklahoma grain elevator operators. This study should be replicated, and additional studies should include other locations and products. Locations may change the results of the study because fumigation times may be longer or shorter depending on temperature, amount of insect infestation, age of facility, etc. Products to be fumigated may also change results because some products are fumigated with magnesium phosphide instead of aluminum phosphide. Magnesium phosphide reacts faster, which requires fewer days of monitoring but increased intensity of monitoring for those days.

The results here were robust based on varying wage rates, fumigation lengths, and over relative weights on costs and benefit components. However, grain elevator operators using these results should carefully evaluate whether the range of variables considered here represents their situations.

BIBLIOGRAPHY

Applicator's Manual for Degesch Phostoxin. Pellets and Tablets. Available from http://www.degeschamerica.com/appl_manuals.html. Accessed on March 27, 2002.

ATI PortaSens II Operation and Maintenance Manual. Available from http://www.analyticaltechnology.com/frames.htm. Accessed on March 27, 2002.

Ballestero, E., and Romero, C. *Multiple Criteria Decision Making and its Applications to Economic Problems.* Kluwer Academic Publishers, 1998, Norwell, MA 02061.

Blondell, J., and M. Spann. "Review of Aluminum Phosphide Incident Reports." United States Environmental Protection Agency Memorandum, Office of Prevention, Pesticides, and Toxic Substances, Washington, D.C. December 1996.

Dixon, J., and F. Massey. *Introduction to Statistical Analysis.* McGraw-Hill Book Company, 1983, New York, NY 10010.

Dräger MiniWarn Operator's Manual. Available from http://www.draeger.com/com/ST/Prod/Detection/Mobile_messtechnik/PI/miniwarn1.jsp. Accessed on March 27, 2002.

Dräger Pac III Operator's Manual. Available from http://www.draeger.com/com/ST/Prod/Detection/Mobile_messtechnik/PI/paciii1.jsp. Accessed on March 27, 2002.

Ducom, P., and C. Bourges. "A New Technique for the Measurement of Phosphine Concentrations." Laboratoire Denrees Stockees, Chemin d'Artiques, France. 66-73.

EPA-A. (United States Environmental Protection Agency Methyl Bromide Phase Out Website). Available from http://www.epa.gov/docs/ozone/mbr/mbrqa.html#q2. Accessed on March 27, 2002.

EPA-B. (United States Environmental Protection Agency Federal Register Document.) Available from http://www.epa.gov/fedrgstr/EPA-PEST/1998/December/Day-23/p34049.htm. Accessed on March 27, 2002.

General Information Concerning Gas Detectors. KC Supply Co., Inc. Brochure. Kansas City, MO, 2001.

Gordon, R. "NGFA: EPA's Proposed Phosphine Fumigant Restrictions to be Costly to Grain Industry." Available from http://www.grainnet.com/info/articles.html?type=ar&ID=4633. Accessed on March 27, 2002.

Harein, P., and R. Davis. "Control of Stored-Grain Insects." *Storage of Cereal Grains and Their Products*. Chapter 14. Stored Product and Structural Pest Management Consulting Services, Inc., St. Paul, MN, 2001.

Jeffreys, K. "Guide to Regulatory Reform: The Cost-Benefit Rule." Available from http://cnie.org/NLE/CRSreports/Risk/rsk-4.cfm. Accessed on March 27, 2002.

Kenkel, P, B. Adam, G. Cuperus, and W.S. Fargo. "A Risk Analysis of Insect Control Strategies in Stored Wheat." Department of Agricultural Economics, Oklahoma State University, Stillwater, OK. August 1991.

Krischik, V., and W. Burkholder. "Stored-product Insects and Biological Control Agents." In Krischik, V., Cuperus, G., Galliart, D. (Eds.) *Stored Product Management.* Oklahoma State University, Stillwater, Oklahoma: Oklahoma Cooperative Extension Services, (1995):85-101.

Leesch, J.G., G. Cuperus, J. Criswell, J. Sargent, and J. Mueller. "Practical Fumigation Considerations." In Krischik, V., Cuperus, G., Galliart, D. (Eds.) *Stored Product Management.* Oklahoma State University, Stillwater, Oklahoma: Oklahoma Cooperative Extension Sercies, (1995):139-152.

Lumidor MicroMax Operator's Manual. Available from http://www.lumidor.com/micromax.htm. Accessed on March 27, 2002.

McCaslin, Brian. Personal Communication, April 18, 2002.

Memorandum of Agreement. (Memorandum of Agreement between the United States Environmental Protection Agency and Signatory Registrants of Phosphine Based Fumigants). Available from http://home.att.net/~degesch/memorandum.htm. Accessed on March 27, 2002.

Moore, J. "Cost-Benefit Analysis: Issues in Its Use in Regulation." Available from http://www.public-policy.org/~ncpa/ea/eama95/eama95h.html. Accessed on March 27, 2002.

MSA Tube Instructions. Available from http://www.westpacmarine.com/msa/tubes.htm. Accessed on March 27, 2002.

Mueller, D. *Stored Product Protection.* Indianapolis: Insects Limited, Inc., 1998.

Munzel, M. "Phosphine Options Depend on Type of Fumigation," *World Grain.* (November/December 1988):14-16.

Navarro, S. "Testing Three Models of Phosphine Detectors." USDA, ARS, Horticultural Crops Research Laboratory, Fresno, CA. (May 1999).

Newman, C. "Grain Fumigation – A New Look." *World Grain*, 16(4):57-62.

"NIOSH Alert – Preventing Phosphine Poisoning and Explosions during Fumigation." Available from http://www.cdc.gov/niosh/99-126.html. Accessed on March 27, 2002.

Noyes, R., P. Kenkel, and G. Tate. "Closed Loop Fumigation Systems." In Krischik, V., Cuperus, G., Galliart, D. (Eds.) *Stored Product Management.* Oklahoma State University, Stillwater, Oklahoma: Oklahoma Cooperative Extension Services, (1995):153-156.

