HGCA

PROJECT REPORT No. 256

PRACTICAL AND MODELLING STUDIES ON THE USE OF MODIFIED ATMOSPHERES FOR INSECT AND MITE CONTROL IN GRAIN STORES

JULY 2001

Price £4.50

PROJECT REPORT No. 256

PRACTICAL AND MODELLING STUDIES ON THE USE OF MODIFIED ATMOSPHERES FOR INSECT AND MITE CONTROL IN GRAIN STORES

by

S. T. Conyers[1], C. H. Bell[1], B. Harral[2] and B. E. Llewellin[1]

[1] Central Science Laboratory, Sand Hutton, York YO41 1LZ
[2] Silsoe Research Institute, Wrest Park, Silsoe, Beds MK45 4HS

This is the final report of a three year project which started in January 1998. The work was funded by a grant of £172.124 from HGCA (project 1889).

Contents

1. Abstract

This research project covered a new area for the use of modified atmospheres (MA) known as storage life protection. MAs for storage life protection are aimed at the weak points in an insect's life cycle and are less extreme than those used to disinfest grain, and as a result have an economic advantage in their operation. Burner gas from controlled propane combustion was chosen as the candidate MA. The project had three aspects. The first involved laboratory tests at 20°C and 25°C on two species of insects, the grain weevil (*Sitophilus granarius*) and the rust-red grain beetle (*Cryptolestes ferrugineus*), and two species of mites, *Acarus siro* and *Tyrophagus longior*. All these are well-known pests of grain and at various stages in their life cycle show a high level of tolerance to MAs and are therefore difficult to control.

The second aspect involved field trials of this MA supported by the third aspect of the project, modelling using computational fluid dynamics. This was used to help augment the practical knowledge of MA application at CSL and thereby establish the optimal strategy for gas application. The operational cost of using burner gas as the MA for storage life protection was then assessed.

Laboratory results

1) There is a hierarchy of O_2 content of the MA required to prevent breeding:

> 5% for the grain weevil (*S. granarius*) at 20°C and *A. siro* at 25°C.
> 4% for the rust-red grain beetle (*C. ferrugineus*) and the grain weevil (*S. granarius*) at 25°C, and *A. siro* and *T. longior* at 20 and 25°C.
> 3% for the rust-red grain beetle (*C. ferrugineus*) at 20°C.

The target for burner gas for storage life protection is 4 - 5% O_2 for most pests.

2) Economy of the system for storage life protection can be improved with the addition of CO_2. Complete cessation of population growth:

> a) The grain weevil (*S. granarius*): 5% O_2 and 10% CO_2 at 20 and 25°C.
> b) The rust-red grain beetle (*C. ferrugineus*): 5% O_2 and 20% CO_2 at 20°C alone.
> c) *Acarus siro*: 20°C - 6% O_2 and 20% CO_2. 25°C - 6% O_2 and 10% CO_2.
> f) *Tyrophagus longior*: 6% O_2 and 10% CO_2 at 20 and 25°C.

Computational modelling has simulated the interactions between external conditions and internal gas flows in bins, and predicted the O_2 concentrations in the grain bulk. The predictions show that under windy conditions the pressures created by MA injection are unable to prevent air penetration into tower and flat stores despite high MA injection rates.

Guidelines and properties for effective MA application to bulk grain

> a) Minimise leakage into the grain bulk through the structure.
> b) Continuous gas flow system applied to the most gas-tight end of the structure.
> c) The system is capable of functioning in storage facilities that are not designed specifically for modified atmospheres.
> d) The modelling simulations have shown that MA as a control strategy is robust enough to survive intermittent climatic weather conditions which are especially prevalent during the winter storage season.
> e) Previous studies have shown that it is possible to hold MAs of 1% oxygen within bins. This study has shown that the same restraints apply when attempting to hold a bin under 5% oxygen.

Propane gas consumption for production of a 5% oxygen atmosphere is reduced by 25% compared to production of an atmosphere with less than 1% oxygen, the level required to kill the most tolerant life stages within a month at 20°C or above.

2. Summary

2.1. Objectives

1. To define the operational parameters for use of modified atmosphere treatments for the long term protection of grain, to demonstrate efficacy in farm-scale and modelling studies, in parallel with MAFF-funded studies on disinfestation techniques.

2. To establish the carbon dioxide and low oxygen parameters under different conditions of temperature and humidity, able to stop population growth of two common grain beetles (*Cryptolestes ferrugineus* and *Sitophilus granarius*) of higher than average tolerance to modified atmospheres.

3. To establish the CO_2 and low O_2 levels required to prevent population growth of two common grain mites (*Acarus siro* and *Tyrophagus longior*) at different temperatures.

4. To investigate in farm scale experiments the practical feasibility and costs of running modified atmosphere treatment regimes with burner gas for storage life protection.

5. To determine the conditions required to sustain for long periods a suitable environment in different weather conditions by CFD modelling studies.

2.2. Background to the project area

A modified atmosphere (MA) is a term given to a group of inert atmospheric gases such as nitrogen and carbon dioxide (CO_2). Their action as insect control agents is through lack of oxygen (O_2) (the former) or by their own toxicity once present in the target organism's system (the latter). Both these can be supplied in cylinders but a cheaper method is on-site production. This is easier for nitrogen as generators are available to separate nitrogen from oxygen by membrane filtration, pressure swing adsorption or hydrocarbon combustion. The requirement is to reduce the atmospheric O_2 content from 20.9% to below 1%, the level required to produce mortality in all stages of insects and mites found on grain. Carbon dioxide on the other hand has to be increased from 0.03% to at least 40% to be effective. MAs based on either of these gases provide a means of control that would be equally as effective as pesticide admixture for grain without the problems of residues. They do not adversely affect the quality of stored grain at recommended moisture content (mc) levels. In this respect nitrogen-based atmospheres are the safest and storage of wheat and barley under the gas had no effect on their germination or end use properties. Low O_2 MAs may also have the advantage of being able to extend the storage life of grains at mcs that would be considered marginal for safe storage. They could be combined with the existing strategies for cooling and drying of grain and have an important role in integrated management systems that minimise pesticide use. They are already used by the horticultural, agricultural and food industries for the protection and preservation of materials from harvest to the finished product. MAs also offer a means of reducing problems of resistance in insect populations to the present insecticides. The legislative requirements placed on all other chemical control methods mean that MAs are becoming an economically viable alternative to the common methods of insect control.

Previous research programmes funded by MAFF and the HGCA (Project Report No. 125) have looked at different gas production systems for MAs and the lengths of exposures to the MAs that are required to kill the immature stages of the common beetle and mite pests. The field trials at commercial UK storage facilities have shown that for MAs to be effective, they have to be applied continuously to the treatment enclosure. The most economic method for MA production for use in grain stores is by propane combustion. The atmosphere is generated by the controlled burning of propane in air. The gas is then cooled and the water of combustion is removed to give a relative humidity of 50%. The 1% or lower O_2 content required to give 100% mortality also produces a CO_2 level of 12.5%. If the O_2 in the output rises the CO_2 is reduced proportionally. The results showed that not only are treatments based on this method economical but they could also be used as a control strategy throughout the grain storage season. This project aimed to use the same propane combustion system for field trails and this system would be mimicked in the laboratory for the efficacy tests. Storage life protection is a different strategy for the use of MAs. The reliance is not upon mortality but on the disruption of the life cycle of the pests. Most data in the literature relates only to the direct effects of MAs on the survival of individual pests. The majority of researchers were looking at the length of time required to give mortality in all stages of the life cycle. Such data are useful for direct disinfestation purposes but are of less value for storage life protection. However they do provide a starting point to avoid conditions that may increase the risk of selection for resistance. Preliminary laboratory tests have shown that under an O_2 level of 5%, insects and mites lay too few eggs for the population to increase.

The life stages most susceptible to MAs are more likely to provide the weak link in the life cycle that can be exploited with storage life protection. However there is little information available on the minimum O_2 level requirement for each stage of the life cycle and therefore for population increase nor whether this differs between species. Of vital importance for burner gas applications is the effect of the CO_2 on the low O_2 threshold levels for limiting population increase. Its presence does have an additive effect when trying to improve mortality with 1% O_2 atmospheres. The laboratory tests with beetles and mites were designed to provide the biological data which would act as a guide for the effective O_2 level.

2.3. Laboratory Tests

These involved two species of insects, the grain weevil (*Sitophilus granarius*) and the rust-red grain beetle (*Cryptolestes ferrugineus*), and two species of grain mites, *Acarus siro* and *Tyrophagus longior*. All these are well-known pests of grain and at various stages in their life cycle show a high level of tolerance to MAs and are therefore difficult to control. A range of temperatures and relative humidities (rh) were used to assess the affect of these factors on the efficacy of the MAs. Preliminary work had shown that some aspect of egg production was the most susceptible stage in the life cycle for these species and therefore only adults for the insects and the mobile stages for the mites were tested. These are suitable candidates as they would be the most likely stage to have survived in harbourages when there was no grain present in the store. They would therefore be able to reinfest the grain at the start of the storage season and because of this risk it is recommended that MA treatments should be started as soon as possible after loading the store.

Simulated burner gas mixtures with four different O_2 levels, 3, 4, 5 and 6%, and their respective empirically reduced CO_2 levels of 9.5, 8.5, 7.5 and 6.5%, were used with rhs of 75 and 85% at 20 and 25^{o}C, to find the combination of the gases that would prevent the test insects from multiplying. Each species was exposed to each combination of environmental conditions with or without each MA for a month. After this exposure the adult insects were removed, a mortality assessment was made and they were then moved to new media under normal atmospheric conditions for a post exposure period of a month.
Nitrogen was selected as the MA for the tests with mites. The mobile stages of the mites were exposed to the MA at three different O_2 levels, 4, 5 and 6%, on whole wheat at 20 and 25^{o}C,

and 75, 80 and 85% rh, to assess the effect on their population growth. A parallel exposure under normal atmospheric conditions was used as a comparison. The exposure length was determined by the generation time of each species at each combination of temperature and rh. The mc of the whole wheat was assessed before and after the exposure to ensure that any decrease in population growth of the treated mites was due to the MA alone rather than a drop in rh.

Further experiments were carried out with the insects and the mites to see if an increase in the level of CO_2 to 10 and 20% would allow an increase in O_2 to achieve the same or better levels of population suppression.

2.3.1. Results

2.3.1.1. Beetles

The temperature difference between 20 and 25^{o}C was an important factor for adult survival but only at the lower levels of O_2. There was a higher level of adult mortality at 25^{o}C for the rust-red grain beetle (*C. ferrugineus*) and for the grain weevil (*S. granarius*) respectively. Relative humidity was not a significant factor at either temperature for either beetle. The treated adults of both species were able to produce similar numbers of progeny to those from the untreated when they were moved to the normal atmosphere from the MA.

Table S1 shows the combinations of O_2 and CO_2 which stop breeding in both species of insects. The rust-red beetle is more tolerant than the granary weevil of the MAs. Neither species showed any strong correlation of increased efficacy of the combination atmospheres with increased temperature, and in fact control was reached first at the lower temperature for the grain weevil (Table S1).

Table S1. Combinations of oxygen and carbon dioxide (marked by an "X") which prevent population growth of the rust-red grain beetle and the grain weevil

		% O_2							
		3	4	5	6	5		6	
	% CO_2	9.5	8.5	7.5	6.5	10	20	10	20
Species	Temperature (^{o}C)								
Rust-red grain beetle	20	X					X		
	25	X	X						
Grain weevil	20	X	X	X		X	X		X
	25	X	X			X	X		

The addition of CO_2 increased the level of O_2 that can be used to completely stop population growth. However it was most effective against the grain weevil. For this species 5% O_2 and 10% CO_2 would be the most economic option at 25^{o}C. This atmosphere could be obtained by propane combustion after allowing a period for concentrations of CO_2 to pick up after initial sorption in the grain. The burner gas option at 5% O_2 would work even more effectively at 20^{o}C.

The difference in the response of these two insects to the MAs means that correct identification is important so that the optimum MA can be used for each set of environmental conditions. However as these two species are the most tolerant of the insects regularly found in UK grain stores the recommendations arising from this study should cover all other species encountered.

2.3.1.2. Mites

For the mite exposures the mc of the grain was used to assess any changes in the relative humidity (rh) throughout the exposures. Relative humidity is a very important factor controlling population growth in mites and if it falls below 70% population growth will cease. Therefore it was essential that it should not fall during the exposures and that the treated grain remained higher than the controls so that the only factor affecting population growth was the MA rather than a drop in rh. Generally there was a drop in the mc of the controls post exposure and in most cases the comparable treated mc was higher than the control and also increased above the original value. Therefore the conditions for population growth were much better in the treated samples than the controls.

