HGCA

PROJECT REPORT No. 24

INTEGRATED PEST CONTROL STRATEGY FOR STORED GRAIN

OCTOBER 1990

PRICE £10.00

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Integrated pest control strategy for stored grain

by

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Final report of a three year project at the ADAS Central Science Laboratory, London Road, Slough SL3 7HJ. The work commenced in June 1987 and was supported by a grant of £62,663 from the Home-Grown Cereals Authority (Project No. 0015/2/87).

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ABSTRACT

A storage strategy, based on reducing grain temperatures by ambient aeration, has been devised and tested in large-scale trials. Twenty-tonne lots of wheat, with an initial moisture content and temperature of between 12.5 - 16.5% and 27 - 35 C, were stored in a nest of metal bins. An infestation of Oryzaephilus surinamensis, Sitophilus granarius and Cryptolestes ferrugineus was introduced into the grain at the rate of 1, 1 and 0.4 insects/kg of grain respectively. During storage the grain was cooled by means of ambient aeration, with air blown up though the grain at the rate of 10 cu. m./tonne/hour. The bins were divided into two batches of three and the aeration system of each batch was controlled separately by a differential thermostat. In one case a differential of 2 C was used but a differential of 4 C was used for the other controller. The effects of time and changes in temperature on the insects were monitored by a combination of trapping and spear sampling. Aeration produced a rapid fall in the temperature of the grain so that the grain at the centre of all bins was below 15 C five days after the start of cooling. Ten weeks after the start of aeration grain temperatures were near or below 5 C. There was a marked difference between the number of hours of fan operation used by the two differential settings to achieve the same grain temperatures. The 4 C differential used only about a third of the hours of the 2 C setting. Numbers of O. surinamensis and C. ferrugineus caught at the surface increased at the start of aeration but, as the trial progressed, declined to a very low level. Spear sampling 24 weeks after cooling began, showed that the insect population had fallen from about 2.4/kg to less than 1/kg. When the grain was sampled during out-loading at the end of the trial, no live insects were detected.

Data to validate the results from practical trials has been generated by calculation or by field observations. These show that the strategy is not susceptible to climatic and geographic variations and would be successful throughout the U.K. in any year. Minimum rates of airflow and the consequences, in terms of rate of cooling and insect infestation, of not achieving these airflow rates have also been calculated. Field observations have confirmed that the method of monitoring insect population developed for the strategy is effective and likely to be more sensitive at low population densities than spear sampling.

Aeration records and trapping data have been collected from a range of commercial stores. These confirm the effectiveness of trapping and have allowed the costs of

aeration, under commercial conditions, to be estimated.

Limited applications of pesticide to bulks of cooled grain were shown to be effective under practical conditions. They were also much less expensive than alternative chemical control options and resulted in a large reduction in pesticide usage.

1. BACKGROUND INFORMATION

Grain is a durable product and, given suitable conditions, can be stored for long periods without loss of quality or quantity. However, safe storage is often jeopardized by insect attack which causes direct losses as well as setting up secondary problems such as insect induced hot spots. The importance of storage problems has increased in recent years as many quality standards for traded grain now specifically exclude all insect pests. As a result, the detection of a single pest in a load can result in the grain being rejected with serious financial penalties to the offerer.

In the light of these developments , current storage practice tends to rely heavily on the prophylactic use of pesticides to prevent infestation (Wilkin, Dyte and Cruikshank, 1982; Wilkin and Hurlock, 1986). Grain is treated with a relatively persistent pesticide as it enters store and the treatment both disinfests and protects from reinfestation for several months. The technique has become widely used because it is effective and inexpensive. However, it does have a number of drawbacks which centre principally on the concern over the application of pesticides to a foodstuff. There is also concern that the continued use of the method could be threatened by resistance in the major pest species. Resistant strains of all the current grain pests have been detected in UK grain and, although current levels do not seem to preclude the continued use of pesticides, the genetic potential for serious resistance problems is well established (Muggleton, 1985).

All stored grain insect pests found in the UK require the temperature to be above a certain minimum level before they can breed (Howe, 1965). To some extent, the moisture content of the grain also influences their life-cycles. Generally, the moisture contents needed to limit development of most grain pests are too low to present an economic method of control. However, many insects require temperatures above 18 C and even the most cold-tolerant pest, Sitophilus granarius L, can only breed if the temperature is above 12 C (Eastham and Segrove, 1947). Therefore, control of grain temperatures must be an obvious consideration in avoiding infestation.

Cooling grain during storage has been employed as a method of reducing spoilage for some time. In the U.K., the climate after the harvest period is such that night time temperatures offer the option of using ambient air to cool grain to temperatures below those needed by insects for breeding. Such cooling also limits the availability of water to mites and spoilage micro-organisms as well as reducing temperature variation within a bulk and, thus, preventing convection-induced moisture migration. This process of aeration with ambient air to cool grain is now well developed in the U.K. (Burges & Burrell, 1964; Hyde and Burrell, 1973). Although the basic principles of aeration are well understood, in practice, the technique is often not used to its full potential. Storekeepers are happy to cool grain to about 15 C; a temperature that will prevent all insect pests breeding except for S. granarius, and even this species will take 140 days to complete a generation. However, it is possible to cool grain and other commodities to temperatures between 0 and 5 C (Armitage, 1980) using night-time air during November and December. At this temperature, mites will not breed and mould growth is inhibited. It has also been shown that many stored product beetles will die during prolonged exposure to temperatures of below 5 C (Armitage and Llewellin, 1987).

In practice, cooling may not be continued to achieve temperatures near 0 C because storekeepers consider that the costs would be too great and the staff are not available to control the cooling process. This latter difficulty is often related to the manual control of aeration fans, where the decision as to whether or not to turn on the fans has to be taken at a relatively early stage of the evening. This decision often cannot be changed until the following morning which may result in inefficient cooling, as air at the wrong temperature may be used or valuable aeration time may be lost. Fears have also been voiced that aeration cannot effectively control the temperature of the periphery of a grain bulk so that insects may migrate to these warmer areas and escape the lethal effects of very low temperatures.

The control of fans can be improved by using a simple electronic controller to turn them on and off. These usually operate by comparing the temperature of ambient with the current grain temperature and activating the fans if there is an appropriate differential. However, there are little data as to the effective use of these devices.

Another difficulty that needs to be addressed is the problem of detecting and monitoring insects, particularly at low population densities, in bulk grain. Traditional methods based on the collection of samples with a grain spear, are very labour intensive and relatively ineffective (Cogan and Wakefield, 1987). However, recent developments of trapping techniques to monitor insects in stored grain (Wright & Mills, 1983; Loschiavo, 1986; Cogan and Wakefield; 1987) have shown that such methods offer substantial improvements over the existing techniques. Thus there now is the potential to monitor accurately low levels of insects in bulk grain using trapping methods, so allowing a greater flexibility in pest management. However, little is known about the effects of low temperature on these methods or how to relate trap catch to commercially significant numbers of insects.

A range of other technical factors could also influence the success of cooling as a method of pest control. The temperature that is achieved by aeration is related to ambient conditions. Therefore, the success of the technique could be dependent on seasonal variation and thus be unreliable. By the same reasoning, the method could be more effective in the colder North and less effective in the South. Further complications may arise from variations in cold-hardiness between species and strains of insects and this is exacerbated by possible difficulties with the new monitoring techniques, outlined in the previous paragraph.

