FUMIGATION AS PART OF AN INTEGRATED PEST MANAGEMENT PROGRAM

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The prevention and control of pest organisms in grain is achieved by a number of policies and procedures that are employed in food storage systems. Careful planning in the design of storage and handling facilities, so that infestation is impeded or prevented, is of great importance. Any peculiarity of the system that might allow the introduction and increase of pest organisms not only endangers the quality of the product but it can also allow cross contamination and undermine the integrity of an entire pest control program. Facilities that are amenable to sanitation and disinfestation procedures are likely to be most beneficial to food storage and handling systems. Best results may be attained by careful integration of all the procedures that will prevent contamination, suppress development or eliminate pest organisms.

Fumigation is a widely used procedure that has served an important role in pest control programs for many years. As fumigants can penetrate into materials to eradicate pest organisms, mainly insects, from sites where no other form of pest control is feasible, they are invaluable agents for use in food preservation programs. The continued utility of fumigants is dependent, not only on their penetrating properties and effectiveness as pest control agents, but also on the introduction of new and adaptable procedures that will meet the demands of an ever-changing food storage technology and on safety procedures that will allow them to be used without harm to human beings. Safety measures, both for workers handling fumigants and for consumers eating treated products, must progress to meet the requirements of present day health standards. Although a great amount of research has been done on fumigants and much information is available on their effectiveness, considerably more information is required to fully exploit the potential applications of these materials for pest control and to ensure that they are used with minimal hazard to man. Continued acceptance of the fumigants by health authorities and the general public is dependent on such information.

CURRENT STATUS OF FUMIGANTS AND FUMIGATION

Fumigants are one of the oldest groups of pesticides in use today. They have been employed on a commercial scale for the treatment of grain and other commodities for over 100 years. There are only a few chemicals that have the appropriate properties to be fumigants and even fewer that are suitable for use in treatment of food materials. Of the variety of compounds that have been tested over the years, less than a dozen have been extensively used as fumigants and many of these have very limited applications; two compounds, methyl bromide and phosphine have proven to be particularly suitable for many different kinds of fumigation treatments and are still extensively used.

Because the statistical possibilities of finding suitable, small molecule compounds, that have not been tested already are very remote, the fumigants that we now have are about the only ones that are likely to be available in the future. This means that the future of the fumigation technique is dependent on a very small number of chemicals and no substitutes are likely to be found. Furthermore, the continued acceptance of these few chemicals is dependent on whether or not the necessary research will be carried out to provide the information needed for them to be used according to modern health standards.

Hazards and Safety Precautions

Fumigants are toxic to man as well as to insects and any exposure before, during or after a fumigation treatment can be harmful to human beings. Safety from occupational hazards and from contamination of food has become a matter of increasing concern in the utilization of fumigants for treatment of food materials. The need for improved safety measures has become more evident as new technology for detection and analysis has become available and as new information on the toxic hazards of fumigants revealed. Both the applicator that uses fumigants and the consumer that eats treated goods must be protected from potentially harmful exposures. Regulatory agencies must move to provide guidelines that will adequately cope with these occupational and residue problems.

Occupational hazards for personnel that handle the toxic gases fall into two categories - acute and chronic hazards. The acute effects of fumigants have long been known and appropriate precautions are usually taken to avoid them. If proper care is taken, work with fumigants is no more hazardous than any other industrial or domestic technique that uses potentially harmful chemicals. Chronic or long-term effects, which may result from overdose to a single exposure of a toxic gas or from repeated exposure to low levels over a period of time, are less evident. The effects may not apppear until long after exposure to the fumigant has taken place and, in some cases, they may not be easily associated with it. Chronic effects may take the form of injury to liver, kidneys or other organs or tissues or there may be other delayed effects. Some of the fumigants have the ability to produce cancer in animals under experimental conditions and it is believed that they may be potential carcinogens for humans. Acrylonitrile, carbon tetrachloride, ethylene dibromide, ethylene dichloride and ethylene oxide are all "suspected" carcinogens (ACGIH, 1981, National Cancer Inst. 1978). Consequently, threshold limit values have been reduced to very low levels and instructions for their use have been revised accordingly, to reduce the hazards.