Table S2 shows the oxygen levels required to stop the growth of both mite species. 4% O_2 was the best option for both species though 5% O_2 could be used for *A. siro* at 25^{o}C. The addition of 7.5% CO_2 did not improve on the population suppression achieved by 5% O_2 alone for either species.

Table S2. Combinations of oxygen and carbon dioxide which prevent population growth (marked X) of *Acarus siro* and *Tyrophagus longior*

		% O_2					
		4	5	6	5	6	
	% CO_2	-	-	-	7.5	10	20
Species	Temperature (^{o}C)						
Acarus siro	20	X					X
	25	X	X			X	
Tyrophagus longior	20	X				X	X
	25	X				X	

The addition of 10% CO_2 to 6% O_2 improved the population suppression of both species significantly except *A. siro* at 20^{o}C, for which 20% CO_2 was required. The use of burner gas to produce a 5% O_2 atmosphere (with approximately 10% CO_2 after reaching equilibrium with the grain) should present an economical option without the need of additional CO_2.

The two species do differ in their responses to the environment and to MAs. Under control conditions *A. siro* had a faster growth rate and multiplied well in all the environmental combinations whereas *T. longior* preferred 80 and 85% rh. There was a notable difference in response to the MAs. Treated *A. siro* cultures only had large adults. The O_2 content had been high enough to allow egg hatch, and the subsequent nymphs had then been killed, and it had also prevented oviposition. Therefore an increase in exposure lengths would have ensured complete mortality. With *T. longior* there were more eggs present and therefore eggs were being laid but their hatch was being inhibited by the low O_2 level. Eggs of this species are extremely tolerant to low O_2 atmospheres and it may be necessary to raise the oxygen content to allow egg hatch and then kill the subsequent susceptible nymphs. However results from population suppression have shown that control of the population is lost at these higher O_2 levels. The addition of CO_2 did reduce the numbers of eggs present and therefore the combination of the two gases must be suppressing the oviposition. However in the field situation identification is difficult and therefore if immediate treatment is required it would be safer to apply a general treatment to cover all species.

2.4. Field Trials

The biological data acted as a guide for the effective O_2 level required. The application strategy required to achieve storage life protection was the same as that used to achieve a less than 1% O_2 atmosphere for 100% mortality. A constant flow of MA at the O_2 level known to be effective for storage life protection was selected for application rather than a 1% O_2 MA at a lower flow rate which would allow leakage. The latter would not give a uniform O_2 level throughout the grain bulk nor would there be accurate control of the O_2 level at the leakage sites. It is also more economical to run the burner with the higher O_2 level in the output. Burner gas set to run at 5% O_2 was chosen as the MA to validate the technique in farm scale experiments, supported by modelling studies, and to assess the effectiveness and economics of MAs for storage life protection.

As well as the lack of laboratory data there have never been any field scale trials with MAs of this nature and therefore CFD modelling was used to guide and support the field tests with this strategy. Computational modelling was used to obtain a detailed view of the gas flow within the grain bulk under controlled conditions. This approach describes numerically the heat and mass transfers in the grain and predicts the gas velocities, temperatures and pressures throughout the bulk and their variation with time. The dimensions of the store and the shape of the bulk are reproduced in the model. The grain was modelled as a porous medium, with the properties of wheat at 13% mc. Leakage points, which were of particular importance, were modelled as regions of very low porosity.

The most important considerations prior to use of modified MAs are the limitation of the volume to be treated and the sealing of the storage structure. This is because the aim is to replace the normal atmosphere in the space between the grains with the generated MA. The treatment volume must be limited to the volume of the grain and this volume must be as uniform as possible to assist in achieving this aim. Whichever MA or application system has been chosen the sealing level of the structure will limit the effectiveness of the treatment and also the cost of the treatment in time and in MA generation. Most MA systems require a constant flow of MA through the storage structure to maintain the correct atmosphere within the whole of the treated grain. This atmosphere will be lost more easily to changes in the weather if the quality of seal on the structure is not high enough. Modelling has shown that wind penetration occurs through side wall cracks and around the edges of the covering sheet. The extent of these leaks in practice was not known, so a ‘worst case’ condition was assumed in which continuous leaks (gaps) of approximately 0.2 mm width were placed at the sheet edges and selected joints in the storage structure. The predicted results show that under windy conditions the pressures created by MA injection are unable to prevent air penetration into silos and flat stores despite high MA injection rates (250 l/min). The simulations also show that low oxygen levels can be restored in calm weather. Low oxygen atmospheres can only be maintained continuously if store floors and walls are gas tight.

MA treatments where the aim is complete mortality can withstand certain rises in O_2 concentration without extensions to the treatment time but these interruptions must not amount to days. The use of prolonged interruptions to allow the insects to develop to a more susceptible stage in their life cycle did not work for 1% O_2 systems and it will be even less viable a strategy for storage life protection with its reliance on preventing oviposition in the adult. Any adults present during the interruption would be able to lay eggs and thus prospects for control would be delayed. Therefore it was concluded that although occasional interruptions of gas supply can be tolerated, the only viable approach for storage life protection lies in the maintenance of a constant O_2 level through a continual input of MA throughout the treatment period.

A trial was run to assess the effectiveness of storage life protection under field conditions in ambient temperatures. An atmosphere of 5% O_2 and 9.5% CO_2 was generated at a flow rate of 150 l/min using the propane burner at CSL. The flow was split and 75 l/min was fed into the base of two bins via their aeration ducts. Each bin (3 x 3 x 4 m high) contained 30 tonnes of wheat and the flattened surface of the grain was covered by a sheet of polythene. The grain mcs of the bins were 14 and 16%.

The O_2 and CO_2 of the output and the atmosphere within the bins was monitored and the temperature of the grain was recorded with thermocouples. An assessment of the efficacy of the treatment was achieved by the use of insects inserted into the grain. Adults and, separately, juvenile stages of the rust-red grain beetle (*C. ferrugineus*) and the grain weevil (*S. granarius*) were placed in polypropylene bags (150 x 150 mm) and buried in the grain at a depth of 150 mm near the middle of the bins. They were kept under the atmosphere for 24 days. Similar bags of insects acted as controls and were placed in buckets filled with the grain from the bins in a controlled environment room at 15^{o}C and 60% rh.

2.4.1 Results

The output from the burner was kept at a constant 150 l/min throughout the trial. This flow was split and passed equally to the two bins. Application was to the bin base previously shown to be the most effective method of entry to the bins. The O_2 and CO_2 content of the output was constant throughout this period with an average of 5.6% (range 5.2 - 6.1%) for the former and 9.1% (range 8.7 - 9.5%) for the latter.

The oxygen levels in the two bins rose with the loss of input. This occurred on the eleventh and nineteenth days after the start of the treatment. This was due to a build up of condensate in the output tube. This also affected the rh of the output which had ranged between 40 and 50% but with the blockage rose to 80%. Once this was cleared the rh level dropped back to the required level. There was also a problem with the condensate accumulating in the flow meters for the two bins. This helped to raise the rh but also reduced the flows to the bins as water filled the floats which affected the functioning of the flow meters. Thereafter the output line was fitted with a moisture trap, allowing it to be drained every few days without the need to interrupt the gas flow. Flow meters would not be required in a practical operation and here they were only used to adjust the flows to the two bins so that the optimum maintenance flow could be found for each.

The bins were constructed of metal sheeting and were not perfectly sealed as shown by the ingress of air when an adjacent bin was aerated one night. The flow of the burner was sufficient to compensate for any loss of MA. A higher level of seal would reduce the flow rate required but this also demonstrated that the system is capable of functioning well in storage facilities that are not designed for MAs. Generally the O_2 levels in the bins were close to that of the output. Bin 1 averaged 5.6% (range 5.1 - 6.2%) O_2 and Bin 2 5.7% (4.9 -6.5%). The O_2 contents of the bins were not affected by any changes in temperature even though the difference between ambient and the grain bulks in the bins sometimes exceeded 10^{o}C. This temperature difference has been enough in previous trials to cause an ingress in normal air driven by the temperature gradient. This is prevented by a good level of seal around the base of the bin. There was a general very gradual decrease in the temperature of the bulks of Bin 1

(12.7 to 9.2^{o}C) and Bin 2 (13.8 to 9.7^{o}C) but the surface of the grain (average 7.4^{o}C, range 2.6-10.1^{o}C) followed the changes in ambient temperature (average 7.3^{o}C, range 0.6-11.7^{o}C).

Adult mortality was affected by grain mc for both species of insect. It was significantly higher at the lower mc. However this did not apply to the juvenile stages especially for the grain weevil. There was also little difference in adult numbers emerged between treated and control for this species. There was a reduction of 43.3% due to the MA for the rust-red grain beetle. These results showed that both species are tolerant of low temperatures and that juvenile stages are capable of surviving and therefore for this strategy to be successful it must be used from the start of the storage cycle. At this time it is adults that will be moving from their harbourages to the new grain and starting the infestation if the environmental conditions for population growth are present.

This was a very successful trial of burner gas with the higher levels of O_2 for storage life protection and it showed that the same constraints apply to this technique as to the use of 1% oxygen. A good level of seal to the structure of the bin is essential as well as a gas-proof sheet over the surface of the grain though this trial has shown that the equipment is capable of producing enough flow to take into account a certain level of leakage in the walls of the storage structure. The absence of any means of ingress at the base of the structure prevents the ingress of O_2 due to differences in temperature between ambient and the bulk. The presence of sheeting means that the surface O_2 can be maintained at a sufficient level to control insect population growth.

Propane gas consumption was at 8 l/min which compares with 10.8 l/min for the production of a 1% O_2 atmosphere in the same bin. This was a very favourable saving which meant that a large 46 kg cylinder of propane would last an extra 12 hours and give 2 full days of running. With the assistance of the higher temperatures present at the start of the storage season this would be a very satisfactory technique to stop the build up of pest populations from the adult insects which have managed to overwinter in the fabric of the storage structure.

2.5. Recommendations

2.5.1. Oxygen levels for MAs for storage life protection

Rust-red grain beetle:	20^{o}C - 3% O_2 Burner gas
	25^{o}C - 4% O_2 Burner gas
Grain weevil:	20^{o}C - 5% O_2 Burner gas
	25^{o}C - 5% O_2 Burner gas
Mite species:	20^{o}C - 4% O_2 Burner gas.
	25^{o}C - 5% O_2 Burner gas

2.5.2. Practical considerations

1) The first step for a treatment with MA must be to minimise leakage into the grain bulk through the structure as much as possible. A gas-proof sheet placed over the surface of the grain is also required. A high level of seal reduced the flow rate required and therefore the cost of the MA application.

2) The MA produced the best results with the use of a low input continuous gas flow system applied to a gas-tight base of the structure.

3) The system is capable of functioning well in storage facilities that are not designed specifically for MAs.

4) Previous studies have shown that it is possible to hold MAs of 1% O_2 within bins. This study has shown that the same restraints apply when attempting to hold a bin under 5% O_2.

5) Propane gas consumption for production of a 5% oxygen is reduced by 25% compared to production of an atmosphere with 1% oxygen.

6) Storage life protection will prevent breeding of insect and mite species as long as the correct O_2 level is selected. Breeding will be prevented and complete mortality will be achieved particularly at lower mcs if the exposure is allowed to run for a sufficient length of time.

3. Introduction to the work undertaken in the current project

Modified atmospheres (MA) are generated by altering the normal ratio of atmospheric gases, by harnessing either natural or artificial means of doing so. MAs provide a method of control for use on grain that would be capable of replacing pesticide admixture. They are in constant use in many areas of the horticultural, agricultural and food industries for the protection and preservation of raw materials from harvest to the finished product. For grain their use can be combined with existing strategies for cooling and drying and could have an important role in integrated management systems that minimise reliance on pesticides (Banks *et al.*, 1991). Consumers today expect a final product that is pesticide-free or with much reduced residue levels. MAs also offer a means of reducing problems of resistance in insect populations to the present insecticides. This was an important consideration in the adoption of nitrogen-based MA treatment at the main grain export terminal in Australia (Banks, 1994). The legislative requirements placed on all other chemical control methods mean that MAs are becoming an economically viable alternative to the common methods of insect control.

Previous research programmes funded by MAFF and the HGCA (Conyers *et al*., 1996) have looked at different gas production systems for MAs and the lengths of exposures to the MAs that are required to kill the immature stages of the common beetle and mite pests. The field trials at commercial UK storage facilities have shown that MAs require continuous flow systems for the maintenance of effective atmospheres. The most economic method for MA production was by propane combustion and the results showed that not only are MA treatments economical but they could also be used as a control strategy throughout the grain storage season. This project aimed to use the same propane combustion system for field trails and this system would be mimicked in the laboratory for the efficacy tests.