This range of problems currently inhibit the recommendation of cooling as a method of protecting grain from insect attack. The project reported in this paper was conceived to investigate the problems, develop solutions and to integrate a range of practical skills into a single grain management package. The principal objectives of the work were to:-

1. Investigate automatic controllers for aeration system and to produce operating procedures.

2. Investigate the effectiveness of cooling as a method of pest control under practical conditions.

3. Develop pest monitoring techniques needed to support the package.

4. Assess the need for and value of limited applications of pesticide to cooled bulks of grain.

5. Determine the effects of climatic, seasonal and regional variation on the use of cooling.

6. Measure the costs of grain cooling under practical conditions

In order to satisfy these objectives a major study was set up that encompassed large-scale laboratory trials, field investigations and calculations based on a wide range of practical data collected over a number of years.

2. LARGE SCALE EXPERIMENT

i) Introduction

This part of the project set out to assess the effectiveness of aeration to control pests under conditions similar to those found in many farm grain stores. It was carried out under laboratory conditions to allow better control over variables and to enable a much greater risk factor to be included without prejudicing a commercial sample of grain. Grain was stored over a 9 month period, using aeration as the only method of pest control.

The trial was started using the worst likely post harvest conditions; hot grain (as would be produced by a high temperature drier) infested with insects. An automated cooling regime was implemented and the infestation was monitored using insect traps, as these give the most accurate picture of the numbers of live insects and their distribution.

ii) Materials and methods

a) Details of store

The experiment was conducted in a nest of six metal bins (3x3x3.5m), each with a capacity of about 25 tonnes (Fig. 1.). Each bin had a single, peforated metal aeration duct in the bottom which was connected to a 200 or 400 watt, single phase, centrifugal fan. The intakes of these fans were restricted so that the rate of airflow delivered to the duct gave an aeration rate of 10cu m/tonne/hour. The running time of the fans was monitored with hours meters (devices to record the number of hours that the electricity was switched on to the fans) connected to the electrical supply. For the experiment, the bins were grouped into two batches of three replicates. The fans for each batch of replicates were connected to one of two commercial differential thermostats. In one batch, the differential between ambient and grain temperature at 1m depth in the centre of the bin needed before the fans were activated was set at 4 C and in the other, a differential of 2 C was used (Fig. 2).

The nest of bins was housed in a barn, together with a conveying system for moving the grain. No specific ventilation was provided, but the structure allowed considerable air exchange. Intakes drawing air from the outside were provided for the aeration fans.

b) Grain

The wheat used was a mixture of two varieties; Slepjna and Moulin. The grain was delivered to the laboratory immediately after being passed over a drier in which the cooling section had been turned off. However, as well as heating the grain this also reduced its moisture content to an unacceptably low value (<12.5%). Therefore, the grain was turned between bins and water was added to raise the moisture content. Ultimately, all the bins were filled to a depth of about 2.5m with about 20 tonnes of grain of moisture content ranging between 12.5 % and 16.5% and with temperatures ranging between 27 C and 35 C.

c) Insects

Seven days after filling the bins, adult S. granarius, Oryzaephilus surinamensis L. and Cryptolestes ferrugineus Steph. were added to the grain. The S. granarius and C. ferrugineus were taken from standard laboratory cultures that had been in culture in the Slough Laboratory for many years. The O. surinamensis were a field strain but had been in culture for 5 years. All insects were reared in bulk cultures at 25 C, 70% R.H. to provide the 300,000 adults needed for the trial. The S. granarius and O. surinamensis were added to the grain at the rate of about 1/kg, and the C. ferrugineus were added at the rate of 0.5/kg. The lower rate of addition of this latter species was because of difficulties in producing it in bulk culture.

The insects were distributed in the grain by inserting a 22 mm diameter plastic pipe to the bottom of the bin, using a vacuum sampler and then pouring a mixture of insects and grain down the pipe as it was withdrawn (Figs. 3a & 3b). This procedure was repeated 13 times in each bin and the position of these insertion points is shown in Fig. 4.

d) Monitoring insect movement and numbers

The insects in the grain were monitored by means of a series of pitfall and probe traps inserted into the grain as shown in Fig 3c. These traps provide a sensitive method of recording the presence of insects and changes in population activity but trap catch results cannot necessarily be related directly to population density.

Sixteen pitfall traps were inserted in the surface of the grain in each bin as shown in Fig. 5. These traps consisted of plastic, 570 ml beakers of diameter 85 mm, with the top inner lip coated with a PTFE suspension. The traps were pushed into the grain so that the rim was flush with the surface. Insects which fell into the traps were unable to escape due to the barrier created by the Fluon coating. Twenty-seven probe traps were inserted at the surface and at depths of 1 and 2 m at the points shown in Fig. 5. The probe traps (supplied by Northern Fumigation Services Ltd.) consisted of a clear perspex cylindrical tube, 36 x 2.5 cm, with the upper two thirds having 186, 3mm diameter holes drilled at an approximate angle of 60 degrees into the tube. A collection tube at the base of the trap allowed easy removal of any insects which fell into the trap via the drilled holes. These traps operated as pitfalls ,but were positioned below the grain surface. Both sets of traps were first inserted 1 week after the insects were added to the grain and thereafter were checked at weekly intervals for the first 6 weeks, fortnightly for 4 weeks and then monthly. The traps were inserted into the grain for one week on each occasion, before the catch was assessed.

The movement of insects away from the bins was assessed by the use of bait bags (Pinniger, 1975) placed at the inside of the wall/floor junction of the barn. Fifty bait bags were distributed evenly around the bins and checked for insects at weekly intervals.

In order to confirm the distribution of insects as obtained by the traps and to help to relate this to population density, further assessments of insect numbers in the grain were made by collecting spear samples using a 200g capacity gravity spear. One week after the insects had been added, three of the bins, chosen at random, were sampled by collecting 3 samples from the bottom layers. A further, but more comprehensive sampling was carried out after the experiment had been running for 28 weeks. On this occasion, 27 samples were removed from each bin, at the surface, 1 and 2m, sieved for insects, and the moisture content of the sieved grains determined.

At the end of the test the grain was sold and samples were collected as it was loaded into lorries for dispatch from the laboratory. One bin was unloaded each day at a rate of about 14 tonnes per hour and samples were taken, both in the conveying system and also from each lorry after loading. A volume of grain, equivalent to about 1 kg., was collected directly from the auger outlet from the bin, every 15 minutes as the grain stream passed from the bin and into the conveyor system. These "conveyor" samples were weighed on a top pan balance and examined individually. Eight samples of about 0.25 kg were collected by vacuum in accordance with BS 4510 for a load of 15 - 30 T. The combined 2 kg sample from each lorry load was divided using a Boerner divider to give two equivalent samples. Only one of these "lorry" samples was examined. All samples collected by both techniques were sifted over a 2 mm test sieve loaded to half its capacity and shaken 30 times. The sievings were then examined for insects and insect fragments.

e) Monitoring physical conditions

The temperature of the grain was monitored using thermocouples conected to data loggers. The thermocouples were inserted at two points in each bin; in the centre and in an outer corner. Sensors were placed at depths of 0.5, 1, 1.5 and 2.0m at each point (Fig.6). An additional two thermocouples measured ambient temperature at the top of the bins and close to ground level outside the barn. Temperatures were monitored hourly but daily and weekly means were generated from this data.

At the start of the trial, after the freshly moistened grain had been loaded into its final bin, samples were collected by spear from the surface and at 0.5m intervals down through the grain for moisture content determination. A further check on the moisture of the grain was made after 28 weeks storage when spear samples were collected (see d) Monitoring insect movement and numbers). All moisture contents were determined by drying finely ground grain in a ventilated oven at 130 C for 2 h (BS 412).

f) Aeration of the grain

Throughout the trial, all aeration was controlled by the differential thermostats without manual interference.

