Current Scope and Usage of Fumigation and Controlled Atmospheres for Pest Control in Stored Products

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Abstract

The prospects for controlling stored product pests with modified or controlled atmospheres (CA) has taken on new dimensions in recent years as increasing numbers of basic scientific and applied studies have pointed up the advantages and feasibility of using such procedures. Both the technology for producing and maintaining controlled atmospheres, and the protocols for applying treatments more effectively and efficiently, are gradually emerging from this research. A somewhat similar technology with similar protocols and similar objectives has been used in the fumigation of grain and food products so that the two processes have often seemed competitive and the choice has been determined by relative efficacies and costs of the two approaches.

For the fumigants, where public concern to reduce or eliminate highly toxic chemicals from the environment is increasing, current research has been directed mainly towards an increased assurance for safety and efficacy. The development of insect resistance to the fumigant phosphine threatens to reduce effectiveness of this very widely used compound. Incorrect or careless usage of phosphine and other fumigants is also a matter of serious concern, particularly for reasons of safety and public acceptance. For the fumigant methyl bromide, the residues and reaction products remaining in treated food must be shown to be relatively innocuous for this product to be reregistered by the U.S. Environmental Protection Agency.

New developments in CA technology, such as the use of oxygen absorbing systems to establish oxygen deficient atmospheres, the development of hollow fibre, selectively permeable membranes to separate oxygen from nitrogen, and the use of new sealing materials and techniques, plus the increasing flow of new information on the toxicity of various atmospheres to pests in various stages and conditions, promises to increase the feasibility of adopting CA treatments for some routine requirements.

THE development of pest control procedures for stored products has been greatly complicated in recent years by rapidly changing practices. Changes in the types and quantities of commodities, in the methods of handling and processing, and in socioeconomic requirements all have had pronounced influence on infestation problems. New species of insects that were formerly of only minor significance have become serious economic pests: for example, the larger grain borer (*Prostephanus truncatus*), a little known insect from Central America, has become a serious pest in several parts of Africa (Hodges 1986). Also, the Khapra beetle (*Trogoderma granarium*) has spread and created problems that have necessitated large and costly eradication programs. All of these changes have made pest control a formidable and continuing challenge. The question is: how can stored products best be protected under these constantly changing conditions?

Various methods have been used for controlling stored product insects in the past.

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One very successful approach has been to modify the atmosphere so that the pest organism cannot survive in it. Atmospheres have been modified mainly in two ways: either by changing proportions of normal components, e.g. oxygen and carbon dioxide, or by injection of toxic gases. Both of these processes have been used in one form or another and with varying degrees of success since time immemorial. However, it is only in recent times that comprehensive studies have been made to understand the dynamics and the potential of the processes. Fumigants have been studied on a scientific basis for just over 100 years and controlled atmosphere storage since the work of Dendy and Elkington (1918a, b). Over the intervening years much research has been done to define the various physical and physiological parameters central to effective pest control. The current usage and potential for future use of these processes is directly dependent on this research. Basic understanding of the parameters of the processes is essential to the development of effective, economic techniques.

Fumigation has been by far the dominant method of pest control in stored products; it has been given preference in many cases because of ease of application and relatively low cost. Sometimes fumigation has been so easy and successful that it has been used to obviate basic requirements of good sanitation. However, as a result of overuse and abuse, and certain adverse features, its popularity has declined in recent years and the need for other approaches has become more apparent.

Controlled atmospheres offer attractive alternatives to the practice of fumigation. The manipulation of normal atmospheric constituents to create conditions lethal to insects is far more compatible with modern philosophies of pest control than is the use of toxic pesticides. However, further information and improved technology is required to exploit the full potential of controlled atmospheres.

Much information on the use of controlled atmospheres and fumigation was brought together and discussed at the two previous conferences on this subject (Shejbal 1980; Ripp et al. 1984). This paper is intended to provide information on research and development in the field since the last conference and to relate this to current pest management strategies.

Fumigants and Fumigation Techniques

The number of fumigants available for pest control in stored products has decreased in recent years and is now limited mainly to the two compounds methyl bromide and phosphine. The continued use of even these two compounds is largely dependent on their continued acceptability to registration authorities and the general public. Misuse, adverse publicity, the discovery of hazardous effects (or even the fear of such effects), all serve to jeopardise continued use of these two materials. Some hazards may be alleviated by research and new data on properties, but misuse and adverse publicity present problems that are almost insoluble. Nevertheless, it is important to know of these problems and accommodate their effects and implications in future plans for fumigants.