Most data in the literature (Annis 1987; Bell and Armitage 1992; Bell 1996) have examined only the direct effects of MAs on the survival of individual pests. They were looking at the length of time required to give mortality in all stages of the life cycle. Such data are useful for direct disinfestation purposes but are of less value for storage life protection. However they do provide a starting point to avoid conditions that may increase the risk of selection for resistance. As well as the lack of laboratory data there have never been any field scale trials with MAs of this nature and for the first time modelling is used to guide and support the field tests with this strategy.

The life stages most susceptible to MAs are more likely to provide the weak link in the life cycle that can be exploited with storage life protection. However there is little information available on the minimum oxygen level required for each stage of the life cycle and therefore for population increase nor whether this differs between species. Of vital importance for burner gas applications is the effect of the carbon dioxide on the low oxygen threshold levels for limiting population increase. Its presence does have an additive effect when trying to improve mortality with 1% oxygen atmospheres. The present proposal is designed to firstly provide biological data necessary to guide dosing and application strategies aimed at achieving effective storage life protection and secondly to validate in farm scale experiments supported by modelling studies, economic and effective usage of MAs for this purpose.

4. Objective 1. To define the operational parameters for use of modified atmosphere treatments for the long term protection of grain, to demonstrate efficacy in farm-scale and modelling studies, in parallel with MAFF-funded studies on disinfestation techniques.

The most important consideration prior to use of MA is the sealing of the storage structure. Whichever MA or application system has been chosen the sealing level of the structure will limit the effectiveness of the treatment and will also determine the cost of the treatment in time and in MA generation. Most MA systems require a constant flow of gas through the storage structure to maintain the correct atmosphere within the structure. This atmosphere will be lost more easily to changes in the weather if the degree of seal of the structure is not high enough. MA treatments can withstand certain rises in concentration of oxygen (O_2) without extensions to the treatment time but this must not amount to days (Conyers and Bell, 1996). The use of prolonged interruptions to allow the insects to development to a more susceptible stage in their life cycle did not work for 1% O_2 systems and it will be even less viable a strategy for storage life protection with its reliance on preventing oviposition in the adult. Any adults present during the interruption would be able to lay eggs and thus any possible control would be delayed. Therefore it was concluded that although occasional interruptions of gas supply can be tolerated, the only viable approach for storage life protection lies in the concept of a continual input of gas throughout the treatment period.

Storage life protection is a different strategy for the use of MAs. The reliance is not upon mortality but on the disruption of the life cycle of the pests. Laboratory tests have shown that under O_2 levels as high as 5%, insects and mites do not lay eggs and therefore there is no population increase. It would therefore be beneficial to start this storage protection at the beginning of the storage season when any adult insects that have survived in harbourages since the last storage season would be moving back into the new grain.

5. Objective 2. To establish the carbon dioxide and low oxygen parameters under different conditions of temperature and humidity, able to stop population growth of two common grain beetles (*Cryptolestes ferrugineus* and *Sitophilus granarius*) of higher than average tolerance to modified atmospheres.

5.1. Materials and Methods

A modified atmosphere (MA) based on propane combustion was selected for these tests. For 100% mortality to be achieved by exposure, the oxygen (O_2) content of the combustion gas needs to be reduced below 1%. This produces a carbon dioxide (CO_2) level of 12.5%. If the O_2 in the output rises the CO_2 is reduced proportionally, and the proportion of may be further reduced by sorption for the first part of the exposure. To stop population growth of an infestation, a higher level of O_2 can be tolerated and the treatments are much more prolonged. Three different oxygen levels, 3, 4, 5 and 6%, and their respective empirically reduced CO_2 levels of 9.5, 8.5, 7.5 and 6.5%, were used with rhs of 75 and 85% at 20 and 25^{o}C, to find the combination of the gases that would prevent the test insects from multiplying. The two species chosen, *Cryptolestes ferrugineus* (Stephens) (Rust-red grain beetle) and *Sitophilus granarius* (L.) (Grain weevil), were of higher than average tolerance to modified atmospheres. Preliminary work had shown that some aspect of egg production was the most susceptible stage in the life cycle for these species and therefore only adults were tested. They are highly representative of the practical situation as they are the stage that reinfests the grain at the start of the storage season, the time at which it is recommended that MA treatments are started.

Three replicates of 30 insects of each species were exposed in glass jars (60 mm diameter x 60 mm height) to each combination of environmental conditions under each MA for a month. They were both exposed on their culture medium, each replicate of *C. ferrugineus* had 15g of a rolled oats, wheat feed and yeast mix (Ratio 5:5:1) and for *S. granarius* this was 40g of whole wheat. After the one-month exposure the adults were then removed, a mortality assessment was made and they were then moved to a fresh jar with a similar amount of culture medium for the post exposure period of a further month. A further set of 3 replicates for each species were exposed to each of the environmental condition combinations without exposure to the MAs to act as controls.

The MAs were generated by mixing nitrogen, CO_2 and compressed air in a gas blender (Signal Instrument Co. Ltd., Camberley, Surrey). The dry gases were humidified to the required level by bubbling through an 80 ml column of glycerol/distilled water solution in a 100 ml measuring cylinder which was designed to give a 5% higher relative humidity (rh) than required to compensate for the moving air stream (Johnson, 1940). The rh was assessed by a remote rh probe in a small glass container with an inlet and outlet tube. The inlet was attached to the outlet from the treatment glass containers and the rh level was read from a Protimeter DP989M (Protimeter plc., Marlow, Bucks). The solutions were topped up to the 80 ml level every three days. The MA was released under the samples at a rate of 90 ml/min. The output of the blender was set using O_2 (Model 570A, Servomex Ltd., Crowborough, Sussex) and CO_2 meters (Anagas CD 95, Environmental Instruments, Leamington Spa, Warwickshire). Gas readings were also taken throughout the exposures from the output of the treated glass containers to ensure that the correct mixture was maintained. The exposures took place in glass containers (220 mm diameter x 250 mm height). The controls were placed in glass containers of similar dimensions over 500 ml of potassium hydroxide solution of correct specific gravity to produce the required rhs of 75 and 85% (Solomon, 1951). The mortality for the MA treatments was corrected for control mortality (Abbott, 1925) and the percentage reduction in progeny produced was calculated.

Further experiments were carried out with these species to see if an increase in the level of CO_2 to 10 and 20% would allow an increase in O_2 to achieve the same or better levels of population suppression. An increase to 10% represents the maximum theoretical amount of CO_2 to accompany a 5% O_2 atmosphere derived from combustion of propane in air. These experiments used the same set-up for the insects and the same gas generation and monitoring equipment. However there was no assessment of progeny produced post-MA exposure. Similar types of analysis were carried out on these results as with the previous experiment.

5.2. Results

5.2.1. C. ferrugineus

With 1% O_2 there was 100% mortality in all the environmental combinations after a month's exposure and therefore there was no projeny produced (Table 1). When the higher O_2 levels are considered there was some difference in adult survival due to temperature (Tables 2 and 3). At 4% O_2 and 75% rh 20^{o}C produced a maximum mortality of 20.0% while at 25^{o}C the maximum was 33.0%. Above 4% O_2 mortality was not significantly different from the controls. Over the range tested, rh did not influence results at either temperature. Progeny were found at both the 4 and 5% O_2 levels with an overall average reduction in numbers of 93.5%. There was little difference in progeny numbers at 20 or 25^{o}C. A further reduction in O_2 to 3% was needed to see complete suppression of population growth. The adults were able to produce similar numbers of progeny to the controls when they were moved from the MA.

Table 1. The percentage mortality of adult *Cryptolestes ferrugineus* and *Sitophilus granarius* and the number of progeny produced during burner gas treatment at 20 and 25°C with 1% oxygen

						Progeny
Oxygen (%)	Carbon dioxide (%)	Species	Temperature (oC)	rh (%)	Mortality (%)	Under MA (% reduction)
1	11.5	*Cryptolestes ferrugineus*	20	75	100	0 (100)
				85	100	0 (100)
			25	75	100	0 (100)
				85	100	0 (100)
		Sitophilus granarius	20	75	100	0 (100)
				85	100	0 (100)
			25	75	100	0 (100)
				85	100	0 (100)

Table 2. The percentage mortality of adult *Cryptolestes ferrugineus* and the number of progeny produced during and after burner gas treatment at 20°C with 3, 4, 5 and 6% oxygen

				Progeny	
Oxygen (%)	Carbon dioxide (%)	rh (%)	Mortality (%)	Under MA (% reduction)	Post MA
3	9.5	75	17.0	0 (100)	322
		85	7.1	0 (100)	195
20.9	0	75	0.8	232	152
		85	0.8	310	156
4	8.5	75	20.0	34 (87.9)	582
		85	16.5	43 (89.5)	447
20.9	0	75	0.0	281	411
		85	2.4	411	442
5	7.5	75	1.0	11 (97.2)	222
		85	3.9	6 (98.4)	121
20.9	0	75	3.7	390	355
		85	2.1	369	175
6	6.5	75	0.9	162 (0.0)	124
		85	0.9	109 (1.8)	21
20.9	0	75	0.0	73	142
		85	0.0	111	34

Table 3. The percentage mortality of adult *Cryptolestes ferrugineus* and the number of progeny produced during and after burner gas treatment at 25°C with 3, 4, 5 and 6% oxygen

				Progeny	
Oxygen (%)	Carbon dioxide (%)	rh (%)	Mortality (%)	Under MA (% reduction)	Post MA
3	9.5	75	45.9	0 (100)	619
		85	17.6	0 (100)	615
20.9	0	75	1.7	248	618
		85	7.5	157	483
4	8.5	75	33.5	12 (95.2)	128
		85	30.9	83 (47.1)	178
20.9	0	75	1.4	248	190
		85	1.5	157	166
5	7.5	75	5.6	21 (96.6)	480
		85	11.7	43 (94.4)	746
20.9	0	75	0.0	617	849
		85	5.0	766	731
6	6.5	75	0.0	184 (0.0)	59
		85	0.0	160 (0.0)	49
20.9	0	75	1.9	150	59
		85	1.7	131	102

5.2.2. S. granarius

With 1% O_2 there was 100% mortality in all the environmental combinations after a month's exposure and therefore there was no projeny produced (Table 1). However when the results from exposure to higher O_2 levels are considered temperature became an important factor in adult survival of granary weevil (Tables 4 to 5). This was best seen at 4% O_2 where the mortalities were 11.0 and 72.9 at 20 and 25°C respectively. The use of 4% O_2 and 25°C was the only time that there was a significant difference in mortality due to rh. Very few progeny were produced at either temperature for 5% O_2 or below with an average reduction of over 99% compared to the controls. Complete control was achieved with 5% O_2, 85% rh at 20°C, whereas 21 progeny were obtained at to at 25°C with 85% rh and 5% O_2 (Tables 5). At 6% where the effect of the low O_2 was reduced at both temperatures, a difference due to rh was apparent, with more progeny produced at 85%. When the original adults were moved on to fresh food they were able to produce as many progeny as the controls.

Table 4. The percentage mortality of adult *Sitophilus granarius* and the number of progeny produced during and after burner gas treatment at 20°C with 3, 4, 5 and 6% oxygen

				Progeny	
Oxygen (%)	Carbon dioxide (%)	rh (%)	Mortality (%)	Under MA (% reduction)	Post MA
3	9.5	75	5.5	0 (100)	73
		85	5.5	0 (100)	111
20.9	0	75	0.0	353	108
		85	4.0	384	140
4	8.5	75	11.0	1 (99.7)	56
		85	9.9	4 (99.1)	81
20.9	0	75	1.1	344	89
		85	0.0	429	151
5	7.5	75	1.1	1 (99.6)	122
		85	3.6	0 (100)	142
20.9	0	75	1.1	249	94
		85	1.1	344	268
6	6.5	75	2.2	161 (57.4)	267
		85	0.0	291 (19.2)	325
20.9	0	75	1.1	378	394
		85	1.1	360	340

The addition of higher levels of CO_2 may increase the effectiveness of the low levels of O_2. Two different oxygen levels, 5 and 6%, and two CO_2 levels, 10 and 20%, were used with at 20 and 25°C, 75 and 85% rh. Adult beetles of the two species were exposed to each set of conditions on their respective food media for a month. For *C. ferrugineus* the most notable effect was the difference due to temperature (Tables 6 and 7). At 20°C, 20% CO_2 was effective with both 5 and 6% O_2 and gave an average reduction in progeny of 96%. The reduction due to 10% CO_2 was significantly lower than 20% particularly at 6% O_2 and it was with this former CO_2 level that the higher level of rh increased the number of progeny produced. The addition of 20% CO_2 to 6% O_2 gave a similar result to burner gas with 5% O_2, and 5% O_2 with 20% CO_2 gave better results than burner gas with 4% O_2. At 25°C the effect of CO_2 was greatly reduced. At this temperature the only effective combination was 5% O_2 with 20% CO_2. Increasing O_2 to 6% with 20% CO_2 gave a larger reduction in progeny than 6% O_2 on its own but the reduction was not as large as that for the 5% O_2 samples.