Residues of fumigants in food materials have also taken on increasing importance as awareness of their presence in food has come about. New instruments and new methods of analysis that can detect and measure residues down to low ranges of parts per billion or less have indicated the occurrence of residues that were previously unsuspected. Consequently the setting of meaningful tolerance levels has become extremely difficult. Acceptable daily intake studies for degradation products and, in some cases, for unchanged fumigant are incomplete and often lacking. Also the toxicological significance of exposure to low levels of fumigants or their residues for extended periods is not known. Authorities are reluctant to set tolerance levels for residues, particularly carcinogens where the long term effects have not been determined.

With the ultra-sensitive methods of detection that are now available, the possibility of fumigating a commodity without leaving some residue that can remain undetected is remote. The question of health hazards cannot be resolved until the toxic effects of these residues have been determined. For fumigants that are suspected carcinogens, the question of health hazards is further complicated by the dearth of knowledge of the cancer-causing process. The possible cumulative effects of repeated exposure to ultra-low levels of carcinogens are not known. Consequently the hazards brought about by exposure to very low levels of suspected fumigant carcinogens cannot be predicted. Further developments in the field of cancer research will be needed, along with additional toxicological data and new developments in safety procedures to adequately cope with this problem.

Health Standards for Fumigants

For the protection of human beings from the toxic effects of airborne substances, such as fumigants, threshold limit values have been established. These values are based on the best available information from industrial experience, from experimental human and animal exposure and, when possible, from a combination of the three. In recent years threshold limit values for many of the fumigants have been reduced to make allowance for known or suspected toxicological effects (Table 1).

Table 1. Threshold limit values for fumigants as listed by the American Conference of Governmental Industrial Hygienists (ACGIH) in 1964 and 1981.

	TLV	
	1964	1981
Acrylonitrile[1]	20	2
Carbon disulphide	20	10
Carbon tetrachloride[2]	10	5
Ethylene dibromide[2]	25	( )[3]
Ethylene dichloride	50	15
Ethylene oxide[2]	50	5
Methyl Bromide	20	5

[1] Listed by ACGIH (1981) as "human carcinogens"

[2] Listed by ACGIH (1981) as "industrial substances suspect of carcinogenic potential for man"

[3] No value assigned because of insufficient information

While threshold limit values are believed to allow adequate protection for customary working situations, i.e. an 8 hour day and 40 hour week, they do not apply to other situations. For fumigation treatments where personnel may be exposed for longer periods of time acceptable threshold values have not been established and the criteria for arriving at such values have not been developed.

In one extensively practised fumigation procedure, i.e. "in transit" ship fumigation, personnel are confined in close proximity to the fumigated areas for continuous and extended periods of time. If current standards for health safety are to be followed it is essential that appropriate threshold limit values should be established to cover such situations. Health authorities state that established threshold limit values based on intermittent exposures cannot be transposed nor related directly to continuous prolonged exposures. The toxicological effects resulting form prolonged exposure could be very different from short intermittent exposures. New information on long term dose-effect relationships is needed to establish meaningful tolerance values for these treatments. Also adequate methods for monitoring the low concentrations of fumigant occurring in such circumstances will be required to meet current health criteria.

Even the data on the toxicity and toxicology of fumigants that we have at present is inadequate as measured by present day health standards. Since fumigants were first used as pesticides in times when knowledge of the hazards of chemicals to human health was far less advanced than it is today, the requirements for health standards were less demanding. Fumigants were registered in those bygone times and are still being used without the information that is presently required for the approval of new pesticides. Regulatory agencies are faced with the dilemma of either by-passing legislative requirements to give continued approval for the fumigants or of de-registering invaluable materials that cannot be replaced.

A review and re-registration process is now underway in Canada and the United States to bring the fumigants in line with the health safety standards set for other pesticides. For this re-registration a considerable amount of toxicological data, that is presently unavailable, will be needed to establish apropriate safety regulations. The question of how to obtain the necessary data and who should underwrite the cost is a difficult one to resolve. Because of the high cost of gathering toxicological data that will meet present day standards, because of the limited markets for fumigants and because most of the fumigants can no longer be covered by patents, chemical manufacturers are reluctant to invest large sums of money in these materials. The benefits derived from the information would, however, be shared by users of fumigants through the world as well as by the manufacturers and suppliers.