Misuse of Fumigants

Fumigants are misused when they are improperly applied or when they are applied for the wrong reasons. Fumigants have in the past sometimes been used in place of good sanitation procedures as well as for other purposes for which they are not intended, such as fulfilling terms of contracts without regard to efficacy in controlling insects. Misuse not only causes excessive waste of materials but can also greatly weaken the main objective in registering fumigants for pest control.

The safe and proper application of fumigants is the responsibility of all of those associated with their production and use. The manufacturers of the materials, the managers that plan for their use, and the fumigators themselves, all have a responsibility in ensuring that the materials are employed with the greatest efficiency and safety. The manufacturer is required to label the product with detailed information indicating the conditions for proper use and safety. In most developed countries, such labels are legal requirements and they must be printed in the official languages of the countries concerned. However, in many of the developing parts of the world these same pesticides are supplied and used without labels in official national languages. This means that the pesticides are very often handled and used by people who are unaware of their properties and hazards and, as a result, accidents—sometimes fatal—occur. Such accidents are more frequent than may be generally known and they would not be tolerated in many developed countries.

In addition to the labelling, the usage of the fumigant is important. Although the intended objective of a fumigation is to control or eliminate insects in commodities, fumigants are sometimes applied to fulfill the terms of a contract without regard to efficacy or control. For example, I recently observed the fumigation of a cargo of rice on a ship where the treatment was conducted not to control insects but merely to satisfy the terms of a contract. The dosage used was considerably below the recommended level and no assessment of efficacy was made: all that was sought was the certificate indicating that the treatment had been carried out. Also, in this particular treatment, safety precautions were grossly deficient. The applicators had gas masks available but did not wear them, despite the presence of dense clouds of white smoke emanating from open packages of the phosphine-producing formulation that was used. The labelling instructions on these packages were in four European languages (German, English, French, and Spanish) but not in the national language of the country concerned. The applicators were unfamiliar with any of these foreign languages and hence were unable to read of the hazards involved.

Accidents are also known to occur in fumigation of barges where families live and work. People, especially children, are particularly vulnerable and are sometimes injured or killed by improper use of fumigants, but occurrence of such accidents seems to go largely unreported. The Intergovernmental Maritime Organization (I.M.O. 1980; 1984) has published 'Recommendations on the Safe Use of Pesticides on Ships' to help overcome such problems but, unfortunately, these recommendations are not always followed.

The misuse of fumigants is a matter of great concern to all, regardless of what part of the world it occurs. Accidents and adverse publicity are likely to have serious implications for the future acceptance of these materials for use on food commodities.

Repercussions from Misuse of Fumigants

The adverse publicity given to fumigants seems already to be producing considerable reaction against their application to stored products. Environmentalists and other reaction groups are questioning the use of any of these toxic materials because of possible long-term effects on human health and the environment.

The State of California in the United States already has a law (Proposition 65) requiring that warning signs be posted by food distributors when food or other materials containing any carcinogenic agent are being sold or retained on the premises. This means, for example, that foods treated with a pesticide shown to have any carcinogenic properties would need to be so labelled. Further developments that could emanate from such policies can easily be envisaged.

Resistance to phosphine is another serious consequence of improper use of fumigants. A number of reports in the past have alluded to the possibility of resistance to phosphine and Taylor and Halliday (1986) have confirmed the geographical spread of resistance to phosphine in several coleopterous pests of stored products. Unsatisfactory sealing of storages, leading to rapid loss of gas and consequent inadequate exposure of the insects, was proposed as the reason for resistance and some strains have been widely dispersed in certain regions of the world.

The fact that most occurrences of resistance have been in tropical regions will no doubt have serious consequences for stored product pest control in those areas but the phenomenon also has long-term implications for temperate areas where tropical commodities are traded. A solution to resistance problems is not likely to be easily found. The possibilities and consequences of resistance to phosphine have been known for some time: part of the answer to them lies in proper management and careful, effective use of the fumigant.

Research on Fumigants and Fumigation

Dosage response studies on insects

Some investigations in this area have been carried out since the previous conference on controlled atmospheres and fumigation in 1983. They have been directed at both efficacy in controlling insects and safety in use. Studies on the toxicity of phosphine to tolerant stages of the very serious stored product pest

Trogoderma granarium have shown that larvae of several stocks (in diapause) can be completely controlled in a 6-day exposure at 20°C to 1.4 mg/L of phosphine. Control could also be achieved in 4 days when 2.0 mg/L methyl bromide was mixed with the phosphine (Bell et al. 1984). These authors concluded that use of the mixture of the two fumigants reduced the chance of selecting for resistance to phosphine.