For *S. granarius* the addition of CO_2 was much more effective, and adding 10% was as effective as adding 20% for both temperatures except at 85% rh with 6% O_2 when there was a significant reduction in efficacy especially at 20°C (Table 8). Complete inhibition of progeny production was achieved by addition of either level of CO_2 to 5% O_2 at both temperatures and by 20% CO_2 to 6% O_2 at 20°C.

Table 5. The percentage mortality of adult *Sitophilus granarius* and the number of progeny produced during and after burner gas treatment at 25°C with 4, 5 and 6% oxygen

				Progeny	
Oxygen (%)	Carbon dioxide (%)	rh (%)	Mortality (%)	Under MA (% reduction)	Post MA
3	9.5	75	60.1	0 (100)	121
		85	17.7	0 (100)	517
20.9	0	75	8.6	530	247
		85	3.0	556	362
4	8.5	75	72.9	0 (100)	235
		85	39.5	2 (99.7)	317
20.9	0	75	8.6	653	125
		85	4.0	634	181
5	7.5	75	10.7	1 (99.8)	426
		85	3.5	21 (97.0)	357
20.9	0	75	3.0	658	338
		85	5.2	700	393
6	6.5	75	6.9	33 (94.6)	518
		85	17.8	123 (79.1)	479
20.9	0	75	3.3	606	652
		85	1.1	588	432

At 20^{o}C, 6% O_2 and 20% CO_2 produced the same progeny reduction as 4% O_2 on its own. A similar reduction can be achieved with 5% O_2 and 10% CO_2 so this may be a better option as this ratio can be achieved by propane combustion. At 25^{o}C both levels of CO_2 with 5% O_2 were the only combinations which could produce complete inhibition of progeny production equivalent to a lower O_2 level (Table 9). Once again 5% O_2 and 10% CO_2 would be the most economic option.

Table 6. The percentage mortality of adult *Cryptolestes ferrugineus* and the number of progeny produced during low oxygen treatments with elevated carbon dioxide at 20^{o}C

			Oxygen (%)			
			5		6	
rh (%)	Regime	Carbon dioxide (%)	10	20	10	20
	Control	Mortality %	0.0	0.0	0.9	2.0
		No. of progeny	133	135	77	160
75						
	Treated	Mortality %	0.0	1.9	1.5	9.9
		No. of progeny	53	1	52	7
		% reduction	60.2	99.3	32.5	95.6
	Control	Mortality %	0.0	0.0	1.1	1.9
		No. of progeny	140	110	103	215
85						
	Treated	Mortality %	0.0	3.0	1.4	4.9
		No. of progeny	67	9	96	6
		% reduction	52.1	91.8	6.8	97.2

Table 7. The percentage mortality of adult *Cryptolestes ferrugineus* and the number of progeny produced during low oxygen treatments with elevated carbon dioxide at 25^{o}C

			Oxygen (%)			
			5		6	
rh (%)	Regime	Carbon dioxide (%)	10	20	10	20
	Control	Mortality %	1.2	3.2	1.1	4.7
		No. of progeny	534	140	131	120
75						
	Treated	Mortality %	0.7	0.0	0.0	0.0
		No. of progeny	47	56	110	64
		% reduction	91.2	60.0	16.0	46.7
	Control	Mortality %	2.0	2.9	0.0	1.0
		No. of progeny	1477	124	159	90
85						
	Treated	Mortality %	0.0	1.3	2.8	0.0
		No. of progeny	220	50	120	61
		% reduction	85.1	59.7	24.5	32.2

Table 8. The percentage mortality of adult *Sitophilus granarius* and the number of progeny produced during low oxygen treatments with elevated carbon dioxide at 20^{o}C

			Oxygen (%)			
			5		6	
rh (%)	Regime	Carbon dioxide (%)	10	20	10	20
	Control	Mortality %	0.0	2.2	0.0	0.0
		No. of progeny	131	232	333	313
75						
	Treated	Mortality %	1.1	1.1	2.2	6.0
		No. of progeny	0	0	34	1
		% reduction	100	100	89.8	99.7
	Control	Mortality %	1.0	2.2	0.0	0.0
		No. of progeny	187	420	292	320
85						
	Treated	Mortality %	2.7	0.4	4.2	10.1
		No. of progeny	0	1	129	2.3
		% reduction	100	99.8	55.8	99.3

Table 9. The percentage mortality of adult *Sitophilus granarius* and the number of progeny produced during low oxygen treatments with elevated carbon dioxide at 25°C

			Oxygen (%)			
			5		6	
rh (%)	Regime	Carbon dioxide (%)	10	20	10	20
	Control	Mortality %	3.3	6.0	5.2	9.8
		No. of progeny	371	453	410	602
75						
	Treated	Mortality %	4.3	8.0	14.7	9.9
		No. of progeny	0	1	41	48
		% reduction	100	99.8	90.0	92.0
	Control	Mortality %	5.4	4.0	1.1	6.1
		No. of progeny	550	494	494	516
85						
	Treated	Mortality %	3.1	17.9	14.4	2.4
		No. of progeny	2	2	147	75
		% reduction	99.6	99.6	70.2	85.5

5.3. Conclusions

1) Burner Gas: O_2 required to stop population growth:

a) *Sitophilus granarius* - 5% at 20 and 25°C.

b) *Cryptolestes ferrugineus* 3% O_2- at 20 and 25°C.

2) Addition of CO_2:

a) With 6% O_2 more effective against *Sitophilus granarius* than *Cryptolestes ferrugineus*, but 5% O_2 still needed for population suppression
b) Effectiveness against *Cryptolestes ferrugineus*:
20°C - Complete cessation of population growth with 5% O_2 and 20% CO_2 which was more effective than 4% O_2 alone.
25°C - 5% O_2 and 20% CO_2 was the only effective combination but was not as good as 4% O_2 alone.

6. Objective 3. To establish the CO_2 and low O_2 levels required to stop population growth of two common grain mites (*Acarus siro* and *Tyrophagus longior*) at different temperatures.

6.1. Materials and Methods

Two species of mites were chosen for this work: *Acarus siro* L. strain A44 and *Tyrophagus longior* (Gervais) strain T3. These were used throughout the experiments. Each mite species was reared on food (yeast and wheat germ (3:1)) in 50 ml conical flasks. The cultures were placed on a 180 μm sieve to remove the eggs. The mites were then exposed to a nitrogen-based MA on whole wheat at two temperatures (20 and 25°C) and three humidities, 75, 80 and 85% rh, to assess the effect on their population growth. A parallel exposure under normal atmospheric conditions was used as a comparison. The exposure length was determined by the generation time of each species at each combination of temperature and rh as shown by Cunnington (pers. comm.) (Table 10). The results for *T. putrescentiae* were a useful basis but preliminary results showed that they had to be increased by at least five days (Table 11).

Table 10. Mean developmental period (egg to adult) of two mite species

		% rh		
Species	Temperature (°C)	75	80	85
Acarus siro	20	-	16	14
	25	14	12	11
Tyrophagus putrescentiae	20	-	22	20
	25	16	14	12

Table 11. Actual exposure lengths (Days) used

		% rh		
Species	Temperature (°C)	75	80	85
Acarus siro	20	22	16	14
	25	16	14	12
Tyrophagus longior	20	34	30	26
	25	26	20	18

6.1.1. Wheat Preparation

A preliminary assessment of the mc of the whole wheat to be used was calculated using the oven method (BS4317), by drying a sample in a ventilated oven at 130°C for 2 h. Six 1200 g batches of wheat were then conditioned to the equivalent mc by dampening the grain with the appropriate quantity of distilled water (Henderson, 1990) (Table 12).

Table 12. The moisture contents of the whole wheat

	% rh		
Temperature (°C)	75	80	85
20	16	17.5	18.5
25	16	17.5	18.5

The samples were placed in ziploc bags at 5°C and left for a week to allow uptake and even distribution of the moisture within the sample. Another mc assessment was done of each sample to ensure they had achieved the correct mc. A further wetting and cool storage period was undertaken if this was not so followed by a further mc assessment. A final mc assessment was also made after the exposure was completed.

For each species the set up was as in Table 13. This was used for each experiment. The only difference between them was the MA used.

Table 13. The set up for each species of mite

	20°C			25°C		
	16	17.5	18.5	16	17.5	18.5
Treated	50 g x5	50 g x5	50 g x5	50 g x5	50 g x5	50 g x5
Control	50 g x5	50 g x5	50 g x5	50 g x5	50 g x5	50 g x5
Total	500 g	500 g	500 g	500 g	500 g	500 g

6.1.2. Handling of Mites

A rounded spatula of mites was added to each 50 g of whole wheat in glass jars (60 mm diameter x 60 mm height). An assessment was made of the mite numbers in the spatula by doing five counts of a spatula’s contents under a low powered binocular microscope. The sample was placed on to a zoned disc (Solomon, 1962) and evenly distributed with a small fine brush. The mobile mite stages on an eighth of the total disc area were counted. This was then multiplied by eight to give the total count. The jars were sealed with two 55 mm Whatman No. 1 filter papers (Whatman International Ltd., Maidstone, England) placed on top and secured with a metal screw lid with its centre removed. This was done 24 hours before the start of the exposure to allow the mites to become settled.

The controls were placed in glass containers (220 mm diameter x 250 mm height) over 500 ml of potassium hydroxide solution of correct specific gravity to produce the required rhs of 75, 80 and 85% (Solomon, 1951). *A. siro* and *T. longior* were placed in separate glass containers so there was a set of three for each species at each temperature.

The treated replicates were placed on mesh grills in glass containers of similar dimensions. *A. siro* and *T. longior* were placed together so that there was a set of three replicates of each at each temperature. Each MA was produced by a gas blender (Signal Instrument Co. Ltd., Camberley, Surrey). The gas stream was humidified by bubbling through an 80 ml column of glycerol/distilled water solution contained in a 100 ml measuring cylinder which was designed to give a 5% higher rh than required to compensate for the moving air stream. The solutions were topped up to the 80 ml level every three days. The MA was released under the samples at a rate of 90 ml/min. The output of the blender was set using O_2 (Model 570A, Servomex Ltd., Crowborough, Sussex) and CO_2- meters (Anagas CD 95, Environmental Instruments, Leamington Spa, Warwickshire). Gas readings were also taken throughout the exposures from the output of the treated glass containers with the same meters to ensure that the correct mixture was maintained.

After completion of an exposure an assessment was made of the mite numbers. A similar system was used to that for the spatula's content. Each of the five replicate wheat samples for the control and the treatment was placed on a sieve (1.70 mm nominal aperture) and shaken for 30 seconds. The sample passed through a further sieve (710 µm nominal aperture) before reaching the collection dish. Its contents were then placed on the disc. If the mite numbers were below 200 the mites on the whole of the disc were counted. An average was then calculated and a percentage reduction in population growth due to the MA was calculated. The five wheat samples for the control and for the treatment were combined for a final mc assessment.

6.2. Results

Moisture content was used to assess the rh within the glass containers throughout the exposures. Relative humidity is a very important factor controlling population growth in mites and if it falls below 70% growth will cease. Therefore it was essential that it did not fall during the exposures and that the treated remained higher than the controls so that the factor affecting population growth was the MA alone rather than a drop in rh. Generally there was a drop in the mc of the controls after exposure and in most cases the comparable treated mc was higher than the control and also increased above the original value (Tables 14 to 19). Therefore the conditions for population growth were much better for subsequent population growth in the treated samples than in the controls.