This seems to be an area where an international co-operative effort would be invaluable. If several national governments could combine their efforts, together with the appropriate industries, to finance such an operation and carry out the research, the information could be obtained without excessive burden on any one group.

The lack of essential data on fumigant toxicology could jeopardize the development of realistic health standards and might imperil the future approval of fumigants for use on food materials. Regulatory authorities could be forced into the position of banning useful materials because of the fear of harmful effects. It would be unfortunate if some of the fumigants were lost simply because the required toxicological data were unavailable.

Detection and Analysis of Fumigants

Although many new possibilities for rapid detection and analysis of fumigants have become available through modern technology, the development of methods that will fill the needs of fumigators and public health officials has been slow. For several fumigants practical methods that will give instantaneous readings of concentration of the gas in air are not available. For instance there are no quick, easy and inexpensive methods for rapid detection of fumigants such as ethylene dibromide, ethylene dichloride and chloropicrin. For other fumigants like carbon tetrachloride, carbon disulphide, hydrogen cyanide, ethylene oxide and phosphine, where procedures using glass detector tubes or indicator tapes are available, analysis is somewhat cumbersome, often limited in range and the lower limits of detection are barely adequate. Even for the fumigants phosphine and methyl bromide, the lower limits of detection with glass detector tubes (0.1 and 3 ppm respectively) are just below the TLV of 0.3 and 5 ppm and consequently the margin of safety is minimal.

Some instruments that have been widely used in the past, such as the halide leak detector, are now considered to be inadequate to meet the demands of present day health regulations. The halide leak detector has given valuable service to fumigators, over a long period of time, particularly, for the fumigant methyl bromide. It is light-weight, economical and easy to use and it gives an instantaneous response when fumigant is present. It is invaluable as a detector for locating leakage of halide fumigants from treated areas and for rapid warning against toxic concentrations of these compounds. However, it is not sufficiently sensitive to detect the low concentrations that are now established for health protection. For methyl bromide, the instrument will show a response for concentrations down to 10-20 ppm but it will not detect the gas at the presently established TLV of 5 ppm. Therefore the halide leak detector should not be used as an indicator to declare areas safe for re-entry of personnel.

Fumigants in the atmosphere can be detected and analysed with great precision with equipment like gas chromatographs. A new instrument (Fig. 1) designed for field use and one that is portable, easy to use and has a high degree of sensitivity over a wide range of concentrations and down to ultra low levels has come on the market recently (Barker and Leveson, 1980, Bond and Dumas 1982, Dumas and Bond, 1982). This instrument is capable of giving rapid and reliable analysis of methyl bromide, phosphine, ethylene oxide and ethylene dibromide in parts per billion range and it can be adjusted to analyse the high concentrations used for insect control. An infra red analyser that will analyse fumigants over the range of concentrations used for insect control is also available (Webley et al 1981).

Figure 1.

Portable gas chromatograph for measuring low concentrations of fumigants at TLV levels and the high concentrations used in fumigation.

A number of new devices that are being developed for monitoring exposure of individuals to toxic gases (McCammon 1979) may have potential value for personnel using fumigants. They are small, light-weight and can be located in the immediate breathing area of the worker. A whole-air sampler known as "critical orifice personal sampler" has been tested successfully for a number of years and is available commerically. Several passive monitors that collect samples on a collection medium are becoming available. A pocket-size gas chromatograph that will provide real-time warning to acute exposures and will accumulate a workers 8-h time weighted average exposure is in the developing stages.

Methods of analysis for residues of fumigants in food materials have progressed to the stage where very minute quantities of compounds can be detected and measured. Information on many of these methods may be found in the following references: Alumot and Bielorai, 1969, Bielorai and Alumot, 1975, Dumas 1973, 1978, 1980, Dumas and Bond 1975, 1977, 1979, Fairall and Scudamore, 1980, Heuser and Scudamore 1968, 1969, 1970, Jagielski et al 1978, Majumder et al, 1965, Monro, 1969, Scudamore and Heuser, 1971, Stijve 1977. Some information is available on reaction products and the nature of residues remaining in food after fumigation, however, much more research is required to fully assess the significance of fumigation residues to human health.

As more knowledge about the long term hazards of fumigants becomes available and as new methods and equipment for detecting and measuring concentrations of fumigants, both in the environment and as residues in food materials, are developed, the whole procedure of fumigation can be made much safer. All of the facilities of modern technology should be employed to achieve this objective.