The rate of airflow in the duct was checked periodically during the experiment using a hot wire anemometer. At the end of the test, the airflows were measured using a pitot tube and inclined micromanometer according to BS 1042 and 848. Estimates of airflow at the surface of the grain were made on a few occasions using a bubble anemometer (Burrell and Armitage, 1979).

iii) Results

a) Grain temperature and fan operating time

In the 15 days before aeration, temperatures were generally stable, in the range 20 - 30 C, with the centre of the bins being hottest. There was some indication that grain heating occurred as some positions in the centre of about half the bins showed an increase in temperature.

There were only very small differences in temperature between replicate bins. Therefore, the temperature data are presented as means for each set of replicates. The temperature trends are reported as average maxima but the exact point at which the maximum was achieved is not shown. However, as a general rule, during cooling the maximum temperatures always occurred at the top of bins and the minimum nearest the bottom where the cool air entered the grain. In the early spring and summer, when the grain was warming, maximum temperatures were recorded by thermocouples nearest the periphery of the bins.

The grain temperatures recorded during this study are presented graphically. Figs. 7 to 10 show the average range of maximum temperatures on a weekly basis. These Figures are arranged so that the results for the two differential controllers can be overlain for comparison. Throughout the experiment, the mean temperatures achieved by both aeration regimes were very similar and the ranges almost always overlapped. Therefore, some general comments can be made about the effects of aeration that apply equally to both regimes. Aeration commenced on the 24 September and, within 5 days, the temperature of the grain at the centre of all bins was below 15 C. After 15 days the highest temperature anywhere in any of the bins was below 15 C. Temperatures throughout the bins had fallen to below 10 C, 63 days after the start of aeration. By the time the aeration system had been in operation for 77 days (early December) the grain was at or close to 5 C (Table 1).

Some differences between the temperatures achieved by the two aeration regimes are apparent after December during the late winter and early spring. Generally, the 2 C differential produced maximum grain temperatures that were 2 or 3 C lower than the 4 C differential.

The number of hours and date of fan operation for each differential are shown in Table 2. There was a substantial difference in the total number of hours used by each control regime, with the 2 C differential allowing the fans to run for almost 3 times as many hours as the 4 C differential. The total amount of electrical energy used by the two cooling regimes was calculated from the number of hours running and the estimated power consumption of the fans (see also Part 6). Assuming a cost of electricity of 6p/kwatt h., the cost per tonne of the 4 C differential was 3.1p/tonne and that for the 2 C differential was 8.1p/tonne.

The airflows (measured by BS method) through the grain in bins 1, 2 and 4, with the 4 C differential thermostat were 11.9, 9.9 and 13.3 (mean 11.7) cu m/T/h and those of bins 3, 5 and 6 with the 2 C differential thermostats; 10.7, 10.3 and 10.3 (mean 10.40 cu M/T/h).

b) Moisture content

The results of the moisture content determinations are given in Table 3. The grain in both sets of bins was initially between 13 and 16% moisture content. After 28 weeks aeration there was little change at the surface or at 1m. At 2m there was little change in the bins cooled by the 4 C differential but in the others there was an increase of 0.6%. This increase was pronounced in samples removed from the centre of the bins immediately above the aeration duct, where a local increase of 1.6% moisture was recorded.

c) Insect populations

The number of insects escaping from the bins during the trial, as determined by bait bag catches, was low. A total of 1282 O. surinamensis (1% of the number released into the bins) were trapped by the bait bags, and only a single S. granarius and no C. ferrugineus were trapped. The results, given in Table 4, do not show any direct correlation between numbers of insects leaving the bins and the operation of the aeration systems .

The cumulative totals and percentages of the original population of insects removed from the grain by trapping and caught in bait bags are given in Table 5. There was no significant difference between the 2 and 4 degree cooling regimes with regard to the total number of the three insect species caught in the pitfall and probe traps throughout the experiment. However, within each layer in any one bin, widely different numbers were trapped at each sampling. The results were, therefore, analysed by considering each trap result within a layer (surface, middle or bottom) for the 3 bins of each regime as a replicate (n=27). Means of these replicates together with standard errors are presented for pitfalls and probe traps (Tables 6-11).

The overall pattern of trap catch indicated that O. surinamensis and C. ferrugineus showed similar behavioural responses to cooling by aeration, whilst the response of S. granarius was markedly different.

Before aeration commenced, few insects of any species were found in surface pitfall and probe traps in any of the bins. Both O. surinamensis and S. granarius were detected evenly in the 1 and 2 metre layers, whereas few C. ferrugineus were found at the 2 metre depth compared with 1 metre (Tables 6-11).

Trap catches of O. surinamensis and C. ferrugineus:-

Seven days after aeration started, the surface probe traps showed a 10 and 20 fold increase in numbers of O. surinamensis and C. ferrugineus, respectively. The following week, numbers fell but were still significantly higher at the surface compared with 1 and 2 metres for both species (Tables 6 and 7).

Numbers of O. surinamensis and C. ferrugineus trapped everywhere by the probe traps continued to fall and were closely correlated with temperature decrease. After 10 December numbers of O. surinamensis fell below 1/trap whilst few C. ferrugineus were caught anywhere.

No further insects were caught, even when the temperature maxima started to rise after 3 March.

The pitfall catches mirrored those of the surface probes (Tables 8 and 9) but fewer insects were caught and the peak catch occurred one week after that of the probe traps. Fewer C. ferrugineus were caught in the pitfall traps than by the surface probe traps.

A pattern of increase followed by decrease may be seen in the overall trend of the pitfall trap catches of both species for both the 2 and 4 degree regimes. This pattern, when compared with fan hours, suggests a correlation between surface activity of these insects, as reflected by trap catch and fan operation (Tables 2 , 8 and 9). This pattern was not shown by the probe trap results.

Trap catches of S. granarius:-

Before aeration, S. granarius were more common in probe traps in all bins at 1 and 2m than at the surface (Table 10). After aeration started, there was some increase in their occurrence at the surface but numbers everywhere remained low throughout the trial, with only single insects trapped beyond 15 October. Numbers caught declined during the trial and catches were less than 1/trap after 1 October and few were caught after 10th December.

Differences between the cooling regimes were noted for S. granarius. Initially there were more of this insect at 1m and the surface and less at 2m in the bins cooled using the 2 C differential. However, thereafter there were no significant differences between treatments.

Numbers of S. granarius caught in the pitfall traps were very low (Table 11) but, as with the other two species, peaked one week after the peak in the surface probe traps and then steadily decreased, following the pattern of the temperature maxima. The mean catch was usually higher in the 4 C bins, but only significantly so on 22nd October.

The numbers of insects collected in the spear samples taken after 1 and 28 weeks are given in Table 12.

The final sampling of the conveyor and the lorries during outloading revealed no live insects but many fragments. Minimum and maximum estimates of dead insects remaining in the grain were made. For the former, complementary fragments were counted as 1 individual and for the latter each fragment was regarded as a separate insect. Samples from the lorry appeared to contain more insect fragments than samples from the conveyor. The results had very large standard deviations and the significance of this type of data will be discussed in another HGCA levy funded project on grain sampling. However, the mean numbers suggested that all the S. granarius had remained in the grain, while a large proportion of the O. surinamensis and all of the C. feruqineus, could not be accounted for.

iv) Discussion

The temperature and level of infestation of the grain at the start of the experiment represented a very severe test of a storage strategy and must be close to the worst possible case likely to be encountered in practice. Despite this stringent test, the ambient air cooling system was able to reduce the grain temperature to 15 C within one week, a level below the breeding temperature of most of the UK grain insect pests. This cooling also reduced the equilibrium relative humidity of the grain and thus would have limited the likelihood of mould growth. However, a further 5 weeks passed before the temperature could be reduced to below 12 C to prevent S. granarius from breeding. Despite this, it seems unlikely that the temperature was sufficiently high during the first 8 weeks of the trial to have allowed this insect to complete a generation, as Eastham and Segrove (1947) estimated that this would take over 140 days at 15 C.