Laboratory investigations on the relationship of concentration of phosphine and exposure time to toxicity have shown that mortality of at least some species of stored product insects may decline at concentrations above 0.5 mg/L (Winks 1984). Exposure to concentrations above this level can cause insects to become narcotised, so that they are more tolerant to the fumigant. This finding has some relevance, particularly for laboratory studies on dosage response of insects to this fumigant, and it should help to alleviate problems of data inconsistencies that have been encountered by investigators in toxicity studies.

Flammability of phosphine at reduced pressures

Phosphine is normally applied at atmospheric pressures, under which condition there is no risk of flammability due to pressure changes. However, there has been some concern about its stability in forced circulation systems where the use of fans to disperse the fumigant is known to create pressure changes in certain regions of the system. Phosphine has not been recommended for use under such conditions in the past because of uncertainty about its stability at reduced pressures.

Bond and Miller (1988) investigated the problem. They found that the lowest concentration at which flammability occurred was 1.67% at a pressure of 150 mmHg. Below this concentration no reaction occurred at any pressure in the range of 760–150 mmHg.

Since a concentration of 1.67% phosphine is far greater than the level used for pest control, there does not seem to be a significant risk of fires or explosions due to reduced pressures. This information may be of some value for improving efficacy of phosphine: the use of recirculation systems to promote rapid and uniform distribution of the gas could be effective in improving the treatment so that resistance cannot develop.

Dispersal of methyl bromide around flour mills after a fumigation

Over the years that fumigants have been used for pest control some concern has been raised about the dispersal and hazard of the residual fumigant exhausted into the atmosphere from fumigated facilities. This concern was highlighted recently in the Province of Ontario in Canada when regulatory authorities applied severe restrictions to the aeration of flour mills after fumigation. One of the main questions was whether or not the gas was moving to residential areas in concentrations above permitted threshold limits. No information was available on the levels of exhausted fumigant that might occur in the vicinity of fumigated buildings during the aeration period and patterns of dispersal of the gas were not known.

An investigation of this matter in three different flour mills showed that concentrations inside the mills dropped by 85% or more during the exposure period, even when the initial dose was supplemented by additional fumigant (Bond and Dumas 1987). Thus, only a small proportion of the original dosage remained to be exhausted into the outside atmosphere during the aeration period. Measurements of the concentrations outside one flour mill showed a maximum concentration of 27 ppm at 25 m distance in the first 5 minutes of the aeration, and 7 ppm at 20 minutes. The results obtained in these tests suggested that dispersal of the fumigant was likely to be erratic and transitory, but when treatments were carried out according to recommended procedures the risk of toxic exposure to personnel outside the mill was not great.

Residues of methyl bromide in treated commodities

The reregistration in the United States of methyl bromide as a fumigant of food commodities is dependent on the availability of information on the nature and safety of its residues. Because methyl bromide is known to have mutagenic potential the U.S. Environmental Protection Agency required data on both the presence of unchanged methyl bromide in food commodities and on products formed by reaction with methyl bromide for the reregistration process.

It is known that proteins are the major site of methylation when commodities are treated with this fumigant. The sites of methylation in several commodities—wheat, oatmeal, peanuts, almonds, apples, oranges, maize, alfalfa and potatoes—were studied by Starratt and Bond (1989). Differences were observed in levels of the major products of *O*- and *S*-methylation (methanol, dimethyl sulphide, and methyl mercaptan) that resulted from treatment of the fumigated materials with 1N sodium hydroxide. In studies of maize and wheat, histidine was the amino acid which underwent the highest level of N-methylation.

The possibility of methyl bromide methylating DNA in foodstuffs, thereby posing a hazard to the genetic constitution of the consumer, was also studied (Starratt and Bond 1988). Methylated purines and/or pyrimidines, nucleotides, and other methylated fragments of nucleic acids might possibly be reincorporated into the DNA, potentially leading to faulty paring of the bases and consequent mutation. The results showed that methylation of DNA occurred to a significant extent in maize and wheat, the two commodities studied. Major products identified were 7 methylguanine and 1 methyladenine, along with lesser amounts of 3 methyl cytosine and 3 methyladenine. Of the guanine residues in the DNA, 0.5–1% were methylated during treatment with 48 mg/L methyl bromide for 72 hours. The significance of these results is not completely known, but the products of the treatment are naturally occurring materials not normally associated with mutagenicity or carcinogenicity.

Controlled Atmosphere Storage

Controlled atmosphere treatments depend for their effectiveness in controlling insects on removal of life-supporting oxygen or addition of toxic levels of carbon dioxide, or a combination of the two. The underlying mechanisms that convey effectiveness of the two processes are quite different and, to be clearly understood, they must be considered separately in laboratory experiments. However, investigation of the combined effects of the two processes is also needed, in order to assess joint action and determine total effectiveness. In practical control treatments, the levels of both oxygen and carbon dioxide are frequently changed so that toxicity may be enhanced by the combined effects of the two (Bell 1984).