Table 14. Moisture contents (mc) before and after exposure to a 6% oxygen in nitrogen modified atmosphere

A. siro

		% rh		
Temperature (^oC)	mc	75	80	85
20	Original	16.28	17.76	18.63
	Post: Control	16.09	17.31	18.61

	Treated	16.59	18.06	18.88
25	Original	16.28	17.76	18.63
	Post: Control	16.21	17.26	18.43
	Treated	16.65	18.20	18.86

T. longior

		% rh		
Temperature (^oC)	mc	75	80	85
20	Original	16.06	17.55	18.59
	Post: Control	16.00	17.07	18.48
	Treated	16.81	18.59	19.23
25	Original	16.06	17.55	18.59
	Post: Control	15.89	16.96	18.41
	Treated	16.78	18.57	19.11

Table 15. Moisture contents (mc) before and after exposure to after exposure to a 5% oxygen in nitrogen modified atmosphere

A. siro

		% rh		
Temperature (^oC)	mc	75	80	85
20	Original	16.20	17.64	18.27
	Post: Control	15.67	16.79	19.68
	Treated	16.74	18.02	18.52
25	Original	16.20	17.64	18.27
	Post: Control	15.64	17.10	19.34
	Treated	16.74	17.87	18.94

T. longior

		% rh		
Temperature (^oC)	mc	75	80	85
20	Original	16.22	17.53	18.14
	Post: Control	15.69	17.03	20.30
	Treated	17.37	18.50	19.12
25	Original	16.22	17.53	18.14
	Post: Control	15.40	16.66	20.50
	Treated	17.11	18.20	18.89

Table 16. Moisture contents (mc) before and after exposure to the atmosphere after exposure to a 4% oxygen in nitrogen modified atmosphere

A. siro

		% rh		
Temperature (^oC)	mc	75	80	85
20	Original	15.77	17.43	18.41
	Post: Control	15.71	17.25	18.58
	Treated	16.19	17.86	18.79

25	Original	15.77	17.43	18.41
	Post: Control	15.82	17.25	18.29
	Treated	16.33	17.86	18.65

T. longior

		% rh		
Temperature (^oC)	mc	75	80	85
20	Original	16.01	17.69	18.43
	Post: Control	15.93	17.27	18.53
	Treated	16.45	18.33	18.99
25	Original	16.01	17.69	18.43
	Post: Control	15.58	17.11	18.47
	Treated	16.56	18.35	18.96

Table 17. Moisture contents (mc) before and after exposure to a 5% oxygen and 7.5% carbon dioxide modified atmosphere

A. siro

		% rh	
Temperature (^oC)	mc	75	80
20	Original	16.58	17.51
	Post: Control	15.87	14.91
	Treated	15.54	16.62
25	Original	16.58	17.51
	Post: Control	14.73	16.24
	Treated	16.25	17.41

T. longior

		% rh	
Temperature (^oC)	mc	75	80
20	Original	16.58	17.51
	Post: Control	16.18	17.58
	Treated	16.85	17.58
25	Original	16.58	17.51
	Post: Control	14.90	14.91
	Treated	16.68	16.38

Table 18. Moisture contents (mc) before and after exposure to a 6% oxygen and 10% carbon dioxide modified atmosphere

A. siro

		% rh		
Temperature (^oC)	mc	75	80	85
20	Original	15.93	17.71	19.07
	Post: Control	16.30	17.47	18.96
	Treated	16.27	17.79	18.96
25	Original	15.93	17.71	19.07
	Post: Control	16.24	17.52	18.91

	Treated	16.30	17.81	19.04

T. longior

		% rh		
Temperature (^oC)	mc	75	80	85
20	Original	16.25	17.71	18.64
	Post: Control	16.14	17.05	17.93
	Treated	16.48	17.83	18.90
25	Original	16.25	17.71	18.64
	Post: Control	15.91	17.17	18.78
	Treated	16.32	17.91	19.02

Table 19. Moisture contents (mc) before and after exposure to a 6% oxygen and 20% carbon dioxide modified atmosphere

A. siro

		% rh		
Temperature (^oC)	mc	75	80	85
20	Original	15.72	17.53	18.47
	Post: Control	15.42	16.88	18.22
	Treated	15.83	17.50	18.33
25	Original	15.72	17.53	18.47
	Post: Control	15.32	16.99	18.33
	Treated	15.90	17.66	18.12

T. longior

		% rh		
Temperature (^oC)	mc	75	80	85
20	Original	15.90	17.42	18.50
	Post: Control	15.46	16.76	18.15
	Treated	15.96	18.05	18.92
25	Original	15.90	17.42	18.50
	Post: Control	15.33	16.66	18.32
	Treated	16.11	18.33	18.69

At 6% O_2 there was only population suppression of *A. siro* at 75% rh for both temperatures, whereas there was no significant population reduction of *T. longior* for which controls consistently showed some population decline at 75% rh (Table 20). Population numbers in the treatments exceeded the number of mites added at the start for *A. siro* at both temperatures at 80 and 85% rh. A reduction in O_2 to 5% brought near complete control of *A. siro* at 25^oC and at 20^oC for 75 and 80% rh (Table 21). For *T. longior* a high level of population suppression was only achieved at 25^oC with 75 and 80% rh. A further reduction to 4% O_2 gave a very good population suppression for both species with a range of 99.7 - 100% for *A. siro* and 90.7 to 99.9 % for *T. longior* (Table 24).

Table 20. Average number of mites per jar after exposure to a 6% oxygen in nitrogen modified atmosphere and percentage reduction in the treated jars compared to the controls

A. siro: Average number of mites added per jar - 419.2

	20°C				25°C			
% rh	Time (Days)	Control	Treated	% Reduction	Time (Days)	Control	Treated	% Reduction
75	21	2724.8	264.8	90.3	18	3656.0	81.2	97.8
80	17	3993.6	684.8	82.9	14	2788.8	473.6	83.0
85	17	4272.0	1032.0	75.8	12	3630.4	594.8	83.6

T. longior: Average number of mites added per jar - 881.6

	20°C				25°C			
% rh	Time (Days)	Control	Treated	% Reduction	Time (Days)	Control	Treated	% Reduction
75	38	625.6	451.4	27.8	28	594.0	261.6	56.0
80	35	1401.6	339.0	75.8	24	638.4	447.0	30.0
85	31	1617.6	269.0	83.4	20	1264.0	831.6	34.2

Table 21. Average number of mites per jar after exposure to a 5% oxygen in nitrogen modified atmosphere and percentage reduction in the treated jars compared to the controls

A. siro: Average number of mites added per jar - 498.6

	20°C				25°C			
% rh	Time (Days)	Control	Treated	% Reduction	Time (Days)	Control	Treated	% Reduction
75	21	1640.0	14.6	99.1	20	1396.8	2.4	99.8
80	20	4637.6	52.6	98.9	14	4745.6	31.2	99.3
85	14	6057.6	138.0	97.7	14	8308.8	61.1	99.3

T. longior: Average number of mites added per jar - 477.0

	20°C				25°C			
% rh	Time (Days)	Control	Treated	% Reduction	Time (Days)	Control	Treated	% Reduction
75	35	173.8	50.0	71.2	27	94.0	9.0	90.4
80	30	1307.2	297.6	77.2	22	867.2	45.8	94.7
85	27	1849.6	493.4	73.3	17	1588.8	258.6	83.7

Table 22. Average number of mites per jar after exposure to a 4% oxygen in nitrogen modified atmosphere and percentage reduction in the treated jars compared to the controls

A. siro: Average number of mites added per jar - 972.8

	20°C				25°C			
% rh	Time (Days)	Control	Treated	% Reduction	Time (Days)	Control	Treated	% Reduction
75	21	3779.2	0.2	99.9	19	3024.0	0	100
80	16	5683.2	15.6	99.7	13	3611.2	4.4	99.9
85	16	9985.6	43.4	99.6	12	4302.4	10.2	99.8

T. longior: Average number of mites added per jar - 785.6

	20°C				25°C			
% rh	Time	Control	Treated	% Reduction	Time	Control	Treated	% Reduction

	(Days)				(Days)			
75	34	267.0	24.8	90.7	27	201.6	0.2	99.9
80	30	1190.4	40.8	96.6	20	1376.0	20.2	98.5
85	28	3438.4	127.6	96.3	20	2001.6	129.0	93.6

The addition of 7.5% CO_2 to 5% O_2 did not improve on the population suppression achieved by 5% O_2 alone with *A. siro* (Table 23). The results for *T. longior* were hampered by very poor survival in controls, especially at 25^{o}C, although virtually complete control was obtained at 25°C and 75% rh.

Table 23. Average number of mites per jar after exposure to a 5% oxygen and 7.5% carbon dioxide modified atmosphere and percentage reduction in the treated jars compared to the controls

A. siro: Average number of mites added per jar - 416.0

	20°C				25°C			
% rh	Time (Days)	Control	Treated	% Reduction	Time (Days)	Control	Treated	% Reduction
75	27	621.3	9.3	98.5	14	624.0	15.7	97.3
80	16	1674.7	50.3	97.0	12	1037.3	48.7	95.4

T. longior: Average number of mites added per jar - 514.7

	20°C				25°C			
% rh	Time (Days)	Control	Treated	% Reduction	Time (Days)	Control	Treated	% Reduction
75	33	119.0	28.0	79.1	20	113.0	2.3	98.1
80	22	602.7	54.3	90.8	14	190.0	27.3	84.4

The addition of 10% CO_2 to 6% O_2 improved the population suppression of both species significantly (Table 24). There was a reduction approaching that of 5% O_2 alone for *A. siro* at 75% rh at both temperatures and 80% rh at 25°C, and for *T. longior* at all humidities the reductions were even greater, being equal to that with 4% O_2 alone. A further increase in CO_2 to 20% brought the levels of population suppression closer to those achieved with 5% O_2 for *A. siro* with all humidities at 20°C and 85% rh at 25°C (Table 25).

Table 24. Average number of mites per jar after exposure to a 6% oxygen and 10% carbon dioxide modified atmosphere and percentage reduction in the treated jars compared to the controls

A. siro: Average number of mites added per jar - 696.0

	20°C				25°C			
% rh	Time (Days)	Control	Treated	% Reduction	Time (Days)	Control	Treated	% Reduction

75	21	5641.6	43.2	99.2	18	5033.6	21.8	99.6
80	19	5292.8	332.8	93.7	15	5169.6	78.4	98.5
85	15	5012.8	444.8	91.1	12	5301.3	244.4	95.4

T. longior: Average number of mites added per jar - 1490.6

	20°C				25°C			
% rh	Time (Days)	Control	Treated	% Reduction	Time (Days)	Control	Treated	% Reduction
75	35	515.2	1.8	99.7	32	766.4	0.0	100
80	33	1202.0	61.8	95.9	22	1958.4	18.4	99.1
85	32	3457.6	91.2	97.4	20	2382.4	75.2	96.2

Table 25. Average number of mites per jar after exposure to a 6% oxygen and 20% carbon dioxide modified atmosphere and percentage reduction in the treated jars compared to the controls

A. siro : Average number of mites added per jar - 466.7

	20°C				25°C			
% rh	Time (Days)	Control	Treated	% Reduction	Time (Days)	Control	Treated	% Reduction
75	24	1729.6	70.0	95.9	18	2169.6	20.0	99.1
80	17	3314.4	100.4	96.9	14	3993.6	91.8	97.7
85	14	4012.8	99.0	97.5	12	3760.0	45.2	98.8

T. longior: Average number of mites added per jar - 1098.7

	20°C				25°C			
% rh	Time (Days)	Control	Treated	% Reduction	Time (Days)	Control	Treated	% Reduction
75	38	425.6	1.2	99.7	33	428.8	2.8	99.3
80	33	1329.6	2.0	99.8	32	2100.8	1.6	99.9
85	32	2820.8	7.4	99.7	20	1840.0	20.0	98.9

Under control conditions *A. siro* had a faster growth rate and multiplied well in all the environmental combinations whereas *T. longior* preferred 80 and 85% rh. There was a notable difference in response to the MAs between the species as the treated *A. siro* cultures only had large adults remaining. The O_2 content had been high enough to allow egg hatch, and the subsequent nymphs had then been killed, and it had also prevented oviposition. Therefore an increase in exposure lengths would have ensured complete mortality. With *T. longior* there were more eggs present and therefore hatch was being inhibited by the low O_2 level. Eggs of this species are extremely tolerant to low oxygen atmospheres and it may be necessary to raise the oxygen content to allow egg hatch and then kill the subsequent susceptible nymphs. However results from population suppression have shown that control of the population is lost at these higher O_2 levels. The addition of CO_2 did reduce the numbers of eggs present and therefore the combination of the two gases must be needed to give the added benefit of suppressing oviposition in this species.

6.3. Conclusions

1) Nitrogen with low O_2:

a) Population levels were less suppressed at 85% rh in most treatments.

b) 5% O_2: stopped population growth of *Acarus siro* at 25°C, and at 75 and 80% rh at 20°C.

c) 4% O_2: stopped population growth of *Acarus siro* at 20°C and of *Tyrophagus longior* at 20 and 25°C.

2) Addition of CO_2

a) 7.5% CO_2 with 5% O_2 content was no more effective than 5% O_2 alone

b) *Acarus siro*:

75 rh at both temperatures and 80% rh at 20°C: - Population growth slowed with 6% O_2 and 10% CO_2.

80 and 85% rh at both temperatures: Population growth halted with 6% O_2 and 20% CO_2

c) *Tyrophagus longior*:

6% O_2 and 10% CO_2: Population growth halted at both 20 and 25°C, raising CO_2 to 20% achieved control faster.

7. Objective 4. To investigate in farm scale experiments the practical feasibility and costs of running modified atmosphere treatment regimes with burner gas for storage life protection.