O'Malley, M., G. Kullman, and J. Cox-Ganser. "Preventing Phosphine Poisoning and Explosions during Fumigation." Available from http://www.cdc.gov/niosh/99~126.html. Accessed on March 27, 2002.

Paulsrud, B. "Phosphide Fumigants: EPA Seeks Comment." Available from http://www.aces.uiuc.edu/~pse/newsletter/html/199902c.html. Accessed on March 27, 2002.

Pestcon – Phosphine Risk Mitigation Summary Update. Available from http://www.pestcon.com/companynews/news 20001108.htm. Accessed on March 27, 2002.

Phillips, T., and W. Burkholder. "Storage Insects." In Bakker-Arkema, F.W., and Maier, D.E. (Eds.). *Handbook of Agricultural Crop Drying and Storage.* Marcell Dekker, Inc. New York (1996).

RED Facts. Aluminum and Magnesium Phosphide. Available from http://www.epa.gov/oppsrrd1/REDs/factsheets/0025fact.pdf. Accessed on March 27, 2002.

Romero, C. Handbook of Critical Issues in Goal Programming. Pergamon Press, 1991, Elmsford, New York, 10523.

Tabucanon, M.T. Multiple Criteria Decision Making in Industry. Elsevier Science Publishing Company, 1988, New York, NY 10010.

Thorn, T., R. Stevens, D. Segers, and S. Macon. "Automated Real-Time Monitoring of Phospine Concentrations Outside Large Fumigated Tobacco Warehouses Using GC/PFPD." CMS Field Products, 1999.

Whittle, C.P., C.J. Waterford, P.C. Annis, and H.J. Banks. "The Production and Accumulation of Carbon Monoxide in Stored Dry Grain." Stored Grain Research Laboratories, Division of Entomology No.1, 30(1993): 23-26.

Wilson, E. "Four Years…And Counting." *World Grain*, February 2001, 19(7):28-30.

Winks, R.G., C.J. Waterford, and G.F. Russell. "Environmental and Workspace Levels of Phosphine Produced by Siroflo." Division of Entomology. Technical Report No. 63, CSIRO Entomology, Canberra, Australia, 1995.

Yoon, K.P. and C.L. Hwang. Multiple Attribute Decision Making, An Introduction. Sage Publications, 1995, Thousand Oaks, CA 91320.

Yu, P.L. "Behavior Bases and Habitual Domains of Human Decision/Behavior – Concepts and Applications." *Multiple Criteria Decision Making Theory and Application*, August 1979, 511-540.

Zeleny, M. Multiple Criteria Decision Making. McGraw-Hill Book Company, 1982, New York, NY 10016.

APPENDICES

APPENDIX A.1

SAMPLE FUMIGATION MANAGEMENT PLAN

Fumigation Management Plan

Stillwater Elevator

202 E 3rd St

Stillwater, OK 74074

Purpose:

The purpose of this Fumigation Management Plan is to help Stillwater Elevator in Stillwater, Oklahoma to ensure the safety of the employees, the community, and the environment. It is also designed to ensure an effective fumigation and to assist the company to be in compliance with all regulations dealing with grain fumigation.

A Checklist Guide

Preliminary Planning and Preparation

1. Determine the purpose of the fumigation.
    a. Elimination of insect infestation. The main insects that have been found through sampling are the rusty grain beetle and the lesser grain borer. The rusty grain beetle is an external feeder and feeds on the fine materials. This insect causes filth but does not contribute to insect damaged kernels. The lesser grain borer is an internal feeder and feeds

on the inside part of the grain. It contributes to the number of insect damaged kernels.

2. Determine the type of fumigation.
    a. Commodity: raw agricultural product. Wheat is being fumigated.
3. Fully acquaint yourself with the site and commodity to be fumigated, including
    a. The general structure layout, construction (materials, design, age, maintenance) of the structure, fire or combustibility hazards, connecting structures and escape routes, above and below ground, and other unique hazards or structure characteristics. Draw or have a drawing or sketch of structure to be fumigated, delineating features, hazards, and other structural issues. See attached flow.
    b. The number and identification of persons who routinely enter the area to be fumigated.
        i. Jane Doe
        345 S Cedar St.
        Stillwater, OK 74074
        Day Telephone: (405)-555-9797
        Evening Telephone: (405)-555-6085
    c. The specific commodity to be fumigated, its mode of storage, and its condition.
        i. Wheat
        ii. Concrete Silos

    iii. The wheat is in good condition. Test weight is 57.6 on the average, dockage is .7%, temperature is 55 degrees F, and moisture content is 11.4 percent.

d. The previous treatment history of the commodity, if available.

    i. All wheat is 2000 wheat and has been stored for a year and a few months. The wheat was treated in 2000 with aluminum phosphide.

e. Accessibility of utility service connections.

    i. Please attach drawing.

f. Nearest telephone or other means of communication. Mark the location of this item on the elevator flow.

    i. Please attach drawing.

g. Emergency shut-off stations for lockout/tag out, electricity, water, and gas. Mark location of these items on the elevator flow.

    i. Please attach drawing.

h. Current emergency telephone numbers.

    i. Health – (405)-555-1234
    ii. Fire – (405)-555-2323
    iii. Police – (405)-555-3333
    iv. Hospital – (405)-555-3944
    v. Ambulance – (405)-555-3544

i. Name and phone number (day and night) of appropriate company officials

    i. Ronda Danley
    ii. Day Telephone: (405)-555-8434
    iii. Evening telephone: (405)-555-3242
j. Check, mark, and prepare the points of fumigation application locations if the job involves entry into the structure for fumigation.
    i. Does not require entry into structure.
k. Review labeling.
    i. Labeling reviewed prior to beginning of fumigation.
l. Exposure time considerations.
    i. Fumigate to be used.
        1. Aluminum Phosphide
    ii. Minimum fumigation period.
        1. 2 weeks.
    iii. Down time required.
        1. None
    iv. Aeration requirements.
        1. The concrete bins are not aerated.
    v. Cleanup procedures.
        1. Canisters are sent to Watonga and then are taken to be recycled.
    vi. Commodity temperature is 55 degrees F and commodity moisture is 11.4%.
m. Determination of dosage.