The lowest mean temperature at the centre of the bins and the time the grain spent at that temperature were similar to those reported by Armitage and Llewellin (1987) and, therefore, likely to have been sufficiently low to kill substantial numbers of all the species tested (Evans, 1983). The 28-week sampling results (Table 6), in which only dead insects were found, confirms this, as does the absence of live insects in samples taken during outloading. Differences between estimates of insect numbers in the conveyor and lorry samples may be accounted for by removal of dust by the dust extraction equipment built into the conveyor and extra damage caused to the grain as it travelled between bin and lorry. Few live insects were detected in any of the pitfall or probe traps after the end of January. O. surinamensis was the last species sufficiently active to be trapped. Clearly the falling temperature must have reduced insect activity, so reducing trap catch, but the picture of the decline in the insect populations given by the trap catches is probably a good representation of the numbers of live insects.

There was a very large difference in the number of hours of aeration use by the two controllers to achieve the similar grain temperatures. The 4 C differential was far more economical, using only slightly more than one third of the aeration hours compared with the 2 C differential. However, when grain is cooled to below 5 C the smaller differential is likely to be better at achieving further temperature reductions. This is confirmed by the lower temperature of the bins aerated using the 2 C differential during the late winter. The most effective method of controlling grain temperatures might involve using a large differential to achieve most of the cooling and then employing a smaller differential to maintain temperatures at a minimum level for as long as possible. However, careful consideration of the benefits compared to the costs of this approach are needed before recommendations can be made. It must also be borne in mind that even the 2 C differential is likely to have been much more energy efficient than manual control of the fans. Therefore, the use of these simple control systems could offer major savings in the running costs of aeration systems, as well as ensuring that grain temperatures are reduced to a level at which insects are not likely to survive.

The size of bin used in these trials should not have affected the rate of cooling at the centre of the bins as this is dependent on the rate of airflow per tonne (McLean 1980). Larger bulks merely require larger fans to maintain the correct airflow. The small bins did ensure even airflow but at the same time did not give the equivalent insulation properties of a larger bulk. The rise in temperature at the centre of the bins that was recorded after December was, almost certainly, a consequence of mild weather and is unlikely to have been so pronounced in a larger bulk.

In general, the aeration had little effect on the moisture content of the grain. The only significant increase in moisture occurred in the bins cooled using the 4 C differential and this was restricted to grain immediately above the duct. This increase can be attributed to the far greater periods of aeration employed by the smaller differential setting.

The numbers of insects caught in the traps showed that the 3 species had largely distributed themselves evenly within the grain in each bin after the initial seeding. The most mobile species, O. surinamensis and C. ferrugineus, had reached the surface layers but few S. granarius had done so. This rapid migration would be expected in grain at approximately 30 C. (Hagstrum, 1989). Furthermore, few of this species were found in the probe traps near the base of the bins, which is also in agreement with Hagstrum's findings.

The immediate effect of aeration and the start of cooling, was a dramatic increase in the numbers of O. surinamensis and to a lesser extent C. ferrugineus trapped in the surface probe traps and one week later in the pitfall traps. A reason for the later peak in insect catch in the pitfall traps may be that the surface layer of the bins was still warmer than the grain just below the surface after the first cooling front had reached the surface. It has also been found (Surtees, 1965) that O. surinamensis shows an increase in activity as temperatures decrease from 25 C to below 20 C. Thus, activity would be expected to increase as aeration produced lower grain temperatures.

As aeration cooled the grain, numbers of all 3 species trapped in the probe and pitfall traps decreased, mirroring the decrease in temperature maxima in both 2 and 4 degree bins. This was a result of a decline in insect activity related to temperature decrease. Following the initial aeration, numbers of insects trapped in the probe and pitfall traps in the 4 degree bins remained higher for longer than the 2 degree bins, with significantly higher numbers of O. surinamensis and C. ferrugineus being trapped at the surface probes. The slightly higher maxima in the 4 degree bins may help to explain why more insects were trapped in these compared to the 2 degree bins during this period.

Temperature maxima remained below 10 C for the period 19 November to the beginning of April and until 12 May in the centre of the bulk. Very few insects were trapped (mainly O. surinamensis) during this period with only 1 C. ferrugineus and 4 S. granarius trapped below the surface. From the beginning of April no further C. ferrugineus or S. granarius were trapped and only a single O. surinamensis, even though temperature maxima in the surface layers rose above 15 C during May. As this temperature should have resulted in increased insect activity and hence a rise in numbers trapped, only two reasons for nil capture are likely: namely death or escape of the insects. The former seems most likely to have occurred. Only 1% of O. surinamensis released into the bins were found in the bait-bags and none were recovered during the later period of the trial when temperatures rose above 15 C. One S. granarius and no C. ferrugineus were trapped in baitbags during the later stages of the trial. Moreover, the spear samples taken during this period and the samples taken at outloading, contained only dead insects.

The observation that O. surinamensis and C. ferrugineus, migrated to the surface in response to the cooling of the grain makes it feasible to initiate the migration of these species through grain using aeration. This, in turn, should offer the option of making the insects accessible to localised application of pesticides. The trapping results for S. granarius did not show the same trend. This may have been due to the trapping method being less effective for this species, but other data show pitfall traps can be successfully used to monitor S. granarius (Cogan et al, 1985). A more likely explanation is that this species is not able to move through the intergranular spaces as readily as the others. The recovery of dead S. granarius at the second gravity spear sampling and at outloading at a level commensurate with the initial seeding further indicates that this species was either too slow to respond to the cooling fronts produced by the aeration regimes or simply is unable to move appreciable distances through the intergranular spaces of bulk grain.

Overall, the trapping results indicate that the combined use of pitfall and probe traps gives a clear picture of the movements of the 3 major grain beetle pests during aeration. However, it is not possible at this stage to relate trap catches to insect population density from these data. Despite this, the use of these traps would appear paramount when employing a pest control strategy based on cooling but, for practical purposes, the numbers of the 2 trap types used in this trial could be greatly reduced. A good indication of the presence of live O. surinamensis and C. ferrugineus after the start of cooling could be obtained by use of probe traps alone in the surface layers only. However, probe traps at various depths in the grain would be needed to establish if S. granarius were present. Other trials (Cogan et al, 1985) and work reported in Part 3 of this report, suggest that pitfall traps are more effective in detecting low levels of S. ganarius than are probe traps. Therefore, it would seem to be advisable to use a combination of the two traps. However, it must be borne in mind that this approach to insect detection has only been tested with upward aeration which moves the insects up to the grain surface and the traps. Downward airflows could result in insects being moved away from the traps and into less accessable parts of the grain bulk.

The numbers of insects caught in the bait bags outside the bins indicates that O. surinamensis was the insect that wandered most actively from the bins. However, in contrast to the results of Armitage and Stables (1984), there was no direct correlation between insects leaving the bins and the use of the aeration system. This could be because Armitage and Stables used an encircling sticky band to collect insects and this may have caught a far higher proportion of the escaping insects. However, the population density of dead insects, as determined by the outloading samples, tends to confirm that a large proportion of the insects did not leave the grain.

v) Conclusions

1. Differential thermostats provide an effective method of controlling aeration fans. However, the economics of their operation is greatly affected by relatively small changes in the setting of the temperature differential.

2. Cooling grain to 5 C and holding it at that temperature for about 2 months would appear likely to kill the adults of the three species of grain insects used in the trial.