7.1. Materials and methods

A trial was run to assess the effectiveness of storage life protection under field conditions in ambient temperatures. An atmosphere of 5% O_2 and 9.5% CO_2 was generated at a flow rate of 150 l/min (9m^3/hour) using the propane burner at CSL. The flow was split and 75 l/min (4.5m^3/hour) was fed into the base of two bins via their aeration ducts, this having been shown to be the optimum site of application in previous trials. The bins were open-topped and in a line of three within a grain storage facility. Each bin (3 x 3 x 4 m high) contained 30 tonnes of wheat and in the two bins used for the trial, the flattened surface of the grain was covered by a sheet of polythene. The bins were at 14 and 16 mc.

All gas monitoring of the output content and the atmosphere within the bins was carried out using 2 mm nylon sampling lines. These were inserted into the grain in each bin, three at the surface diagonally across the bin in the corners and one in the middle. A further line in the centre was pushed down to a depth of 2 m. Thermocouples were also inserted into the grain in the middle of the bin at the surface and at 2 m depth to record temperatures throughout the trials. All trials employed a unique sampling and detection system built by CSL. A pump drew a sample of atmosphere down the line and through a series of instruments, one for O_2 and one for CO_2 (1400 Series, Servomex Ltd., Crowborough, Sussex). Four minutes were allowed to elapse so that lines were thoroughly purged and that the correct atmosphere reading was being taken before the data from each sample was recorded on a chart. The sampling system was programmed to sample a line every eight minutes, with a total of ten used for the trial. A complete set of data from each position was collected every two hours.

7.1.1. Insect Preparation

Adults of *Cryptolestes ferrugineus* (rust-red grain beetle) and *Sitophilus granarius* (grain weevil) were placed in polypropylene bags (15 x 15 cm) and buried in the grain at a depth of 150 mm near the middle of the bins. 3 replicates of 50 adults of each species with 15 g of rolled oats, wheat feed and yeast mix (Ratio 5:5:1) and 50 g of whole wheat respectively were kept under the atmosphere for 24 days. Three replicates acted as controls and were placed in buckets filled with the grain from the bins in a controlled environment room at 15^{o}C and 60% rh. A further single bag of the former species was placed in each location and contained 13.7 g of culture medium and all the juvenile stages. For the latter species three bags were placed in each location and each contained respectively, 50 g of grain with eggs, 35 g of grain with eggs and early stage larvae and 60 g of grain with older larvae and pupae.

7.2. Results

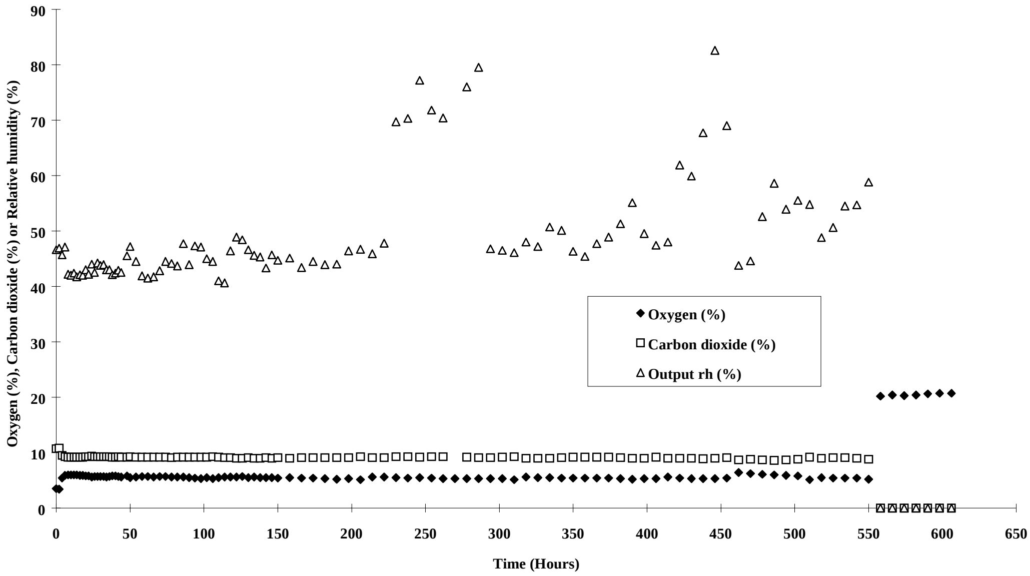
The output from the burner was kept at a constant 150 l/min (9m^3/hour) throughout the trial, the product gas passing equally to the two bins through the aeration ducts. The O_2 and CO_2 content of the output was constant throughout this period although the O_2 was slightly higher than the projected 5% (Table 26) (Figure 1).

Table 26. The average and the range of the oxygen present in the output and the bins during the trial

	Position	Average	Range
Output	-	5.55	5.2 - 6.1
Bin 1	2 m depth	5.70	5.2 - 6.0
	Surface Front right	5.57	5.1 - 6.2
	Surface Middle	5.64	5.3 - 6.2
Bin 2	2 m depth	7.03	6.6 - 7.6
	Surface Front Right	5.61	4.9 - 5.9
	Surface Middle	5.78	5.1 - 6.5
	Surface Front Left	5.59	5.0 - 6.2

The oxygen levels in the two bins rose with a loss of gas input (Figures 2 and 3). This occurred at 250 and 450 hours after the start of the treatment. This was due to a build-up of condensate in the output tube. This also affected the rh of the output which had ranged between 40 and 50% but with the blockage rose to 80%. Once this was cleared the rh level dropped back to the required level. There was also a problem with the condensate accumulating in the flow meters for the two bins. This helped to raise the rh but also reduced the flows to the bins as water filled the floats which affected the functioning of the flow meters. These would not be required in a practical operation and were only used here to ensure that there was an equal split in the flow of gas to each bin. For operational purposes of this experimental system, it was important to ensure that the output line was kept clear of condensate and drained every third day to ensure smooth running of the system. For all MA applications based on a carbohydrate fuel where water is a product of combustion, a moisture trap would be a useful addition to the output line as it allows the tube to be drained without the need to interrupt the gas application by detachment from the enclosure.

Figure 1. Oxygen, carbon dioxide and relative humidity content of the output



In Bin 2 there was an earlier rise in O_2 at 125 hours (Figure 3). This was due to operation of the aeration of the adjoining bin which was untreated. The aeration pushed air into the treated bin which showed that the sealing at the joints between the bins was incomplete. However, the flow of the burner was sufficient to compensate for this temporary loss of the low O_2 atmosphere. A higher level of seal would reduce the flow rate required for atmosphere maintenance but the trial demonstrated that the system is capable of functioning well in storage facilities that are not designed for modified atmospheres (MA). Generally the O_2 levels in the bins were close to that of the output (Table 26). Bin 1 had a constant high oxygen level in one surface position, back right, but this was subsequently shown to be a damaged line. This allowed the ingress of air when suction via the sample pump was applied to it. The other surface positions in both bins had O_2 levels very similar to those of the input. They were not affected by any changes in temperature even though the difference between ambient and the contents of the bins sometimes exceeded $10^{o}C$ (Figure 4). There was a general decrease in the temperature of the bulk of the grain but the surface of the grain followed the changes in ambient temperature.

Figure 2. Oxygen content of Bin 1 during the trial

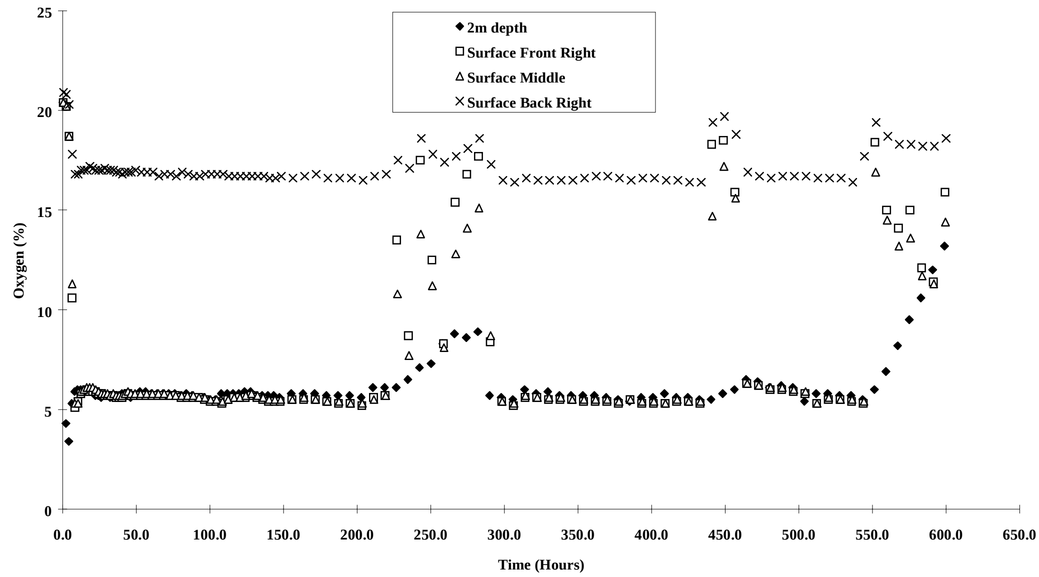
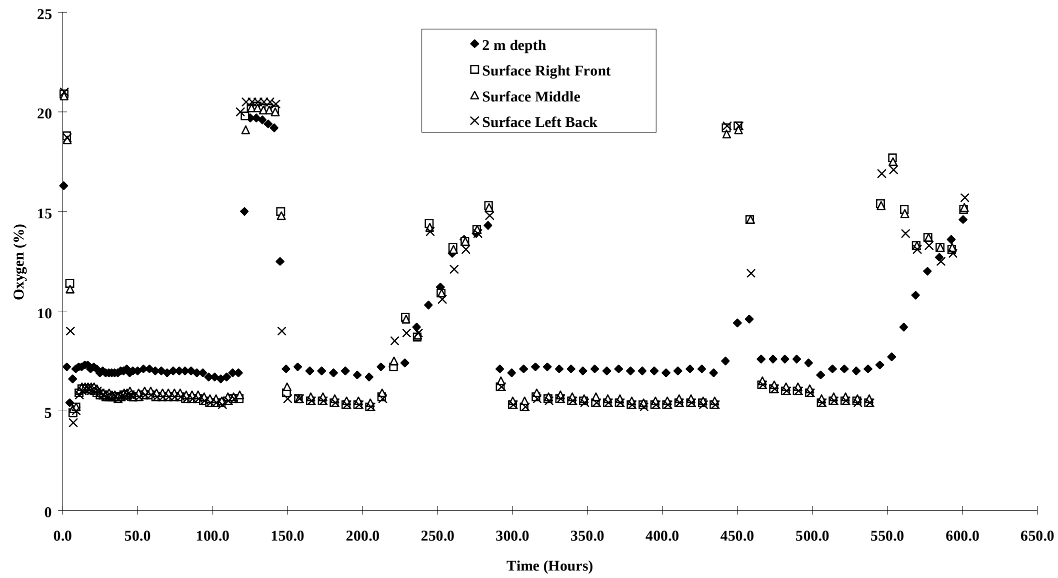
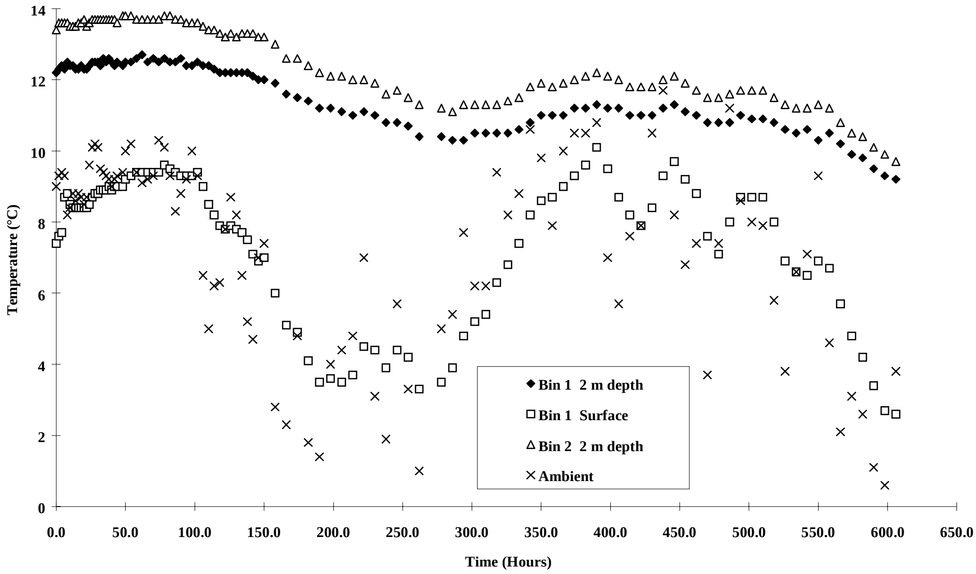


Figure 3. Oxygen content of Bin 2 during the Trial



This was a very successful trial of burner gas with the higher levels of O_2 for storage life protection, showing that the same constraints apply to this technique as to the use of 1% oxygen. A good seal to the bin is essential though this trial has shown that the equipment is capable of producing enough flow to take into account any leakage in the walls of the storage structure. The absence of any means of ingress at the base of the structure prevents the ingress of oxygen due to differences in temperature between ambient and the bulk. The presence of sheeting means that the surface O_2 can be maintained at a sufficient level to control insect population growth.