i. Cubic footage of facility.
    1. See attached spreadsheet.

ii. Structure sealing capability and methods.
    1. Foam around manhole covers and bin tops.
    2. Tape around the foam and around all other possible leakage points.

iii. Label recommendations

iv. Temperature, humidity, wind
    1. Temperature 73 degrees F
    2. Humidity 42%
    3. Wind Speed 14 mph, (180 degrees)

v. Commodity volume
    1. Commodity is taken into a bin and filled completely while aluminum phosphide pellets are being added with an automatic pellet dispenser. Each bin has a different capacity but each one is completely filled so that commodity volume is equal to cubic footage of the silo. The rate is set so that one pellet drops about every four seconds.

vi. Past history of fumigation of structure
    1. Has been fumigated with aluminum phosphide for the past 10 years at least.

vii. Exposure time

        1. Concrete: Approximately 3-6 days depending on temperature, humidity, and wind speed.

Personnel

- Confirm in writing that all personnel in and around the area to be fumigated have been notified prior to application of the fumigant.
    - Use attached check sheet to inform personnel of the fumigation and have them write their name in the provided blank when informed about all check sheet information.
- Instruct all fumigation personnel about the hazards that may be encountered; and about the selection of personal protection devices, including detection equipment.
    - Dräger MiniWarn
    - Dräger Pac III
    - ATI PortaSens II
    - Lumidor MicroMax
    - MSA Kwik-Draw Pump with low-range tubes
    - Two SCBAs are available for use at local fire station
- Confirm that all personnel are aware of and know how to proceed in case of an emergency situation.
    - Tell all personnel about the emergency action steps and be sure that they are familiar with aluminum phosphide and its affects. It would be a good idea for all personnel (even if they do not plan to

be around the fumigated facility) to read the label so that they are informed of the dangers associated with aluminum phosphide.

- Instruct all personnel on how to report any accident and/or incidents related to fumigant exposure. Provide a telephone number for emergency response reporting.
    - Report all accidents and/or incidents on a log sheet and get treatment immediately.
- Instruct all personnel to report to proper authorities any theft of fumigant and/or equipment related to fumigation.
    - Report all thefts to the police department for investigation.
- Establish a meeting area for all personnel in case of emergency.
    - This is detailed in the Emergency Action Plan. All personnel should read the Emergency Action Plan each year before aluminum phosphide is applied to wheat.
- Attach a table for a checklist to complete these items. These are items that must be discussed among workers.
    - The checklist will be a reminder of what to do in case of an emergency.

Monitoring

1. Safety
    a. Monitoring must be conducted in areas to prevent excessive exposure and to determine where exposure may occur. Document where monitoring will occur.

- i. Monitor at the following locations
    1. Outside of facility (on ground) by bins being fumigated
    2. 10-30 feet from facility (on ground)
    3. By all seams and potential leakage points
    4. By manhole covers
    5. By dump pit
    6. On manlift up to bin-top floor
    7. On bin-top floor
    8. On distributor floor
    9. By all entrances into the elevator
    10. Downwind at property line
- ii. Note that readings were taken at each location every day, but if gas levels were 0, nothing was listed on the data sheet.

b. Keep a log or manual of monitoring records for each fumigation site. This log must contain the timing, number of readings taken and level of concentrations found in each location.

- i. See attached log of 2001 data plus empty sheet for future monitoring.

c. When monitoring log records, document there is no phosphine present above safe levels, subsequent monitoring is not routinely required. However, spot checks should be made occasionally, especially if conditions significantly change.

        i. Monitoring was done for 4 days. After this date, gas levels were not detectable.

    d. Monitoring must be conducted during aeration and corrective action taken if gas levels exceed the allowed levels in an area where bystanders and/or nearby residents may be exposed.

        i. No gas levels exceeded the allowed level of 0.3 ppm

2. Efficacy

    a. Gas readings should be taken within the fumigated structure to insure proper gas concentrations. If the phosphine levels have fallen below the targeted level, the fumigators may reenter the structure to add additional product.

        i. Fumigators never reenter the structure.

    b. Document readings.

        i. No readings to document.

Notification

1. Confirm all local authorities have been notified.
2. Prepare written procedure ("Emergency Response Plan") that contains explicit instructions, names, and telephone numbers so as to be able to notify local authorities if phosphine levels are exceeded in an area that could be dangerous to bystanders.

    Emergency Action Plan is attached.

Sealing Procedures

1. Sealing must be complete. All bin lids, vents, fumigation motors, aeration fans, PVC pipe connections, and manhole covers are sealed with plastic and tape.
2. If the site has been fumigated before, review the previous FMP for previous sealing information. Also, look at last years monitoring data to see which areas had the highest levels of gas. Be sure to seal those areas well and monitor more frequently where leaks are possible. Leaks were noted in the 2001 fumigation. The leaks were around the aeration fans and fumigation motor. These areas were sealed well with tape and plastic. This method was not 100% effective and gas escaped. A new method may be used in future fumigations. One suggestion is that foam and a different tape should be used.
3. Make sure that construction/remodeling has not changed the building.
    i. Construction has not changed.
4. Warning placards must be placed on every possible entrance to the fumigation site. The placards must be at least 10"X12"
    i. Warning placards should be placed at all doors, on the sides of each fumigated silo, manhole, bin lid, and all other entrances.