3. Cooling to a level needed to kill insects was achieved during a mild winter (1987/88) and at a cost substantially lower than comparable control methods using pesticides.

4. The use of pitfall and probe traps allowed the insect population and its distribution to be monitored.

5. From a practical standpoint, some aspects of the results of this experiment can be applied immediately. However, before a viable storage strategy can be constructed further points, such as ranges in cold tolerance of the insects, the effects of cooling on mites and climatic and geographic influences, require further study.

Table 1. Time taken and fan-hours needed to pass cooling fronts of 15 C, 10 C, 5 C and 6 C through wheat using differential thermostats set at 4 C or 2 C.

	Differential setting					
	4 C			2 C		
Bin	1	2	4	3	5	6
			Centre			
			15 C			
Date	27.9	29.9	27.9	26.9	27.9	28.9
Days	3	5	3	2	3	5
Hours	42	51	42	34	45	58
			10 C			
Date	26.11	26.11	12.11	5.11	19.11	26.11
Days	63	63	49	42	56	63
Hours	139	139	111	207	367	422
			6 C			
Date	3.12	*	10.12	3.12	3.12	10.12
Days	70		77	70	70	77
Hours	181		188	489	489	516
			5 C			
Date	10.12	*	10.12	3.12	21.1	10.3
Days	77		77	70	119	168
Hours	188		188	489	620	767

* 2.8 - 7.6 C on 10.12 = 77 days

Table 1. Continuation

Side

			15 C			
Date	29.9	9.10	29.9	29.9	1.10	29.9
Days	5	15	5	5	7	5
Hours	51	57	51	58	86	58
			10 C			
Date	12.11	19.11	5.11	5.11	26.11	19.11
Days	49	56	42	42	63	56
Hours	111	133	93	207	423	367
			6 C			
Date	10.12		10.12	10.12	25.2	3.3
Days	77		77	77	154	161
Hours	188		188	516	701	734
			5 C			
Date	10.3		14.1	10.12	3.3	10.3
Days	168		119	77	161	168
Hour	290		202	516	738	767

Bin 2: 5.6 - 6.4 C on 10.12 77 days
Bin 5; 5.2 - 6.4 C on 10.12
Bin 6; 4.4 - 6.8 On 10.12

Table 2. The number of hours run by aeration fans controlled by a 2 or 4 degree differential thermostat.

Week endg.	Week	Weekly		Cumulative	
		2 deg.	4 deg.	2 deg.	4 deg.
24.9	0	0	0	0	0
1.10	1	72.8	55.0	72.8	55.0
8.10	2	12.7	0	85.5	55.0
15.10	3	63.7	26.3	149.2	81.3
22.10	4	11.2	0	160.4	81.3
29.10	5	0	0	160.4	81.3
5.11	6	47.0	11.7	207.4	93.0
12.11	7	106.9	18.2	314.3	111.2
19.11	8	52.2	22.0	366.5	133.2
26.11	9	56.4	5.4	422.9	138.6
3.12	10	65.9	42.7	488.9	181.3
10.12	11	26.9	6.4	515.7	187.7
17.12	12	34.3	13.9	550.0	201.6
24.12	13	0	0	550.0	201.6
31.12	14	4.0	0	554.0	201.6
7.1	15	0	0	554.0	201.6
14.1	16	11.0	0	565.0	201.6
21.1	17	54.1	6.6	619.1	208.2
28.1	18	12.0	10.8	631.1	219.0
4.2	19	3.1	8.5	634.2	227.5
11.2	20	35.0	13.9	669.2	241.4
18.2	21	22.0	15.2	691.2	256.6
25.2	22	10.0	0	701.2	256.6
3.3	23	36.6	12.6	737.8	269.2
10.3	24	29.0	20.3	766.8	289.5
17.3	25	0	0	766.8	289.5
24.3	26	0	0	766.8	289.5
31.3	27	0	0	766.8	289.5
7.4	28	6.3	1.0	773.1	290.5
14.4	29	19.6	8.4	792.7	298.9
21.4	30	0	0	792.7	298.9
28.4	31	13.5	3.0	806.2	301.9
5.5	32	3.8	1.1	810.0	303.0
12.5	33	0	0	810.0	303.0
19.5	34	0	0	810.0	303.0
26.5	35	5.9	3.5	815.9	306.5
2.6	36	0	0	815.9	306.5
9.6	37	2.4	2.0	818.3	308.5
16.6	38	0	0	818.3	308.5
23.6	39	2.1	0	820.4	308.5
30.6	40	0	0	820.4	308.5

Table 3. Change in moisture content (%) of wheat aerated using a 2 degree and a 4 degree differential thermostat.

	Initial Centre row (n=3) Mean Range	28 weeks Centre row (n=3) Mean Range	Overall (n=27) Mean Range
4 degree			
surface	15.9 (15.5-16.5)	15.3 (14.7-15.8)	15.5 (14.7-16.2)
0.5	14.5 (14.0-15.4)		
1.0	14.1 (13.6-14.9)	14.0 (13.4-14.8)	13.9 (13.7-14.6)
1.5	14.2 (13.7-15.0)		
2.0 m	13.8 (13.7-14.0)	14.2 (13.9-14.4)	13.8 (13.1-14.4)
2 degree			
surface	15.8 (15.1-16.8)	15.3 (14.4-16.1)	15.2 (14.6-16.1)
0.5	14.5 (14.0-15.2)		
1.0	14.3 (13.9-14.9)	14.4 (14.2-14.9)	14.0 (13.2-14.9)
1.5	14.2 (13.8-14.5)		
2.0 m	13.7 (13.2-14.0)	15.3 (15.1-15.6)	14.3 (13.2-15.6)

Table 4. Number of O.surinamensis * caught in bait bags surrounding the trial bins.

Week	Nos trapped	week	Nos. traped
1	47	21	19
2	4	22	13
3	54	23	21
4	89	24	23
5	102	25	5
6	59	26	2
7	54	27	8
8	77	28	3
9	75	29	5
10	185	30	4
11	43	31	2
12	43	32	2
13	39	33	4
14	55	34	0
15	73	35	0
16	99	36	0
17	42	37	1
18	21	38	0
19	22	39	0
20	13	40	0

* Only 1 S. granarius (week 4) was caught and 0 C.ferrugineus.

Table 5. Total trap catch (pitfall and probe) of *O. surinamensis*, *C. ferrugineus* and *S. granarius* for each of the 2 and 4 degree differential bins. Percentages of total numbers added to the grain are in parentheses.

Regime	Bin	*O. surinamensis*	*C. ferrugineus*	*S. granarius*
	3	4726 (3.9)	432 (0.9)	137 (0.1)
2	5	4107 (3.4)	528 (1.1)	125 (0.1)
	6	1679 (1.4)	207 (0.4)	134 (0.1)
Total 2 degree		10512 (8.8)	1167 (0.3)	396 (0.3)
	1	2929 (2.4)	461 (1.0)	121 (0.1)
4	2	2044 (1.7)	535 (1.1)	175 (0.1)
	4	5336 (4.5)	377 (0.8)	84 (0.1)
Total 4 degree		10309 (8.6)	1373 (2.9)	380 (0.3)

Table 6. Mean probe trap catch (+/- SE) of *Oryzaephilus surinamensis* in 2 and 4 degree differential bins.