Figure 4. Bin and ambient temperatures during the trial



Propane gas consumption was at 8 l/min which compares with 10.8 l/min for the production of a 1% O_2 atmosphere in the same bin. This was a very favourable saving which meant that a large 46 kg cylinder of propane would last an extra 12 hours and give 2 full days of running. With the assistance of the higher temperatures present at the start of the storage season this would be a very satisfactory technique to stop the build up of pest populations from the adult insects which have managed to overwinter in the fabric of the storage structure.

Adult mortality was affected by grain mc for both species. It was significantly higher at the lower mc (Table 27). However this did not apply to the juvenile stages especially for *S. granarius*. There was also little difference in adult numbers emerged between treated and control for this species. There was a reduction of 43.3% due to the MA for *C. ferrugineus.* These results showed that both species are tolerant of low temperatures and that under these conditions juvenile stages are capable of surviving. Therefore for this strategy to be successful it must be used from the start of the storage cycle. At this time adults will be starting the infestation and the results have shown that application of a suitable MA will prevent breeding and will lead to complete mortality particularly at the lower grain mcs if the exposure is allowed to run for a sufficient length of time.

Table 27. Average % mortality of adults and numbers of adults emerged after exposure to the MA

	Stage	*Sitophilus granarius*		*Cryptolestes ferrugineus*	
		Treated	Control	Treated	Control
Bin 1 14% mc	Adults	56.3	3.2	42.7	5.1
	Eggs	468	496	}51	123
	Larvae	357	436		
	Pupae	205	536		
Bin 2 16% mc	Adults	11.9	4.3	24.6	1.4
	Eggs	387	595	}71	157
	Larvae	297	333		
	Pupae	321	343		

7.3. Conclusions

1) The first step for a treatment with an MA must be to minimise leakage into the grain bulk through the structure as much as possible. A high level of seal reduced the flow rate required and therefore the cost of the MA application.

2) The MA produced the best results with the use of a low input continuous gas flow system applied to a gas-tight base of the structure.

3) The system is capable of functioning well in storage facilities that are not designed specifically for modified atmospheres.

4) Previous studies have shown that it is possible to hold MAs of 1% oxygen within bins. This study has shown that the same restraints apply when attempting to hold a bin under 5% oxygen.

5) Propane gas consumption for production of a 5% O_2 atmosphere is reduced by 25% compared to production of an atmosphere with 1% oxygen.

6) 5% oxygen will prevent breeding and will lead to complete mortality particularly at lower mc if the exposure is allowed to run for a sufficient length of time.

8. Objective 5. To determine the conditions required to sustain for long periods a suitable environment in different weather conditions by CFD modelling studies.

8.1. Methodology

Previous work by the authors developed an approach using Computational Fluid Dynamics (CFD) techniques for predicting the gas flows, pressures and temperatures inside grain stores. The method solves the differential equations that describe heat and mass transfer within the grain bulk, and produces details of the gas flow throughout the store. The grain is treated as a porous medium and recorded meteorological data (wind speed, ambient pressure and ambient air temperature) can be used as boundary conditions to model a realistic storage environment.

8.1.1. Description of the Model

The CFD technique subdivides the store geometry into cells in which the differential equations that describe heat and mass transfer are solved numerically. The CFD package CFX 4.3 (AEA Technology, 1999) was used to create the cells and solve the linearised equations. Body-fitted co-ordinates are used which enable complex shapes to be reproduced. The number of cells used depended on the store being modelled, and ranged from 60,000 to 750,000. Small cells, about 30 mm thick, were placed near leakage points. Leaks were modelled by ascribing a porosity of 0.05 (c.f grain = 0.4) to the cells adjacent to the leakage points. This porosity corresponds to an average leakage gap of approximately 0.2 mm. As the extent of these leaks in practice was not known, a 'worst case' condition was assumed in which continuous leaks of approximately 0.2 mm width were placed at the sheet edges and selected joints in the store structure.

Wind flowing around the store creates a pressure field that either causes air to flow into or gas to flow out of leaks (gaps) in the retaining walls and around the edges of the sealing sheet, depending on their position in relation to the prevailing wind. The wind effect was included either by incorporating part of the surroundings in the store model or by using a separate model of the surroundings to calculate the pressure distribution.

The floor and retaining walls of each store were assumed to be adiabatic, i.e. no heat transfer. The plastic sheet covering the grain was modelled as a very thin membrane directly on top of the grain surface. This acts as a barrier to gas flow but allows heat transfer by conduction. Its temperature was assumed to be equal to the ambient temperature.

The modified atmosphere (MA) was injected through the ducts in the floor normally used for aeration. In the model these inlets were defined as mass flow boundaries with fixed flow rates. Mass fractions of oxygen and carbon dioxide in the injected gas were assumed constant. Gas temperature was assumed to be the same as the ambient temperature.

The quantities of primary interest were the gas concentrations in the grain, particularly oxygen, and the temperatures, and their variation with time. Time steps of up to 1 hour were used in the simulations, although steps as short as 2 minutes were necessary in some cases to maintain numerical stability.

8.1.2. Physical properties

Modelling the gas flow and heat transfer in a grain store requires data on the physical and thermal properties of the solids and gases. The properties used throughout are given in Table

28 for wheat at 13% mc (w.b) (ASAE 1995), although they can be used with any grain type if the corresponding properties are known. It is assumed that these are uniform and constant throughout the grain within the operating range. The properties of the gases involved, nitrogen, carbon dioxide and oxygen have been taken from Bejan (1993) and diffusion coefficients from Bird *et al*. (1960).

Table 28. Material properties used in the CFD model

Wheat bulk density	757.2 $kg.m^{-3}$
Wheat specific heat	1929.7 $J.kg^{-1}.°C^{-1}$
Wheat bulk conductivity	0.1317 $J.m^{-1}.°C^{-1}$
Wheat volume porosity	0.4
O_2 diffusion coefficient	$1.629x10^{-5}$ $m^2.s^{-1}$
CO_2 diffusion coefficient	$1.592x10^{-5}$ $m^2.s^{-1}$

An expression relating the pressure gradient in the grain to the gas velocity was taken from ASAE Standards (1995), because it applies to the low velocity regimes encountered in this work. However, because the natural alignment of grain kernels produces less resistance horizontally (Kumar and Muir, 1986), a 15% difference in resistance between horizontal and vertical directions was assumed.

8.1.3. Grain stores

Two bin types have been used in simulations, a tower silo of 800 tonne capacity and a flat store of 350 tonne capacity. These corresponded to stores used in these and previous trials. In each case the dimensions of the store, the covering sheet, and the inlets and outlets were known and reproduced in the CFD model.

8.2. Model predictions

Selected examples will be shown from the large number of simulations carried out, to illustrate the important and useful results. Purging strategies to remove air from the stores, and the effect of wind and a change in barometric pressure on oxygen concentration are shown.

8.2.1. 800 tonne tower silo

This bin was modelled without using test results or environmental data; instead, assumed values of gas flow rate (15 $m^3.h^{-1}$), minimum and maximum daily temperatures (2°C and 12°C), and wind speed (5 $m.s^{-1}$) have been used. The oxygen concentrations at selected points during the initial purge phase are shown in Figure 5a, which suggests that complete atmosphere replacement is possible in 72 hours. Reducing the gas flow to zero allows the penetration of oxygen in a few hours, as shown in Figure 5b. However, it was found that despite a wind speed of 5 $m.s^{-1}$ the flow required to exclude ambient oxygen was about 2% of the initial flow rate. This is well below the maintenance flow rate expected in practice, which suggests that leaks other than those around the covering sheet, in the walls for example, are the critical ones.

To illustrate the importance of wall leaks, Figure 6 shows the effect of a 5 m.s^{-1} wind impinging directly on a side wall leak 1.9 m from the base. The modelled leak simulates a horizontal crack approximately 0.2 mm wide along the joint between two side panels. Despite the gas supply being maintained at the purge rate (15 m^3.h^{-1}) oxygen levels rise rapidly adjacent to the leak and the affected volume expands for about 36 hours before reaching equilibrium. From this condition 40 hours of purging is required to bring the oxygen concentration at all points below 5% once the wind ceases, and 72 hours of purging to bring the oxygen concentration below 1%.

Figure 5. Predicted oxygen concentration in an 800 tonne silo with a 5 m.s^{-1} external wind; a) Purging with a gas flow of 15 m^3.h^{-1}; b) Wind only after purging

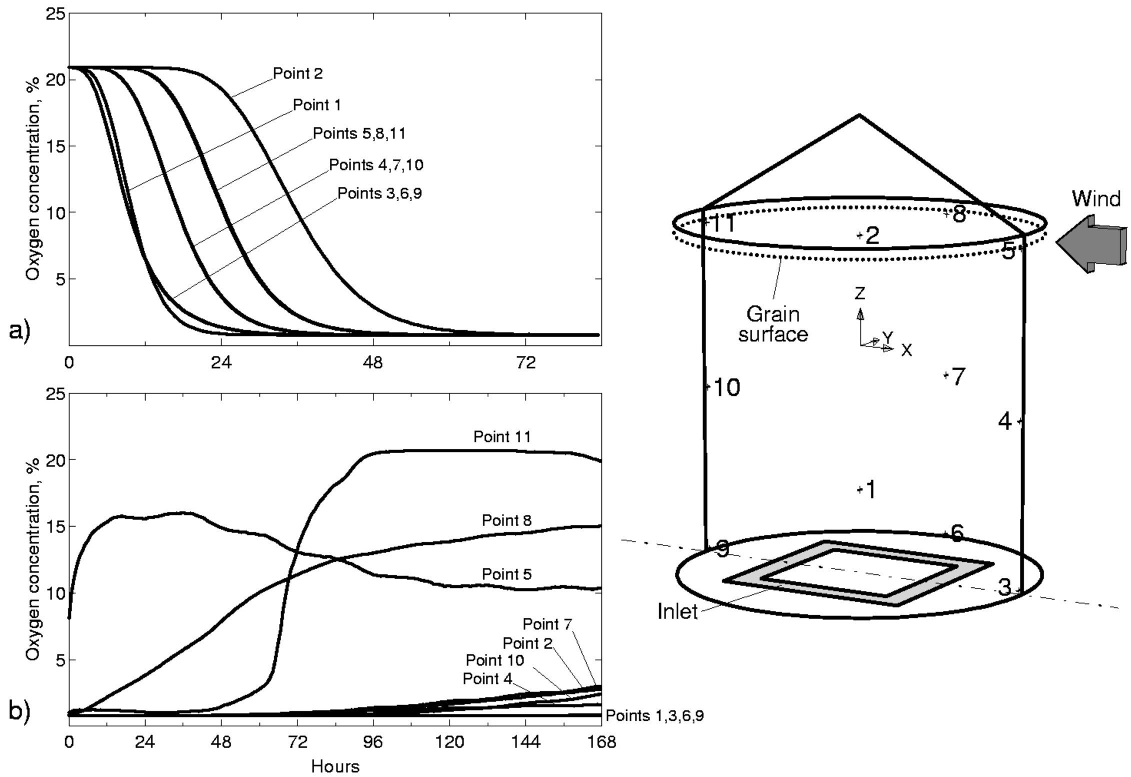
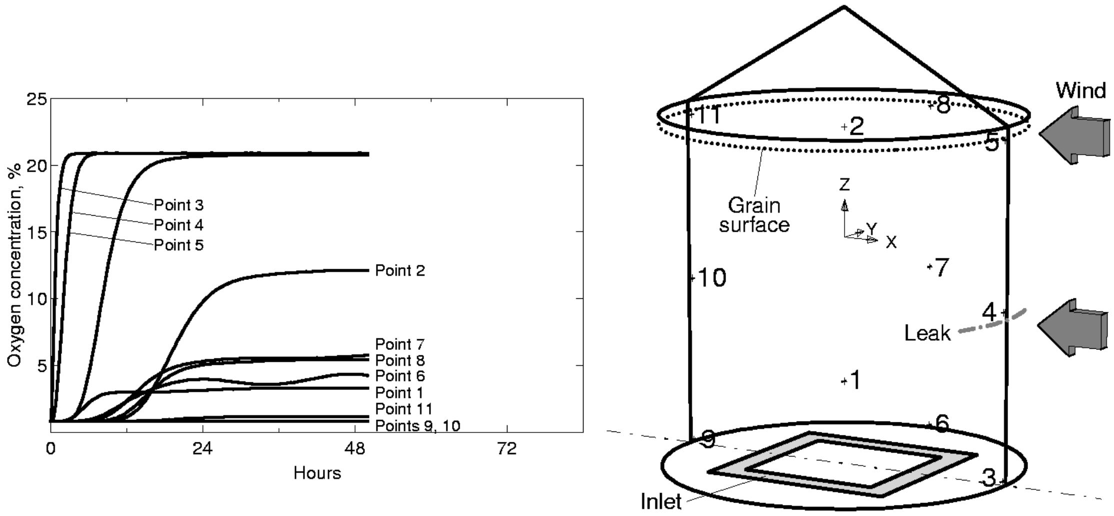