Application Procedures and Fumigation Period

1. Plan carefully and apply all fumigants in accordance with the registrants label requirements. Open canisters in an open area with the canister lid not facing personnel. This is because the canisters sometimes have a rush of gas coming out when opened. The canisters were opened in open air by the bin being fumigated or by the automatic pellet dispenser.
2. When entering into the area under fumigation, always work with two or more people under the direct supervision of a certified applicator wearing appropriate respirators.
    i. There were certified fumigation applicators at the 2001 fumigation.
3. Apply fumigant from the outside where appropriate.
    i. The fumigants are always applied from the outside. The bin is never entered during fumigation.
4. Provide watchmen when a fumigation site cannot otherwise be made secure from entry by unauthorized persons.
    i. All entrances are secure.
5. When entering structures, always follow OSHA rules for confined spaces.
    i. Not applicable.
6. Document that the receiver of in-transit fumigation has been notified and is trained to receive commodity under fumigation.
    i. Not applicable.

Post-Application Operations

- Provide watchmen when you cannot secure the fumigation site from entry by unauthorized persons during the aeration process. All entrances are secure.
- Ventilate and aerate in accordance with structural limitations. Aeration is conducted by turning the grain. There are also aeration fans that are used to completely aerate and cool the silos. The process did not yield any dangerous gas levels (exceeding 0.3 ppm).
- Turn on ventilating or aerating fans where appropriate. All fans were used to aerate during the 2001 fumigation until gas levels were less than 0.3 ppm.
- Use a suitable gas detector before reentry to determine fumigant concentration.
- Keep written records of monitoring to document completion of aeration. See attached spreadsheet.
- Consider temperature when aerating. Temperature was in the 70s. This is an acceptable aeration temperature.
- Insure aeration is complete before moving vehicle into public roads.
- Remove warning placards when aeration is complete.
- Inform business/client that employees/other persons may return to work or otherwise be allowed to reenter.

Application Procedures For Vertical Storages Specifically (kind of a repeat but is included because all storage areas at Omega are vertical storages)

- Inspect the site to determine its suitability for fumigation. The Omega facility was found to be suitable for fumigation in the 2001 season.
- Determine if the structure is in an area where leakage during fumigation or aeration would expose nearby workers or bystanders to concentrations above the permitted levels. Areas were check and monitored before and throughout the fumigation to determine if levels were below 0.3 ppm in worker and bystander areas.
- Develop an appropriate Fumigation Management Plan. (Refer to FMP guidelines.)
- Consult previous records for any changes to the structure. Close openings and seal cracks to make the structure as airtight as possible. Prior to the fumigation, seal the vents near the top of the silos. These vents cause the gas to seep out quickly.
- Apply pellets with an automatic dispenser into the wheat stream in the up leg of the elevator while wheat is being turned or apply pellets on top of the grain mass when using a closed-loop fumigation system and/or with bins that cannot be turned.
- Seal the bin deck openings after the fumigation has been completed. Seal the bin lid and the distributor top on with foam. Tape all manhole covers closed. Also, seal all PVC pipes and aeration fans with foam, plastic, and/or tape.
- Place warning placards on the discharge gate, on all entrances, manholes, and by the automatic pellet dispenser.

- Fill out the grain fumigation record. See attached table.
- An easy way to go through the fumigation process is by a checklist. Attached is a checklist that goes from the pre-application to the post-application processes. This has all of the above information plus smaller details that are easily overlooked.

This plan was created from the Degesch Phostoxin Label. This is only a sample and does not have all necessary attached drawings and check sheets.

APPENDIX B.1

SURVEY GIVEN TO GRAIN ELEVATOR MANAGERS AND RESULTS

This device is easy to set up/turn on for use.							
ATI PortaSens II	10	6	5	5	4	6	9
Dräger MiniWarn	10	7	5	5	4	5	9
Dräger Pac III	10	7	5	5	4	5	9
Lumidor MicroMax	10	8	5	10	3	8	9
MSA Tube	10	3	6	10	9	5	4
ATI PortaSens II	4	3	10	4	4	5	6
Dräger MiniWarn	4	3	10	3	7	5	10
Dräger Pac III	4	3	10	2	2	5	10
Lumidor MicroMax	4	3	10	1	2	5	6
MSA Tube	7	2	1	9	10	7	10
ATI PortaSens II	8	10	7	8	8	7	8
Dräger MiniWarn	8	10	7	8	8	7	8
Dräger Pac III	8	10	7	8	8	7	8
Lumidor MicroMax	9	10	7	3	6	7	8
MSA Tube	9	10	8	5	9	8	10
ATI PortaSens II	10	8	7	6	3	8	8
Dräger MiniWarn	10	8	8	7	3	8	5
Dräger Pac III	10	8	7	8	3	8	8
Lumidor MicroMax	10	8	7	6	2	8	8
MSA Tube	10	10	8	7	7	8	10
	Sum	Average	High	Low	Range	Mode	St Dev
ATI PortaSens II	187	6.923	10	3	7	8	2.178
Dräger MiniWarn	192	7.111	10	3	7	8	2.289
Dräger Pac III	189	7.000	10	2	8	8	2.518
Lumidor MicroMax	183	6.778	10	1	9	8	2.769
MSA Tube	212	7.852	10	1	9	10	2.631

The electronic-type monitoring devices are more convenient than the tube-type monitoring device.

10	9	7	10	9	10	10	8	10
8	10	10	10	10	10	10	10	10
1	10	9	8	1	10	10	9	10
3								
Sum	Average	High	Low	Range	Mode	St Dev		
241	8.926	10	1	9	10	2.615		

This device seems to be rugged enough that it could last for years to come without needing replacement.