DATE	SURFACE		1 METRE		2 METRE	
	2	4	2	4	2	4
18-09-87	1.67 (0.66)	2.74 (0.87)	6.41 (2.94)	7.07 (2.82)	0.33 (0.2)	6.33 (3.78)
24-09-87	247.6 (73.2)	160.5 (49.1)	2.07 (0.65)	6.48 (2.68)	1.59 (0.66)	4.22 (1.68)
01-10-87	14.7 (2.24)	39.19 (9.46)	1.63 (0.38)	1.22 (0.32)	1.0 (0.93)	0.93 (0.23)
08-10-87	5.30 (1.69)	33.30 (9.19)	0.56 (0.22)	0.37 (0.12)	0.59 (0.22)	3.59 (3.14)
15-10-87	2.33 (0.69)	7.59 (3.04)	1.15 (0.37)	0.33 (0.19)	1.0 (0.28)	0.67 (0.49)
22-10-87	2.22 (0.54)	3.22 (0.58)	0.56 (0.12)	0.19 (0.09)	0.74 (0.18)	0.48 (0.18)
12-11-87	1.37 (0.41)	1.41 (0.28)	0.41 (0.12)	0.26 (0.11)	0.22 (0.10)	0.07 (0.05)
10-12-87	0.04 (0.04)	0.26 (0.09)	0.07 (0.05)	0.04 (0.04)	0.30 (0.30)	0.07 (0.05)
07-01-88	0.30 (0.04)	0.44 (0.14)	0	0.04 (0.04)	0.22 (0.16)	0.19 (0.12)
04-02-88	0.07 (0.05)	0.07 (0.05)	0	0	0	0.07 (0.07)
03-03-88	0.07 (0.05)	0.15 (0.07)	0	0.07 (0.05)	0.04 (0.04)	0.04 (0.04)
31-03-88	0	0	0	0	0	0
28-04-88	0	0	0	0	0	0
26-05-88	0	0.04 (0.04)	0	0	0	0
30-06-88	0.04 (0.04)	0.04 (0.04)	0	0	0	0
21-07-88	0.04	0	0	0	0	0

Table 7. Mean probe trap catch (+/-SE) of *Cryptolestes ferrugineus* in 2 and 4 degree differential bins.

DATE	SURFACE		1 METRE		2 METRE	
	2	4	2	4	2	4
18-09-87	0.82	0.89	1.41	0.44	0.04	0.04
	(0.42)	(0.61)	(0.84)	(0.27)	(0.04)	(0.04)
24-09-87	22.48	20.48	0.33	0.48	0.15	0.41
	(8.89)	(6.93)	(0.21)	(0.19)	(0.09)	(0.16)
01-10-87	1.96	4.26	0.26	0.26	0.11	0.07
	(0.75)	(1.68)	(0.14)	(0.16)	(0.11)	(0.05)
08-10-87	1.07	2.82	0.04	0.07	0.07	0.15
	(0.35)	(0.45)	(0.04)	(0.05)	(0.05)	(0.07)
15-10-87	0.85	2.26	0.11	0.15	0.11	0.07
	(0.27)	(0.52)	(0.08)	(0.07)	(0.06)	(0.07)
22-10-87	1.22	1.93	0.11	0.07	0.04	0.04
	(0.26)	(0.49)	(0.06)	(0.05)	(0.04)	(0.04)
12-11-87	0.56	1.52	0.22	0.26	0.04	0
	(0.17)	(0.33)	(0.08)	(0.10)	(0.04)	
10-12-87	0	0.11	0	0	0	0
		(0.06)				
07-01-88	0	0.07	0	0	0	0
		(0.05)				
04-02-88	0	0	0	0	0	0
03-03-88	0	0	0	0.04	0	0
				(0.04)		
31-03-88	0	0	0	0	0	0
28-04-88	0	0	0	0	0	0
26-05-88	0	0	0	0	0	0
30-06-88	0	0	0	0	0	0
21-07-88	0	0	0	0	0	0

Table 8. *Oryzaephilus surinamensis* pitfall trap results. Mean trap catch (+/-S.E.) for 2 and 4 degree regimes (n=48).

DATE	2 DEGREE BINS	4 DEGREE BINS
18-09-87	0.19 (0.06)	0.40 (0.11)
24-09-87	0.89 (0.20)	1.29 (0.39)
01-10-87	34.29 (3.99)	36.60 (6.47)
08-10-87	2.73 (0.50)	2.10 (0.32)
15-10-87	4.48 (0.73)	4.29 (0.56)
22-10-87	1.60 (0.24)	1.94 (0.28)
29-10-87	3.21 (0.34)	3.35 (0.43)
19-11-87	1.65 (0.32)	1.35 (0.26)
17-12-87	1.29 (0.20)	1.60 (0.24)
14-01-88	2.17 (0.29)	2.21 (0.28)
11-02-88	0.60 (0.13)	1.08 (0.25)
10-03-88	0.15 (0.05)	0.15 (0.05)
07-04-88	0	0
05-05-88	0	0
02-06-88	0	0
01-07-88	0	0
28-07-88	0	0

Table 9. Cryptolestes ferrugineus pitfall trap results. Mean trap catch (+/- SE) for 2 and 4 degree bins (N=48).

DATE	2 DEGREE BINS	4 DEGREE BINS
18-09-87	0	0
24-09-87	0	0
01-10-87	2.27 (0.54)	2.90 (0.5)
08-10-87	0.94 (0.21)	0.69 (0.12)
15-10-87	1.54 (0.24)	2.33 (0.34)
22-10-87	0.60 (0.14)	1.02 (0.19)
12-11-87	0.83 (0.16)	1.13 (0.20)
10-12-87	0.42 (0.03)	0.42 (0.03)
07-01-88	0.83 (0.04)	0.02 (0.02)
04-02-88	0	0
03-03-88	0	0
31-03-88	0	0
28-04-88	0	0
26-05-88	0	0
30-06-88	0	0
21-07-88	0	0

Table 10. Mean probe trap catch (+/-SE) of <u>Sitophilus granarius</u> in 2 and 4 degree differential bins.

Date	Surface		1 metre		2 metre	
	2	4	2	4	2	4
18-09-87	0.15 (0.09)	0.04 (0.04)	4.89 (1.24)	1.93 (0.41)	1.89 (0.76)	2.93 (1.29)
24-09-87	0.41 (0.21)	0.82 (0.32)	1.33 (0.41)	1.11 (0.32)	1.37 (0.70)	1.22 (0.38)
01-10-87	0.22 (0.11)	0.41 (0.18)	0.30 (0.13)	0.30 (0.14)	0.85 (0.39)	0.48 (0.22)
08-10-87	0.22 (0.08)	0.22 (0.10)	0.33 (0.13)	0.19 (0.09)	0.11 (0.06)	0.15 (0.09)
15-10-87	0.15 (0.15)	0.37 (0.13)	0.19 (0.12)	0.22) (0.09)	0.15 (0.12)	0.26 (0.11)
22-10-87	0	0	0.07 (0.05)	0.15 (0.07)	0.19 (0.12)	0.11 (0.08)
12-11-87	0.04 (0.37)	0.04 (0.37)	0.11 (0.06)	0.11 (0.08)	0.15 (0.10)	0
10-12-87	0	0	0	0	0	0.04 (0.04)
07-01-88	0	0	0.04 (0.04)	0	0	0
04-02-88	0	0	0	0	0.04 (0.04)	0.04 (0.04)
03-03-88	0	0	0	0	0	0
31-03-88	0	0	0	0	0	0
28-04-88	0	0	0	0	0	0
26-05-88	0	0	0	0	0	0
30-06-88	0	0	0	0	0	0
21-07-88	0	0	0	0	0	0

Table 11. <u>Sitophilus granarius</u> pitfall trap catch results. Mean trap catch (+/- SE) for 2 and 4 degree bins (n=48).