Oxygen Deficient Atmospheres

Insects can survive without oxygen or with depleted oxygen for varying lengths of time depending on species of insect, stage of development, temperature, previous history of the population, and other factors. Oxygen concentrations around 1% or less are usually recommended for control, but some species can be controlled with oxygen concentrations as high as 4% (Reichmuth 1986). Eggs of *Ephestia elutella* and *Plodia interpunctella*, and adults of *Oryzaephilus surinamensis* and *Tribolium confusum*, were controlled in 10 days at 15°C and 6 days at 20°C in 3% oxygen, and in 18 days using 4% oxygen. However, the granary weevil *Sitophilus granarius* at various stages of development required up to 41 days at 20°C and 55 days at 15°C. The pupal stage was most tolerant at both temperatures. In an atmosphere completely devoid of oxygen, the granary weevil has been shown capable of surviving for more than 4 days at 25°C (Bond 1961) and this survival rate has been extended to over 11 days when insects were selected for tolerance to anoxic conditions over a number of generations (Bond, unpublished data).

In a review of controlled atmosphere requirements, Annis (1986) has concluded that, while the majority of stored product insects are killed in 10 days with oxygen deficient atmospheres, dosage regimes should be based on the response of the pupae of *Sitophilus oryzae*. Control of this very tolerant insect would give control of other species present. He has suggested a provisional dosage regime of 0–1% oxygen for 20 days for grain temperatures of 20°–29°C.

Carbon Dioxide Enriched Atmospheres

Since the addition of carbon dioxide (CO_2) to storage atmospheres usually involves simultaneous depletion of oxygen, the toxicity of carbon dioxide to insects is frequently studied in association with some degree of oxygen deficiency. Consequently, the response of the insects may be due to both anoxia and the toxicity of carbon dioxide: oxygen deficiency may give an enhanced effect but complete anoxia may reduce or nullify the effectiveness of carbon dioxide.

Using a range of low oxygen atmospheres Krishnamurthy et al. (1986) have shown that CO_2, at levels which alone would not be effective in controlling insects, substantially reduced the length of the exposure period necessary for control. In all of the five species tested except one (*Sitophilus granarius*) mortality increased as the concentration of CO_2 was increased and that of oxygen decreased down to 0.5%. With *S. granarius,* adult survival in CO_2 declined with decreased oxygen down to 1.5% but at oxygen concentrations below 1% more insects survived. Some requirement for oxygen seems necessary for the carbon dioxide to exert its maximum effect on this insect.

Following studies of the effect of high concentrations of CO_2 on the Khapra beetle, *Trogoderma granarium,* Spratt et al. (1985) suggested that insects can be classified into two categories according to their response to modified atmospheres. Some insects, e.g. *Sitophilus* spp., are more susceptible to CO_2 in atmospheres with some oxygen, while others are more susceptible in completely anoxic atmospheres. The Khapra beetle was found to belong to the latter group and very low oxygen atmospheres gave more effective control than mixtures of CO_2 with higher levels of oxygen.

The data of both Reichmuth (1986) and Krishnamurthy et al. (1986) show that effectiveness of CO_2 is appreciably increased with reduced oxygen concentrations, at least down to the 1% level. The reversal in response shown by *Sitophilus* species, and possibly others, at very low oxygen concentrations may simply indicate that these insects have some appreciable tolerance to anoxia and that the toxic effects of CO_2 are dependent on some functioning of aerobic metabolic systems. Other factors such as water loss from the insects could also be involved.

From the point of view of practical application of controlled atmospheres, these investigations, plus many previous studies, are providing the biological information necessary to fully exploit these types of treatments. Although some of the information may not be directly applicable to field situations, it does provide greater understanding of the way that insects respond and the conditions that will give control. We now have a reasonable knowledge of the dynamics and potential of CA in providing effective insect control and safe food storage. The challenge for the future seems to centre mainly on the technology of establishing and maintaining controlled environments in an efficient and economical manner.

Developments in the Technology of CA Storage

The success of the CA process is heavily dependent on the technology that is developed coincident with scientific research on toxicity. Considerable progress has been made in the past few years on the technology of both producing and maintaining modified atmospheres. A variety of methods for establishing atmospheres of nitrogen and/or carbon dioxide in sealed spaces (from pressure cylinders or tanks, by using exothermic generators, by using oxygen absorbants, or by metabolism of micro-organisms) has been tested and developed. Much information on these developments has been brought together in the proceedings of the two previous conferences on CA and fumigation (Shejbal 1980; Ripp et al. 1984) and in other publications such as Banks and Sharp (1979), Banks et al. (1979), Banks and Annis (1981), and Fleurat Lessard and Le Torc'h (1986). A comprehensive assessment of sealant systems for treatment of concrete grain storage bins to permit their use with fumigants or controlled atmospheres has been compiled by Banks (1984).