MSA Tube	10	3	5	6	3	5	1
ATI PortaSens II	2	5	5	6	2	10	4
Dräger MiniWarn	5	5	5	6	3	9	7
Dräger Pac III	10	5	5	6	4	5	7
Lumidor MicroMax	8	5	5	10	5	5	4
MSA Tube	2	10	5	8	9	3	10
ATI PortaSens II	2	5	9	6	9	5	10
Dräger MiniWarn	2	2	10	5	7	6	10
Dräger Pac III	2	3	10	3	2	7	10
Lumidor MicroMax	2	2	10	6	2	6	10
MSA Tube	1	8	3	8	8	5	10
ATI PortaSens II	2	4	6	8	7	4	7
Dräger MiniWarn	2	4	7	9	7	6	8
Dräger Pac III	2	4	7	9	7	7	7
Lumidor MicroMax	1	4	7	8	7	8	8
MSA Tube	2	9	1	8	7	8	3
ATI PortaSens II	3	8	7	5	5	7	7
Dräger MiniWarn	8	7	7	5	5	7	9
Dräger Pac III	8	8	6	7	2	7	9
Lumidor MicroMax	7	7	6	5	1	7	9

	Sum	Average	High	Low	Range	Mode	St Dev
MSA Tube	161	5.963	10	1	9	8	3.111
ATI PortaSens II	160	5.926	10	2	8	5	2.370
Dräger MiniWarn	173	6.407	10	2	8	7	2.278
Dräger Pac III	169	6.259	10	2	8	7	2.546
Lumidor MicroMax	165	6.111	10	1	9	5	2.644

I believe that this device is user-friendly.

MSA Tube	1	4	5	5	9	10	1
ATI PortaSens II	10	6	5	5	3	10	2
Dräger MiniWarn	10	6	5	5	5	10	10
Dräger Pac III	10	6	5	5	5	6	10
Lumidor MicroMax	10	7	5	10	3	10	2
MSA Tube	3	10	1	9	8	5	10
ATI PortaSens II	3	3	10	8	3	3	5
Dräger MiniWarn	3	1	10	6	3	6	10
Dräger Pac III	3	3	10	3	2	8	10
Lumidor MicroMax	3	3	10	4	1	7	5
MSA Tube	5	7	7	4	5	7	10
ATI PortaSens II	5	7	6	6	5	6	10
Dräger MiniWarn	5	8	7	4	5	7	7
Dräger Pac III	10	10	7	7	5	8	8
Lumidor MicroMax	1	8	7	3	5	7	8
MSA Tube	10	2	1	7	7	5	8
ATI PortaSens II	5	3	3	4	5	7	7
Dräger MiniWarn	4	8	8	5	4	8	9
Dräger Pac III	4	10	6	8	4	9	9
Lumidor MicroMax	4	10	6	7	1	5	9

	Sum	Average	High	Low	Range	Mode	St Dev
MSA Tube	166	6.148	10	1	9	5	3.042
ATI PortaSens II	155	5.741	10	2	8	5	2.396
Dräger MiniWarn	179	6.630	10	1	9	5	2.470
Dräger Pac III	191	7.074	10	2	8	10	2.611
Lumidor MicroMax	161	5.963	10	1	9	10	2.977

I would feel safe working near a fumigated area if I had this device with me.

MSA Tube	1	3	4	1	4	5	1
ATI PortaSens II	8	7	6	1	3	10	6
Dräger MiniWarn	9	7	6	1	5	10	10
Dräger Pac III	10	7	6	1	4	10	10
Lumidor MicroMax	7	7	6	10	3	10	6

MSA Tube	5	7	1	1	3	4	10
ATI PortaSens II	5	10	10	9	5	5	10
Dräger MiniWarn	5	10	10	8	5	6	10
Dräger Pac III	5	10	10	8	9	7	10
Lumidor MicroMax	5	10	10	8	9	6	10

MSA Tube	7	5	7	9	5	7	10
ATI PortaSens II	7	8	8	9	8	8	10
Dräger MiniWarn	7	8	10	9	8	8	5
Dräger Pac III	10	10	10	9	8	8	5
Lumidor MicroMax	7	8	10	9	8	8	5

MSA Tube	5	9	2	7	6	5	10
ATI PortaSens II	5	9	6	7	5	9	9
Dräger MiniWarn	5	9	9	7	5	9	9
Dräger Pac III	5	10	8	9	3	10	9
Lumidor MicroMax	5	10	8	9	1	9	9

	Sum	Average	High	Low	Range	Mode	St Dev
MSA Tube	144	5.333	10	1	9	5	2.902
ATI PortaSens II	203	7.519	10	1	9	8	2.303
Dräger MiniWarn	210	7.778	10	1	9	9	2.253
Dräger Pac III	221	8.185	10	1	9	10	2.514
Lumidor MicroMax	213	7.889	10	1	9	10	2.315

I feel that safety is the most important part of my job.								
8	10	10	10	8	10	9	10	10
9	10	10	10	10	10	10	10	9
8	10	10	10	8	10	1	10	1
10								
Sum	Average	High	Low	Range	Mode	St Dev		
233	8.630	10	1	9	10	2.441		

I think my facility should invest in some type of electronic-type monitoring device.								
10	10	8	10	9	10	10	8	10
10	9	10	10	10	10	10	10	10
9	8	10	10	10	8	10	1	10
1								
Sum	Average	High	Low	Range	Mode	St Dev		
251	9.296	10	1	9	10	2.365		

The operation of this device would interfere with my daily tasks.

MSA Tube	10	8	5	5	5	10	10
ATI PortaSens II	1	3	5	5	7	4	9
Dräger MiniWarn	1	3	5	5	6	4	1
Dräger Pac III	1	4	4	5	6	4	1
Lumidor MicroMax	1	3	5	10	5	1	9
MSA Tube	7	10	10	5	5	5	6
ATI PortaSens II	6	8	5	4	5	3	1
Dräger MiniWarn	6	3	5	3	5	5	8
Dräger Pac III	6	4	5	1	2	7	10
Lumidor MicroMax	6	5	5	7	7	5	5
MSA Tube	8	1	7	6	6	6	2
ATI PortaSens II	6	1	4	7	4	4	6
Dräger MiniWarn	5	1	4	2	3	5	5
Dräger Pac III	7	1	4	2	3	7	5
Lumidor MicroMax	9	1	4	7	3	5	7
MSA Tube	6	6	6	5	9	8	4
ATI PortaSens II	3	6	6	8	7	3	2
Dräger MiniWarn	8	5	1	6	7	3	5
Dräger Pac III	3	1	6	6	7	2	5
Lumidor MicroMax	7	5	8	6	8	3	3

	Sum	Average	High	Low	Range	Mode	St Dev
MSA Tube	181	6.704	10	1	9	5	2.349
ATI PortaSens II	133	4.926	9	1	8	4	2.171
Dräger MiniWarn	120	4.444	8	1	7	5	1.979
Dräger Pac III	119	4.407	10	1	9	1	2.351
Lumidor MicroMax	150	5.556	10	1	9	5	2.422

Do you think the devices are intimidating?