DATE	2 DEGREE BINS	4 DEGREE BINS
18-09-87	0.02 (0.02)	0.02 (0.02)
24-09-87	0.10 (0.10)	0
01-10-87	0.36 (0.15)	0.46 (0.06)
08-10-87	0.19 (0.10)	0.19 (0.10)
15-10-87	0.06 (0.06)	0.17 (0.06)
22-10-87	0.08 (0.02)	0.17 (0.09)
12-11-87	0.08 (0.06)	0.08 (0.06)
10-12-87	0.08 (0.07)	0
07-01-88	0	0.02 (0.02)
04-02-88	0	0
03-03-88	0	0
31-03-88	0	0
28-04-88	0	0
26-05-88	0	0
30-06-88	0	0
21-07-88	0	0

Table 12. Number of insects collected in spear samples taken at week 1 and 28 (presented as number / Kg.)

Week 1 [all samples taken at the bottom (2m) of each bin.]

Bin No.	Number/Kg. O. surinamensis	C. ferrugineus	S. granarius
1	1.1	0	1.1
3	0	0	4.4
5	0	0	1.7
Week 28 (Bins combined)			
Top	0.3	0.1	0.2
Middle	0.2	0	2.4
Bottom	0	0	2.1

Table 12a Estimates of maximum numbers of dead S. granarius and O. surinamensis (x 1000) remaining in 120 tonnes of wheat after aerated storage.

Sampling method	S. granarius		O. surinamensis	
	Nos	s.d	Nos	s.d.
Conveyor	120	60	48	24
Lorry	312	204	156	108

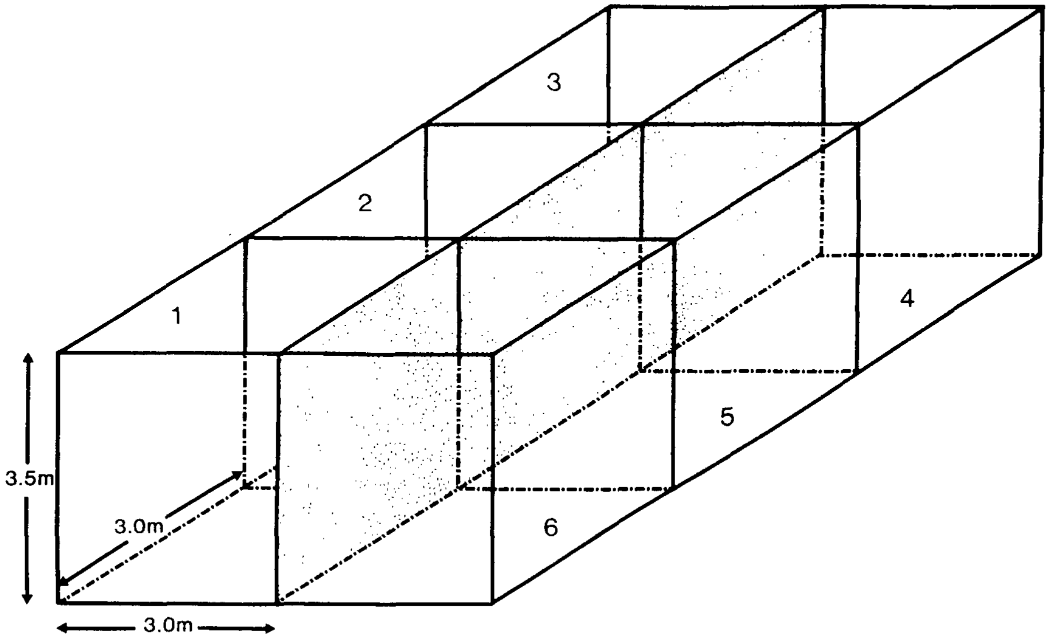
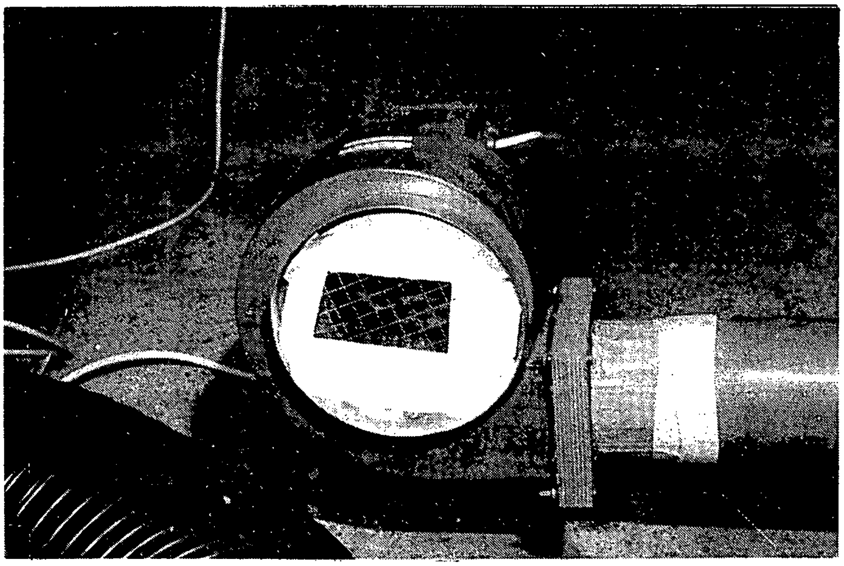


Fig. 1. Schematic diagram showing the layout of the nest of six bins used in the experiment.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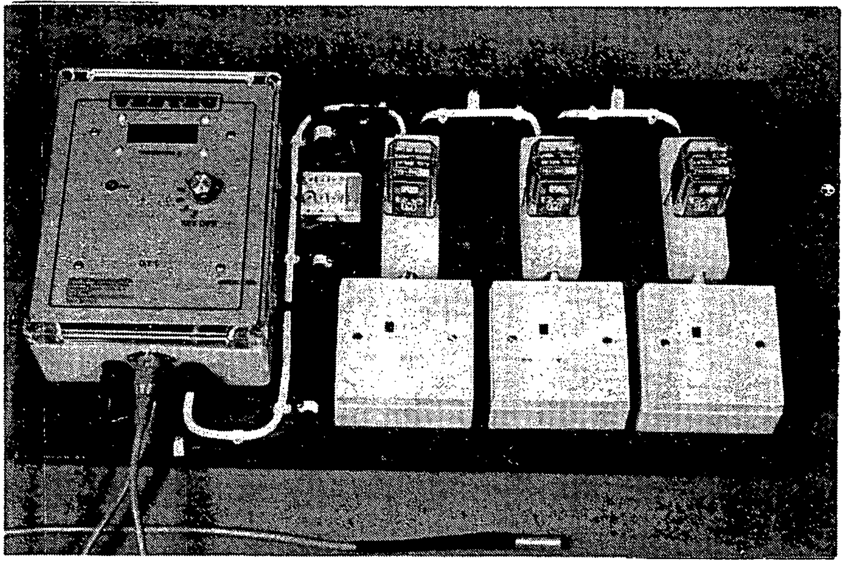

b

Fig. 2 . a) An aeration fan with the inlet restricted to reduce the airflow and b) the differential controller.