Effectiveness of Fumigants in Controlling Insects

The toxicity of fumigants to insects is influenced by environmental factors, particularly temperature, and by the innate characteristics of the insects themselves. Much information has been published concerning the toxicity of various fumigants to stored product insects. In general it can be said that tolerance varies considerably amongst different species of insects and, even within a species, various stages and conditions of the insects may exhibit a range of tolerances. LD_{50} and LD_{99} values for most of the fumigants have been established for most species, particularly for the stages of these insects that are easiest to obtain and treat. Unfortunately the stages that are difficult to procure for experimentation (often eggs and pupae) are the ones that are most difficult to control and toxicity data for these stages are lacking.

The effectiveness of fumigants on insects can also be altered by other characteristics of the insects. Certain stages of some species enter a state of diapause in response to extreme environmental conditions (Howe 1962) and this alters their tolerance to fumigants. For insects in this state, tolerance to methyl bromide and phosphine may be several times greater than for non diapausing insects (Bell 1977a, b).

Protective narcosis can also be a significant factor in fumigant toxicity. If insects are exposed to sublethal concentrations or to excessively high concentrations at the beginning of a treatment they may go into a depressed state where the fumigant is less effective than it would be at normally recommended concentrations. The tolerance of insects to the fumigant phosphine at concentrations in excess of 0.5 mg/l may increase considerably above that which occurs at low concentrations of 0.005 and 0.5 mg/l (Winks 1974a). This makes insect populations more difficult to control.

Several species of stored product insects have the ability to develop resistance to fumigants. Research has shown that strains of insects resistant to methyl bromide and phosphine can be easily produced in the laboratory (Monro et al. 1972, Winks 1974b, Bond and Upitis, 1976). In a global survey Champ and Dyte (1976) found resistance to both methyl bromide and phosphine in wild populations of insects in widely scattered areas of the world. In collections of 849 strains of insects from 82 countries, 5% had some resistance to methyl bromide and 10% to phosphine. It was concluded from this survey (which was made in 1972-73) that resistance to fumigants was, as yet, limited in extent and often at marginal levels, but that it was of some consequence as it posed a real threat to the future use of fumigants as control agents. Considering the facts that (a) further resistance has probably developed in diverse populations of stored product insects since the survey was made some 10 years ago, (b) the number of fumigants approved for use is declining (c) the few fumigants remaining are being used with increasing frequency, the future utility of fumigants will be very limited unless appropriate means are developed to counteract resistance.

The significance of insect resistance to fumigants can be determined best by continual monitoring of insect populations for tolerance. Comprehensive surveys such as that carried out by Champ and Dyte (1976) are needed periodically to estimate the magnitude and gravity of the problem. Much research is required to understand the basic mechanisms of resistance and to design effective countermeasures to cope with resistant population of insects. Information on the characteristics of the resistant insects - the tolerance of different stages of a species, the tendency of different stages to develop resistant traits, cross resistance to other pesticides, biochemical mechanisms conferring resistance, as well as genetic and behavioural features, are necessary to develop comprehensive methods to cope with resistance on a rational basis.

Properties of Fumigants

Although much is known about the properties of fumigants, more information is needed to use them most effectively and safely. For example, sufficient information on flammability and stability of some compounds and on possible relationships between fumigation and dust explosions is not available. With the fumigant phosphine, data on flammability are meager - the influence of temperature and pressure stability of the molecule under the variety of conditions that exist in fumigation milieu have not been defined.

For many years phosphine was not recommended for use in recirculation systems in grain storages for fear of explosion or fire that might occur if the fumigant was subjected to abnormal pressures. Recently practical trials with the fumigant have shown that treatments using a low-flow recirculation technique can be carried out successfully (Cook 1980). The interstitial air of a grain mass is slowly displaced with fumigant-air mixture so that the fumigant is not exposed to appreciable changes in pressure. In this way it can be uniformly dispersed in a few hours to increase the efficacy of the treatment. However, essential information on the parameters related to stability, flammability and explosion hazard of the compound is lacking. The pressure limits to which phosphine can be subjected without danger of fire or explosion, the influence of temperature (in the ranges found in grain storages) on the stability molecule and the possible influence of other factors as dusts, moisture and other gases on the reaction must be determined if the technique is to be used with complete confidence.