MSA Tube	8	1	5	5	3	10	1
ATI PortaSens II	7	1	5	5	8	1	1
Dräger MiniWarn	7	1	5	5	5	1	1
Dräger Pac III	2	1	5	5	7	1	1
Lumidor MicroMax	4	1	5	10	6	1	1
MSA Tube	5	1	1	10	5	1	1
ATI PortaSens II	5	1	1	10	7	1	1
Dräger MiniWarn	5	1	1	10	7	1	7
Dräger Pac III	5	1	1	10	3	1	3
Lumidor MicroMax	5	1	1	10	3	1	10
MSA Tube	7	1	1	2	4	5	4
ATI PortaSens II	6	1	1	7	7	5	3
Dräger MiniWarn	8	1	1	7	7	5	5
Dräger Pac III	2	1	1	4	7	5	5
Lumidor MicroMax	8	1	1	7	7	5	5
MSA Tube	1	1	2	9	2	5	2
ATI PortaSens II	2	3	3	7	6	5	2
Dräger MiniWarn	3	3	2	5	7	5	2
Dräger Pac III	4	7	2	8	9	5	2
Lumidor MicroMax	5	7	2	4	9	5	2

	Sum	Average	High	Low	Range	Mode	St Dev
MSA Tube	103	3.815	10	1	9	1	2.932
ATI PortaSens II	112	4.148	10	1	9	1	2.735
Dräger MiniWarn	118	4.370	10	1	9	1	2.685
Dräger Pac III	108	4.000	10	1	9	1	2.718
Lumidor MicroMax	127	4.704	10	1	9	1	3.097

Do you think the training time for the devices is too long?

MSA Tube	6	4	5	1	5	1	5
ATI PortaSens II	5	6	5	1	5	1	5
Dräger MiniWarn	5	6	5	1	5	1	5
Dräger Pac III	3	6	5	1	5	1	5
Lumidor MicroMax	3	6	5	10	5	1	5
MSA Tube	7	1	1	1	8	1	1
ATI PortaSens II	7	5	1	1	8	1	5
Dräger MiniWarn	7	5	1	1	6	1	5
Dräger Pac III	7	5	1	1	2	1	1
Lumidor MicroMax	7	5	1	1	5	1	5
MSA Tube	5	1	3	6	3	3	3
ATI PortaSens II	5	1	3	6	6	3	3
Dräger MiniWarn	5	1	3	5	6	4	2
Dräger Pac III	5	1	3	5	6	3	2
Lumidor MicroMax	5	1	3	6	6	4	2
MSA Tube	1	5	5	8	1	1	1
ATI PortaSens II	2	5	8	6	1	1	1
Dräger MiniWarn	3	5	5	3	1	1	5
Dräger Pac III	3	5	5	6	3	1	3
Lumidor MicroMax	3	5	5	8	10	1	1

	Sum	Average	High	Low	Range	Mode	St Dev
MSA Tube	93	3.444	8	1	7	1	2.389
ATI PortaSens II	107	3.963	8	1	7	1	2.374
Dräger MiniWarn	103	3.815	7	1	6	5	2.001
Dräger Pac III	95	3.519	7	1	6	5	1.969
Lumidor MicroMax	120	4.444	10	1	9	5	2.623

Could you remember how to use each device in one month?

MSA Tube	5	3	5	1	3	10	10
ATI PortaSens II	4	5	5	1	9	10	10
Dräger MiniWarn	7	5	5	1	9	10	10
Dräger Pac III	9	5	5	1	9	10	10
Lumidor MicroMax	7	5	5	1	9	10	10
MSA Tube	3	10	10	9	5	9	10
ATI PortaSens II	3	6	10	9	5	8	8
Dräger MiniWarn	3	5	10	9	5	7	8
Dräger Pac III	3	5	10	9	7	9	10
Lumidor MicroMax	3	5	10	9	6	9	8
MSA Tube	4	10	10	10	9	3	10
ATI PortaSens II	4	10	10	7	7	3	10
Dräger MiniWarn	5	10	10	9	7	3	10
Dräger Pac III	9	10	10	9	7	3	10
Lumidor MicroMax	3	10	10	7	7	3	10
MSA Tube	10	9	8	9	4	10	1
ATI PortaSens II	9	6	3	7	2	10	2
Dräger MiniWarn	9	6	7	7	2	10	2
Dräger Pac III	8	8	5	8	2	10	1
Lumidor MicroMax	8	6	5	4	2	10	2

	Sum	Average	High	Low	Range	Mode	St Dev
MSA Tube	200	7.407	10	1	9	10	3.251
ATI PortaSens II	183	6.778	10	1	9	10	2.963
Dräger MiniWarn	191	7.074	10	1	9	10	2.842
Dräger Pac III	202	7.481	10	1	9	10	2.998
Lumidor MicroMax	184	6.815	10	1	9	10	2.937

Ranking of the devices. Favorite gets a 1 and least favorite gets a 5.