Small containers for storage and shipment of 50 kg quantities of peanuts in low oxygen or CO_2 enriched atmospheres have also been developed and tested (Slay et al. 1982). These containers, which had a laminated plastic liner, were found to maintain integrity for several months after shipment and storage, with no sign of insect or mould contamination. An oxygen absorbing material for producing oxygen deficient atmospheres within small packages has also been tested (Ohguchi et al. 1983). With such a material inside packages the contents could be preserved for long periods without deterioration or unwanted residues.

One problem encountered with the use of carbon dioxide in concrete storages has been reaction of the gas with the concrete (carbonation). Investigation of the reaction by Banks and McCabe (1988) suggested that the risk of corrosion of reinforcing steel was low under normal conditions of grain storage at 9.5 to 13.5% moisture content. However, in well-sealed enclosures, the CO_2 in the atmosphere might be rapidly depleted thereby reducing its insecticidal effect and also causing substantial, possibly hazardous, pressure reductions. They recommended that carbonation and associated risks be considered during the design and operation of storages built of reinforced concrete.

Research has also been carried out on the recirculation-rate requirements for adequate distribution of carbon dioxide in grain bins (Navarro et al. 1986) and on the coefficient of diffusion of carbon dioxide through samples of cereals and rapeseed (Singh et al. 1984).

Perhaps one of the most pressing needs for the CA process is the means to generate the atmosphere effectively and economically at the storage site. Recent developments in separating oxygen and nitrogen from the air by the use of hollow fibre membrane separators show great potential in this regard. With this technique, oxygen deficient atmospheres can be produced on site as required, with little or no adverse effect on the commodity and with no apprecia-ble risk to the environment.

The technique relies on the phenomenon of selective permeation of gases through a membrane. Each gas has a characteristic rate of permeation thus permitting 'faster' gases such as oxygen to be separated from 'slower' gases such as nitrogen. Bundles of semipermeable membranes formed into tiny hollow fibres are attached to a manifold and pressurised air is applied. Oxygen permeates the fibres, leaving mainly nitrogen in the exit gas stream. The efficiency of the system in separating oxygen and nitrogen is dependent on its size and operating conditions, and on properties of the membrane. The Prism Alpha nitrogen system produced by Permea Inc. of St. Louis, Missouri, U.S.A. comes in a variety of standard sizes with product flows ranging from less than 200 SCFH (5.7 m^3/h nitrogen) to over 2500 SCFH (670 m^3/h nitrogen). It can operate on compressed air pressures of 80–150 psig but special systems can be designed for pressures up to 600 psig. Nitrogen product from 95–99% oxygen-free can be drawn off at the exit of the system.

The future prospects for the CA technique as a result of this and similar technological developments seem increasingly promising. Procedures that improve efficacy, facilitate application and maintenance, and promote greater economy are of great importance to the CA process. With such developments, CA will be more acceptable as an additional technique or as an alternative to the use of fumigants and other pesticides.

Conclusions

Current trends in stored product insect pest management point to increasing emphasis on prevention and control without traditional pesticides. Public concerns with toxic chemicals in food and the environment are growing, and justifiably so, reflecting a more generally perceived need to restrict their production and use.

While fumigants are likely to be needed for many more years to come, their use must be much more carefully regulated. Manufacturers, fumigators, and government regulatory authorities and, indeed, the stored food industries that benefit from the use of fumigants, all have a great responsibility in ensuring that these materials are not misused or abused. For some situations, because of ease of application and rapid action, fumigants appear to be the only feasible means available for controlling stored product insects.

There remains, however, a pressing need for alternative control measures that do not require toxic chemicals. In the boardrooms of many food storage and processing industries, decisions are, more and more, being directed away from the use of toxic pesticides. The consumer is demanding food that is free from pesticide residues and this demand is likely to become increasingly forceful in the future. Controlled atmospheres, which have minimal adverse effects on either the commodity or the environment, have many of the features that suit current philosophies and requirements. In addition, new techniques and developments are providing expanding possibilities for increasingly efficient and economical procedures for stored products pest control and preservation. Increased emphasis on CA and the research and technology that is required to fully exploit these techniques is likely to provide great benefit to the food storage and processing industries of the future.

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