Concern also has been expressed over a possible connection between grain dust explosions and fumigant in grain. Some tests have given evidence to suggest that there may be significant interactions between fumigant vapours and explosible dusts. Tests with a non-flammable mixture of carbon tetrachloride and carbon disulphide showed that the explosible concentration of commercial flour dust could be lowered appreciably by the fumigant (Atallah, 1979). However, another investigation with three fumigant mixtures containing carbon tetrachloride and ethylene dichloride or carbon disulphide showed that there was no increase in the severity of grain dust explosions and in some cases the vapours actually suppressed the explosion (Tait et al, 1980).

The uncertainty about any connection between fumigation and dust explosions will remain until further information is available. In the meantime due precautions against creating a hazardous combination of circumstances may be warranted, particularly with fumigants that have relatively low flammability limits.

Another problem sometimes encountered with fumigants concerns corrosion of metals. Phosphine reacts avidly with the metal copper and sometimes causes considerable damage to copper components of equipment exposed to it. Very little information on this problem is available. Some experiments carried out in our laboratory recently have provided some data on the reaction and have shown that anticorrosive agents can reduce the effects of the fumigant to a very low level (Bond et al, 1984). Here again more research is required on the chemistry of the reaction to provide a rational basis for counteracting the effect.

FUMIGATION AND PEST MANAGEMENT PROGRAMS

Fumigation is just one of a number of methods that can be used for controlling pests in stored products. Best control is likely to be obtained when all appropriate measures are taken to eliminate pest organisms. In an effective pest management program, methods of prevention and control are integrated to give maximum protection of goods at the lowest possible cost. A number of other procedures that have been found effective in preventing and controlling infestations are as follows:

1. Sanitation.
2. Exclusion of pests.
3. Low temperature - "freeze-outs", refrigeration, aeration.
4. High temperature - heating of mills.
5. Moisture control - grain drying.
6. Aeration - cooling, drying, elimination of temperature gradients.
7. Protectants - chemicals, inert dusts, natural compounds.
8. Residual insecticide sprays.
9. Atmospheric gases - carbon dioxide, nitrogen.
10. Gamma radiation, radio and sonic waves, microwaves, infrared radiation.
11. Pheromones.
12. Insect growth regulators.
13. Insect pathogens.
14. Predators.
15. Insect resistant packaging.
16. Resistant varieties.

An effective integrated pest management system should begin with comprehensive planning to include all aspects of the problem, followed by the application of appropriate preventative and control methods. For example, the planning of pest management for a commodity like farm-stored grain may be divided into five major categories:

1. Exclusion of the pest organism.
2. Inspection procedures.
3. Good housekeeping and sanitation.
4. Physical and mechanical control.
5. Chemical control.

Infestation problems can often be reduced by careful planning so that the possibilities of pest organisms reaching the commodity will be minimized. Location of the storage relative to sources of infestation is important as well as quality of the structure. Well built storages with a minimum of sites where debris can accumulate and insects develop are desirable. Other features of the storage that should be considered include - facilities for conditioning such as aeration systems or driers, provision for proper inspection and cleaning and appropriate facilities for pest control procedures. An effective pest management program may include the following steps:

1. Use of sound structures for storage of commodities.
2. Maintaining clean conditions around storages.
3. Removal of residues of grain or other material from storage facility 4 to 6 weeks prior to storing newly harvested produce.
4. Spraying of storage with approved residual insecticide after removal of food residues.
5. Storage of commodity in a condition suitable for optimum storage e.g. grain is best stored at low moisture levels.
6. Treatment with appropriate insecticide protectant at time of storage may be desirable.
7. Use of aeration or other procedures to cool grain and maintain uniform temperatures below those favourable for development of pest organisms.
8. Regular inspection to determine:
   (a) evidence of insect activity or the development of micro-organisms
   (b) accumulation of moisture
   (c) changes in temperature
9. If insects are detected grain should be fumigated; where field infestation occurs grain should be fumigated within 6 weeks after harvest. If micro organisms are developing, further drying may be required.