MSA Tube	5	1	5	2	2	5	5
ATI PortaSens II	4	4	2	3	5	1	4
Dräger MiniWarn	3	3	4	4	4	2	1
Dräger Pac III	1	2	1	1	1	3	2
Lumidor MicroMax	2	5	3	5	3	4	3

MSA Tube	5	5	5	5	5	5	5
ATI PortaSens II	3	4	1	2	3	4	3
Dräger MiniWarn	2	1	2	3	4	2	2
Dräger Pac III	1	2	3	1	1	1	1
Lumidor MicroMax	4	3	4	4	2	3	4

MSA Tube	5	4	5	5	3	5	1
ATI PortaSens II	3	5	4	4	2	4	2
Dräger MiniWarn	4	2	2	3	1	3	3
Dräger Pac III	1	1	1	1	4	1	4
Lumidor MicroMax	2	3	3	2	5	2	5

MSA Tube	2	5	5	2	5	5	5
ATI PortaSens II	5	2	4	5	3	4	3
Dräger MiniWarn	4	3	1	4	4	2	4
Dräger Pac III	3	1	2	1	2	1	1
Lumidor MicroMax	1	4	3	3	1	3	2

	Sum	Average	High	Low	Range	Mode	St Dev
MSA Tube	117	4.333	5	1	4	5	1.416
ATI PortaSens II	93	3.444	5	1	4	4	1.156
Dräger MiniWarn	77	2.852	5	1	4	4	1.076
Dräger Pac III	45	1.667	5	1	4	1	0.956
Lumidor MicroMax	88	3.259	5	1	4	3	1.145

APPENDIX C.1

TABLE XL

MADM MODEL – COSTS AND BENEFITS

Decision matrix after quantification of nonnumerical attributes

	Cost Initial Equipment	Cost Additional Equipment	Cost Recalibration	Cost Labor	Benefit User-Friendly	Benefit Convenience	Benefit Ruggedness	Benefit Worker safety	Benefit Accuracy
MSA Tube	215	32	0	6.8	3.05	3.95	3	2.65	90.12
Dräger MiniWarn	1810.38	0	50	0.4	3.3	3.55	3.2	3.9	84
Dräger Pac III	779	0	50	0.4	3.55	3.5	3.15	4.1	97.63
ATI PortaSens II	1500	0	150	0.8	2.85	3.45	3	3.75	76.63
Lumidor MicroMax	1482	0	50	0.4	3	3.4	3.05	3.95	95

Initial Equipment Cost and Recalibration Cost Combined

	Cost Initial Equipment	Cost Additional Equipment	Cost Labor	Benefit User-Friendly	Benefit Convenience	Benefit Ruggedness	Benefit Worker safety	Benefit Accuracy
MSA Tube	56.71645838	32	6.8	3.05	3.95	3	2.65	90.12
Dräger MiniWarn	518.3976625	0	0.4	3.3	3.55	3.2	3.9	84
Dräger Pac III	246.3222167	0	0.4	3.55	3.5	3.15	4.1	97.63
ATI PortaSens II	518.1681587	0	0.8	2.85	3.45	3	3.75	76.63
Lumidor MicroMax	431.7718457	0	0.4	3	3.4	3.05	3.95	95

APPENDIX C.2

TABLE XLI

MADM MODEL – VECTOR NORMALIZATION

Normalized Decision Matrix (Rij)

	Cost	Cost	Cost	Benefit	Benefit	Benefit	Benefit	Benefit
	Initial Equipment	Additional Equipment	Labor	User-Friendly	Convenience	Ruggedness	Worker Safety	Accuracy
MSA Tube	0.06391007	1	0.988104929	0.43169143	0.494068545	0.435446207	0.319700857	0.452833516
Dräger MiniWarn	0.584148443	0	0.058123819	0.46707597	0.444036288	0.464475954	0.470503148	0.422081839
Dräger Pac III	0.277564406	0	0.058123819	0.50246052	0.437782255	0.457218518	0.494631515	0.490569642
ATI PortaSens II	0.58388983	0	0.116247639	0.40338379	0.431528223	0.435446207	0.452406873	0.385049182
Lumidor MicroMax	0.486535472	0	0.058123819	0.42461452	0.425274191	0.442703644	0.47653524	0.477354461

APPENDIX C.3

TABLE XLII

MADM MODEL – SIMPLE ADDITIVE WEIGHTING

Weighted Normalized Decision Matrix

	Cost	Cost	Cost	Benefit	Benefit	Benefit	Benefit	Benefit
	Initial Equipment	Additional Equipment	Labor	User-Friendly	Convenience	Ruggedness	Worker Safety	Accuracy
Decision Maker Weights (Wi)	0.066	0.066	0.066	0.25	0.25	0.1	0.1	0.1
MSA Tube	0.004218065	0.066	0.065214925	0.10792286	0.123517136	0.043544621	0.031970086	0.045283352
Dräger MiniWarn	0.038553797	0	0.003836172	0.11676899	0.111009072	0.046447595	0.047050315	0.042208184
Dräger Pac III	0.018319251	0	0.003836172	0.12561513	0.109445564	0.045721852	0.049463151	0.049056964
ATI PortaSens II	0.038536729	0	0.007672344	0.10084595	0.107882056	0.043544621	0.045240687	0.038504918
Lumidor MicroMax	0.032111341	0	0.003836172	0.10615363	0.106318548	0.044270364	0.047653524	0.047735446

APPENDIX C.4

TABLE XLIII

MADM MODEL – IDEAL AND NEGATIVE IDEAL SOLUTIONS

Ideal Solution

	Cost	Cost	Cost	Benefit	Benefit	Benefit	Benefit	Benefit
Best	Initial Equipment	Additional Equipment	Labor	User-Friendly	Convenience	Ruggedness	Worker Safety	Accuracy
A*	0.004218065	0	0.003836172	0.12561513	0.123517136	0.046447595	0.049463151	0.049056964

Negative-Ideal Solution

	Cost	Cost	Cost	Benefit	Benefit	Benefit	Benefit	Benefit
Worst	Initial Equipment	Additional Equipment	Labor	User-Friendly	Convenience	Ruggedness	Worker Safety	Accuracy
A-	0.038553797	0.066	0.065214925	0.10084595	0.106318548	0.043544621	0.031970086	0.038504918