Figure 6. Predicted oxygen concentration in an 800 tonne silo when a 5 m.s^{-1} external wind impinges on a side wall leak 1.29 m from the base, starting with fully purged conditions and maintaining a gas flow rate of 15 m^3.h^{-1}



8.2.2. 350 tonne flat store

The store is shown schematically in Figure 7. The simulations include diurnal variations in ambient temperature between 2°C and 12°C. Figure 7 shows the predicted effect on oxygen concentrations of a light wind, 0.5 m.s-1, and a barometric pressure cycle of 6 mbar amplitude (600 Pa amplitude). There is no MA injection into the store, and the prevailing wind direction is from the back to the front of the store. The change in barometric pressure causes a volume change and without the wind the air would enter, or the gas would leave, at all the leaks. However, the presence of the wind ensures that air enters in the corner adjacent to sampling points 8 and 9 during both the positive and negative parts of the pressure cycle, causing gas to be lost elsewhere.

Figure 8 shows the predicted ingress of oxygen as a result of a 1 m.s-1 wind. The leakage gaps in this case are assumed to be 1.5 mm, a worst case condition. Approximately 3% of the store volume has an oxygen concentration greater than 5% after 4 hours and 11% of the volume is above 1% oxygen. This occurs despite a maintenance flow rate of 7.5 $m^3.h^{-1}$.

After variable weather conditions further MA must be injected to reduce the oxygen concentration. The simulation, Figure 9(b), showed that the most effective point for gas injection is at a point furthest from the main leaks, in this case at the front of the store. In this way the excess oxygen inside the bulk is carried towards the leakage points at the back wall. In practice, the positions of leaks are not always known and multiple injection points are necessary.

Figure 7. Predicted oxygen concentration at sampling points in a 350 tonne flat store as a result of a pressure cycle and a 0.5 $m.s^{-1}$ wind blowing from the back to the front. Initial oxygen concentration is 0.8%. No gas injection.

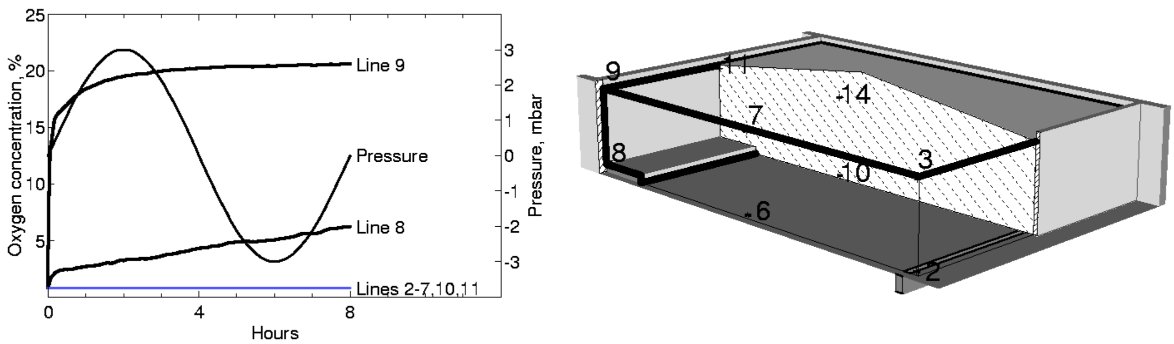


Figure 8. Predicted growth of the volume affected by a 1.0 $m.s^{-1}$ wind, in a 350 tonne flat store. Initial oxygen concentration is 0.8%. Gas injection rate is 7.5 $m^3.h^{-1}$.

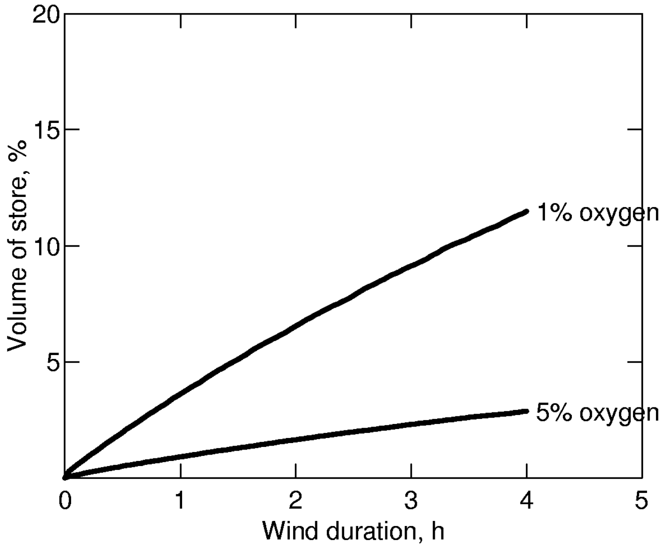
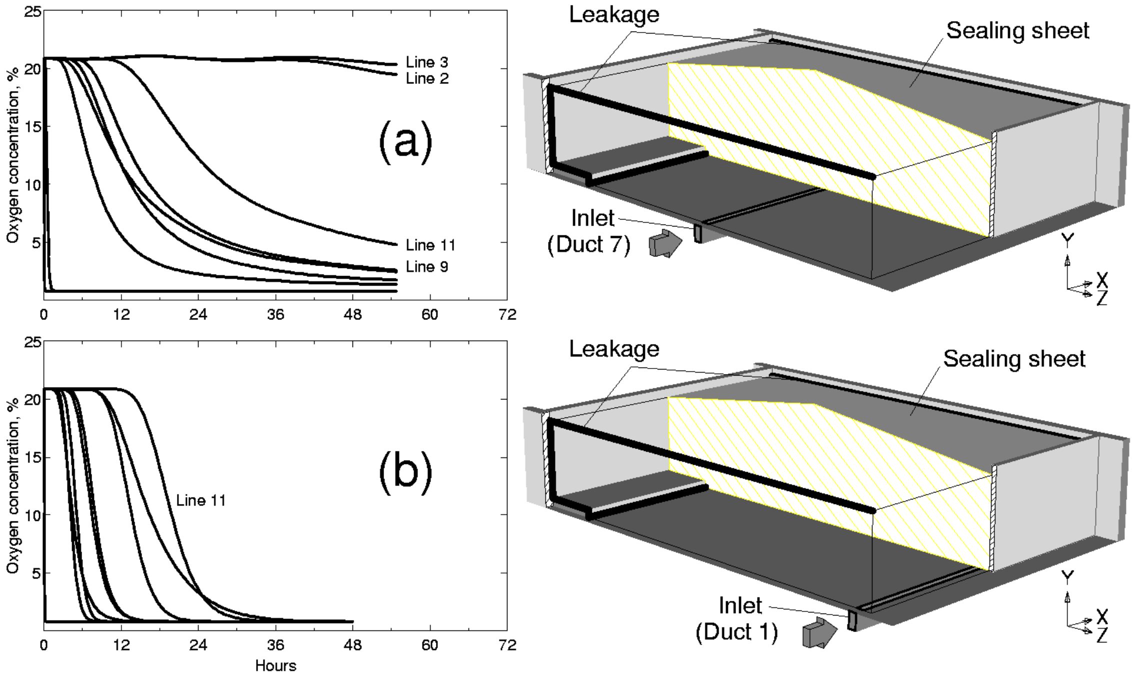


Figure 9. Predicted oxygen concentrations at sampling points during purging in a 350 tonne flat store, using two gas injection positions. The purging flow rate (15 $m^3.h^{-1}$) and leakage points are the same in both cases. (a) Gas injection near the middle (Duct 7); (b) Gas injection near the front (Duct 1)



8.3. Conclusions

1) CFD modelling of grain stores, with time-varying boundary conditions, has simulated the interactions between weather conditions and internal gas flows, and predicted the oxygen concentrations in the bulk.

2) The predictions show that under windy conditions the pressures created by MA injection are unable to prevent air penetration into grain stores despite high MA injection rates.

3) If the major leak positions are concentrated in one area and their position is known then the most efficient purge, or MA replenishment, is obtained when the MA injection position is placed at the opposite end of the store.

4) Low oxygen atmospheres can only be maintained if store floors and walls are reasonably gas-tight.

9. Bibliography

Abbott, W. S. (1925) A method of computing the effectiveness of an insecticide. *J. Econ. Ent*. **18**, 265-267.

Annis, P. C. (1987) Towards rational controlled atmosphere dosage schedules: A review of current knowledge. In: Proceedings of the 4th International Working Conference on Stored-Product Protection, Tel Aviv, Israel, September 1986, eds., Donahaye, E. and Navarro, S., pp. 128-148.

ASAE Standards. (1995) Thermal properties of grain and grain products. D243.3

Banks, H. J., Annis, P. C. and Rigby, G. R. (1991) Controlled atmosphere storage of grain: the known and the future. In: Proceedings of the 5th International Working Conference on Stored-Product Protection, Bordeaux, France, 9-14th September 1990, eds. Fleurat-Lessard, F. and Ducom, P., pp. 695-706.

Banks, H. J. (1994) Fumigation - an endangered technology? In: Proceedings of the 6th International Working Conference on Stored-Product Protection, Canberra, Australia, 17-23rd April 1994, eds. Highley, E., Wright, E. J., Banks, H. J. and Champ, B. R., CAB International, Wallingford, pp. 2-6.

Bejan A. (1993) *Heat Transfer.* Wiley.

Bell, C. H. (1996) Alternatives - Physical methods and emission reduction. *In The Methyl Bromide Issue*, eds. Bell, C. H., Chakrabarti, B. and Price, N. R., pp. 323-389. John Wiley and Sons, Ltd., London.

Bell, C. H. and Armitage, D. M. (1992) Alternative storage practices. In: Sauer, D. B., ed., Storage of Cereal Grains and their Products. 4th Edition, St. Paul, Minn., American Association of Cereal Chemists, pp. 249-311.

Bird R.B., Stewart W.E. and Lightfoot E.N. (1960) *Transport Phenomena.* Wiley.

CFDS. (1995) CFX 4.1 User Manual, Harwell Laboratory, Oxfordshire, UK.

CFX4.3 (1999), AEA Technology, Harwell, Oxfordshire, UK.

Conyers, S. T. and Bell, C. H. (1996) The effect on the mortality of *adult Cryptolestes ferrugineus* (Stephens) (Coleoptera: Cucujidae), *Sitophilus granarius* (L.) (Coleoptera: Curculionidae) and *Oryzaephilus surinamensis* (Coleoptera: Silvanidae) of interrupting low oxygen exposures with periods of elevated oxygen. *J. stored Prod. Res.* **32**, 187-194.

Conyers, S. T., Bell, C. H., Llewellin, B. E. and Savvidou, N. (1996) Strategies for the use of modified atmospheres for the treatment of grain. Home-Grown Cereals Authority Project Report No. 125, pp. 122.

Henderson, S. (1990) Conditioning Stored Products to the Moisture Content Required, by Wetting or Drying. CSL Operating Procedure PPI 006. Central Science Laboratory, Ministry of Agriculture, Fisheries and Food, York.

Johnson, C. G. (1940) The maintenance of high atmospheric humidities for entomological work with glycerol-water mixtures. *Ann. Appl. Biol*. **27**, 295-300.

Kumar A. and Muir W.E. (1986) Airflow resistance of wheat and barley affected by airflow direction, filling method and dockage. *Transactions of ASAE* **29**, 1423-1426.

Solomon, M. E. (1951) The control of humidity with potassium hydroxide, sulphuric acid, and other solutions. *Bull. Ent. Res*. **42**, 543-554.

Solomon, M. E. (1962) Notes on the extraction and quantitative estimation of the Acaridae (Acarina). progress in soil zoology. In: Proceedings of a Colloquium on Research Methods in Soil Zoology, pp. 305-307. Rothampstead Experimental Station.