Several fumigation techniques may be combined or incorporated with other practices such as controlled atmosphere techniques or aeration and drying procedures. Some information on the potential usefulness of combining fumigants with carbon dioxide has already been obtained (Calderon and Carmie 1973, Jones 1938, Kashi and Bond 1975). The toxicity of fumigants may be greatly enhanced by combination with treatments where the insects have been weakened by exposure to carbon dioxide or to an anoxic atmosphere. The use of fumigants in conjunction with aeration procedures has yet to be explored.

By careful planning and management, fumigation may be incorporated into food preservation systems so that fumigants can be used more effectively and safely than when used independently. They should never be used as a substitute for sound management and good sanitation procedures The benefits derived can include: reduced cost of storage with improved food quality, reduced residues in food materials, greater occupational safety and less environmental contamination. All of these benefits are of great concern to the general public and will be factors that have to be taken into consideration in the future use of fumigants. The ultimate goal in the control of pests in stored products should be to so improve the methods of handling, storing and processing commodities, that the need for pesticides will decrease. However, the protection of grain from the ravages of pest organisms, particularly insects, will still depend on the judicious use of fumigants for many years in the future. New approaches to effective fumigant utilization can only come through intensive investigation of all the factors that relate to insect control. To date, research on fumigants has trailed far behind other developments in science and technology and users of fumigants have failed to make maximum use of research data and technological innovations. Hopefully increased effort will be made in the future to provide and to employ the necessary information and instrumentation, so that these valuable materials can be utilized with greatest efficacy in comprehensive pest management programs.

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REFERENCES

ACGIH, (1981). Threshold limit values for chemical substances in workroom air adopted for 1981. American Conference of Governmental Industrial Hygienists, 6500 Glenway, Bldg. D5, Cincinnati, Ohio 45211, U.S.A.

Alumot, E. and Bielorai, R. (1969). Residues of fumigant mixtures in cereals fumigated at two different temperatures. *J. Agric. Fd. Chem.* 17:869870.

Atallah, S. (1979). Fumigants and grain dust explosions. *Fire Technology* 15.5-9.

Barker, N. J. and Levson, R. C. (1980). A portable photionization GC for direct air analysis. *American Laboratory*, December, 1980, 76-83.

Bell, C. H. (1977a). Tolerance of the diapausing stages of four species of Lepidoptera to methyl bromide. *J. stored Prod. Res.* 13:119-127.

Bell, C. H. (1977b). Toxicity of PH_3 to the diapausing stages of Ephestia elutella, Plodia interpunctella and other Lepidoptera. *J. stored Prod. Res.* 13:149-158.

Bielorai, R. and Alumot, E. (1975). The temperature effect on fumigant desorption from cereal grains. *J. Agric. Fd. Chem.* 23:426-429.

Bond, E. J. and Dumas, T. (1982). A portable gas chromatograph for macro and micro-determination of fumigants in the field. *J. Agric. Fd. Chem.* 30:986-988.

Bond, E. J. and Upitis, E. (1976). Toxicity and uptake of methyl bromide in hybrid descendants of resistant and susceptible Sitophilus granarius (L). *J. stored Prod. Res.* 12:261-267.

Bond, E. J., Dumas, T. and Hobbs, S. (1984). Corrosion of metals by the fumigant phosphine. *J. stored Prod. Res.* 20 (in press).

Calderon, M. and Carmie, Y. (1973). Fumigation trials with a mixture of methyl bromide and carbon dioxide in vertical bins. *J. stored Prod. Res.* 8:315-321.

Champ, B. R. and Dyte, C. E. (1976). Report of the FAO global survey of pesticide susceptibility of stored grain pests. FAO Pl. Prod. and Prot. Series No. 5, FAO, Rome.297 pp.

Cook, J. S. (1980). Use of controlled air with fumigants in mass grain storages. Report of Degesch Technical Meeting, 21-27 Sept. 1980, 79-85.

Dumas, T. (1973). Inorganic and organic bromide residues in foodstuffs fumigated with methyl bromide and ethylene dibromide at low temperatures. *J. Agric. Fed. Chem.*21:433-436.

Dumas, T. (1978). Modified gas chromatographic determination of phosphine. *J. Assoc. Off. Anal. Chem.* 61:5-7.

Dumas, T. (1980). Phosphine sorption and desorption by stored wheat and corn. *J. Agric. Fd. Chem.* 27:337-339.