APPENDIX C.5

TABLE XLIV

MADM MODEL – SEPARATION MEASURE

Separation Measure from Ideal Solution (Si*)	
s1	0.093621806
s2	0.038293288
s3	0.019934375
s4	0.046776673
s5	0.038240525
Separation Measure from Negative-Ideal Solution	
s1	0.039632862
s2	0.092997045
s3	0.097868136
s4	0.088575969
s5	0.092329452

APPENDIX C.6

TABLE XLV

MADM MODEL – RELATIVE CLOSENESS TO IDEAL SOLUTION

Relative closeness to the ideal solution (Ci*)		
c1	0.297421943	MSA Tube
c2	0.708331246	Dräger MiniWarn
c3	0.830781408	Dräger Pac III
c4	0.654408869	ATI PortaSens II
c5	0.707126201	Lumidor MicroMax

APPENDIX C.7

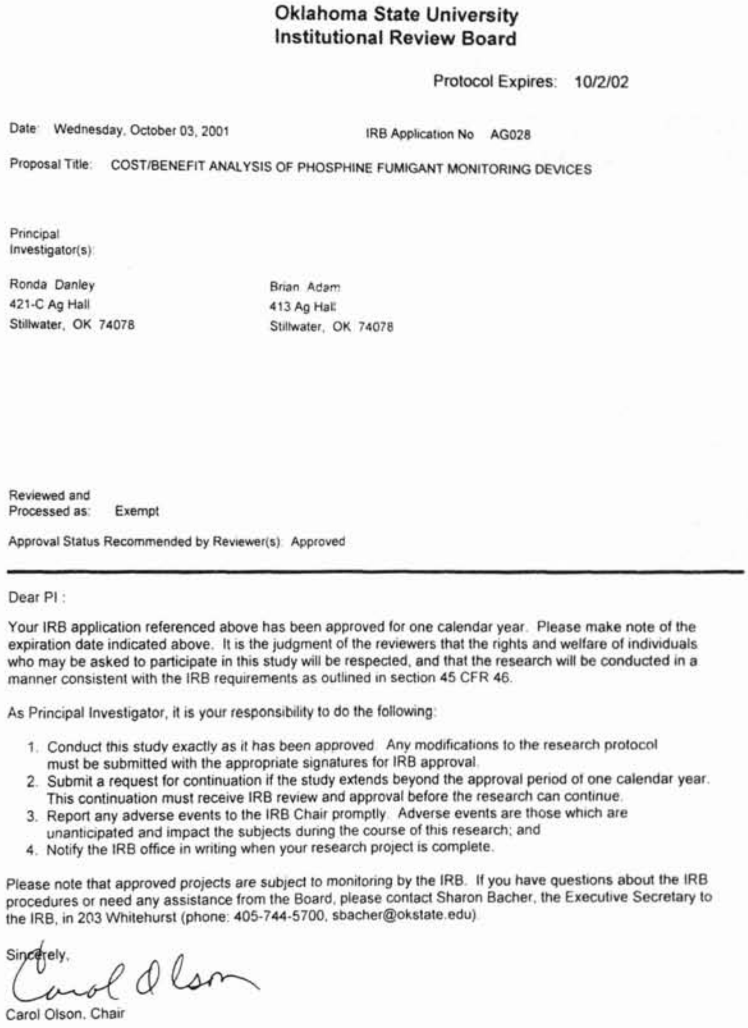
TABLE XLVI

MADM MODEL – RANK PREFERENCE ORDER

Rank Preference Order	
1	Dräger Pac III
2	Dräger MiniWarn
3	Lumidor MicroMax
4	ATI PortaSens II
5	MSA Tube

APPENDIX D.1

IRB REVIEW FORM



Oklahoma State University
Institutional Review Board

Protocol Expires: 10/2/02

Date: Wednesday, October 03, 2001

IRB Application No AG028

Proposal Title: COST/BENEFIT ANALYSIS OF PHOSPHINE FUMIGANT MONITORING DEVICES

Principal Investigator(s):

Ronda Danley 421-C Ag Hall Stillwater, OK 74078	Brian Adam 413 Ag Hall Stillwater, OK 74078

Reviewed and Processed as: Exempt

Approval Status Recommended by Reviewer(s): Approved

Dear PI :

Your IRB application referenced above has been approved for one calendar year. Please make note of the expiration date indicated above. It is the judgment of the reviewers that the rights and welfare of individuals who may be asked to participate in this study will be respected, and that the research will be conducted in a manner consistent with the IRB requirements as outlined in section 45 CFR 46.

As Principal Investigator, it is your responsibility to do the following:

1. Conduct this study exactly as it has been approved. Any modifications to the research protocol must be submitted with the appropriate signatures for IRB approval.
2. Submit a request for continuation if the study extends beyond the approval period of one calendar year. This continuation must receive IRB review and approval before the research can continue.
3. Report any adverse events to the IRB Chair promptly. Adverse events are those which are unanticipated and impact the subjects during the course of this research; and
4. Notify the IRB office in writing when your research project is complete.

Please note that approved projects are subject to monitoring by the IRB. If you have questions about the IRB procedures or need any assistance from the Board, please contact Sharon Bacher, the Executive Secretary to the IRB, in 203 Whitehurst (phone: 405-744-5700, sbacher@okstate.edu).

Sincerely,

Carol Olson

Carol Olson, Chair

V

VITA

Ronda Christine Danley

Candidate for the Degree of

Master of Science

Thesis: ECONOMIC EVALUATION OF PHOSPHINE FUMIGANT MONITORING DEVICES USED IN OKLAHOMA COMMERCIAL GRAIN ELEVATORS

Major Field: Agricultural Economics

Biographical:

Education: Graduated from Uniontown High School, Uniontown, Kansas in May 1995; received Bachelor of Science degree, majoring in Milling Science and Management from Kansas State University, Manhattan, Kansas in August 2000. Completed the requirements for the Master of Science degree with a major in Agricultural Economics at Oklahoma State University in May, 2002.

Experience: Employed as research assistant; Oklahoma State University; Department of Agricultural Economics, 2000 to present.