Dumas, T. and Bond, E. J. (1975). Bromide residues in apples fumigated with ethylene dibromide. *J. Agric. Fd. Chem.* 23:95-98.

Dumas, T. and Bond, E. J. (1977). Penetration sorption and desorption of fumigant in the treatment of food materials with a methyl bromide - acrylonitrile mixture. *J. Agric. Fd. Chem.* 25:677-680.

Dumas, T. and Bond, E. J. (1979). Relation of temperature to ethylene dibromide desorption from fumigated wheat. *J. Agric. Fd. Chem.* 27:1206-1209.

Dumas, T. and Bond E. J. (1982). Microdetermination of ethylene dibromide in air by gas chromatography. *J. Assoc. Off. Anal. Chem.* 65:1379-1381.

Fairall, R. F. and Scudamore, K. A. (1980). Determination of residual methyl bromide in fumigated commodities using derivative gas-liquid chromatography. *Analyst* 105:251-256.

Heuser, S. G. and Scudamore, K. A. (1968). Determination of residual methyl bromide and ethylene oxide in flour and wheat. *Analyst* 93:252-258.

Heuser, S. G. and Scudamore, K. A. (1969). Determination of fumigant residues in cereals and other foodstuffs: a multi-detection scheme for gas chromatography of solvent extracts. *J. Sci. Fd. Agr.* 20:566.

Heuser, S. G. and Scudamore, K. A. (1970). Selective determination of ionized bromide and organic bromides in foodstuffs by gas-liquid chromatography. *Pestic. Sci.* 1:244.

Howe, R.W. (1962). The influence of diapause on the status as pests, of insects found in houses and warehouses. *Ann. Appl. Biol.* 50:611-614.

Jagielski, J., Scudamore, K. A. and Heuser, S. G. (1978). Residues of carbon tetrachloride and 1,2-Dibromoethane in cereals and processed foods after liquid fumigant grain treatment for pest control. *Pestic. Sci.* 9:117-126.

Jones, R.M. (1938). Toxicity of fumigant-CO_2 mixtures to the red flour beetle. *J. Econ. Ent.* 31:298-309.

Kashi, K. P. and Bond, E. J. (1975). The toxic action of phosphine: role of carbon dioxide on the toxicity of phosphine to Sitophilus granarius (L) and Tribolium confusum Du val. *J. stored Prod. Res.* 11:9-15.

Majumder, S. K., et al. (1965). A paper chromatographic technique for screening volatile chemicals for their reactivity with the constituents of foods. *J. Chromatog.* 17:373-381.

McCammon, C. S. (1979). Advances in personal gas vapour monitoring. *J. Envir. Path. Toxicol.* 2:325-334.

Monro, H. A. U. (1969). Manual of fumigation for insect control. FAO Agricultural Studies No. 79, FAO, Rome, 381 pp.

Monro, H. A. U., Upitis, E. and Bond, E. J. (1972). Resistance of a laboratory strain of Sitophilus granarius (L), to phosphine. *J. stored Prod. Res.* 8:199-202.

National Cancer Inst., (1978). Report: Bioassay of 1,2 Dichloroethane for possible carcinogenicity. *Bull. Brit. Ind. Biol. Res. Assoc.* 17:445.

Scudamore, K. A. and Heuser, S. G. 1971. Ethylene oxide and its persistent reaction products in wheat flour and other commodities: residues from fumigation or sterilization and effects of processing. *Pestic. Sci.* 2:80-91.

Stijve, T. (1977). Improved method for the gas chromatographic determination of inorganic bromide residues in foodstuffs fumigated with methyl bromide. *Deutsche Lebensm. Rund.* 73:321.

Tait, S. R., Repucci, R. G. and Tori, J. C. (1980). The effects of fumigants on grain dust explosions. *J. Hazardous Materials* 4:177-183.

Webley, D. J., Harris, A. H. and Kilminster, K. (1981). The use of a portable gas analyser to measure phosphine concentrations in experimental fumigations in the tropics. *Int. Pest Control* 23:47-50.

Winks, R. G. (1974a). Characteristics of response of grain pests to phosphine. *CSIRO. Div. Ent. A. Rep.* 1973-74, 38-39.

Winks, R. G. (1974b). Fumigant resistance studies. *CSIRO Div. Ent. A. Rep.* 1973-74, 38-39.