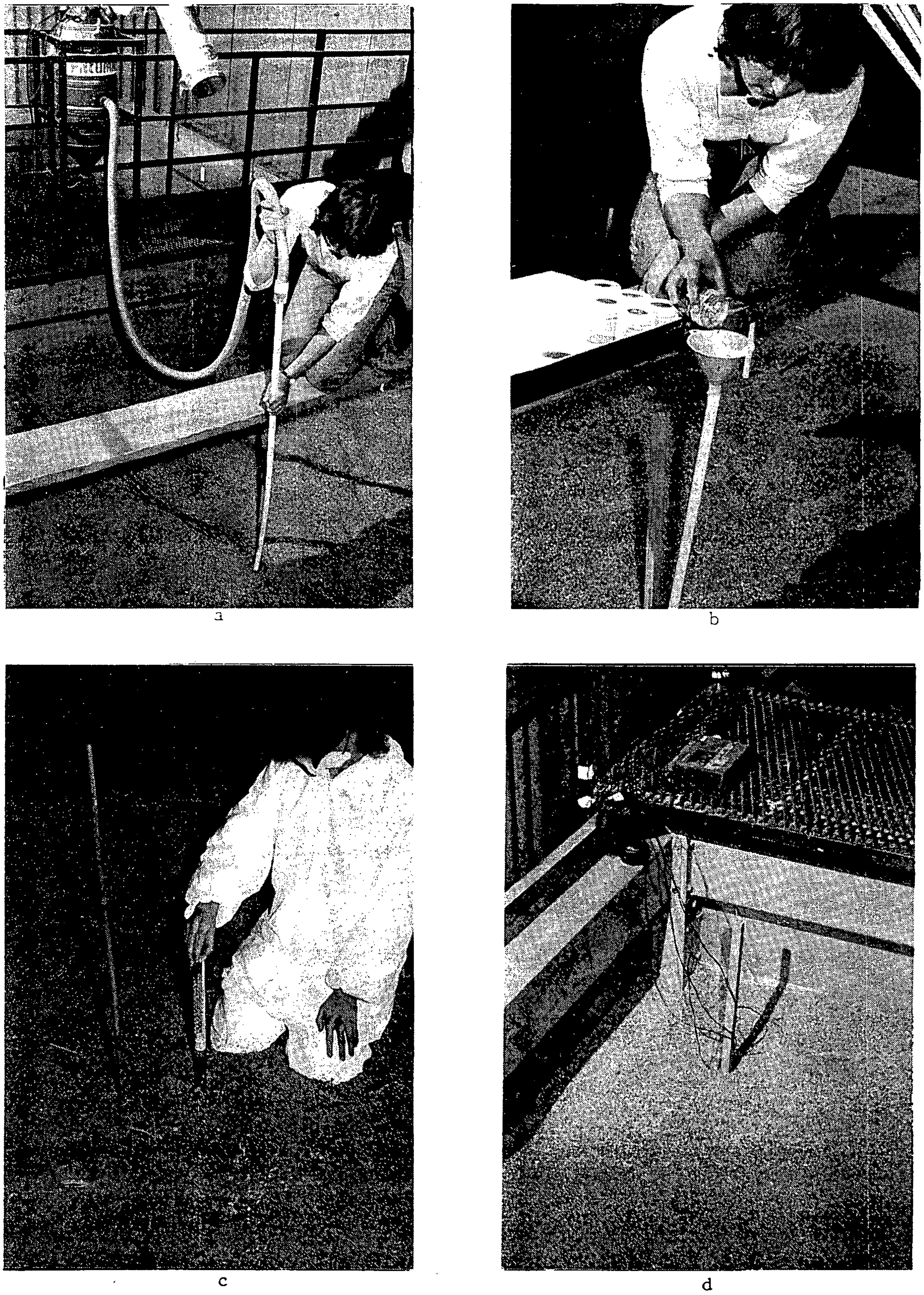


Fig. 3. a) Use of a vacuum sampler to insert plastic conduit into the grain, b) introduction of the insects into the bins, c) insertion of pitfall and probe traps and d) temperature monitoring equipment at the side of one bin.

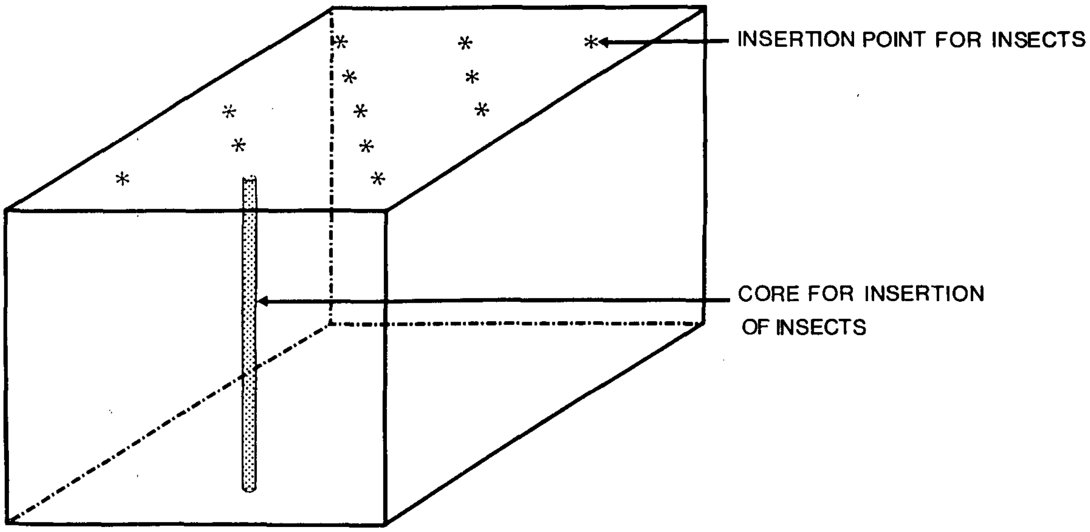


Fig 4. Schematic diagram showing the positions of insertion of the insects in one of the six bins.

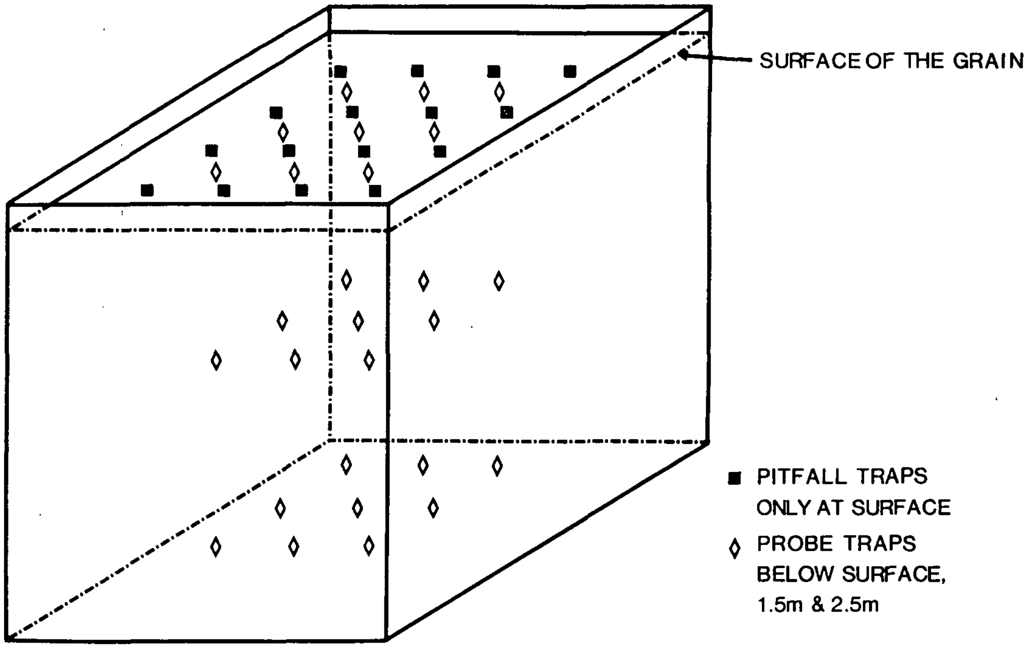


Fig. 5. Schematic diagram of one of the six bins showing the position of the probe and pitfall traps.

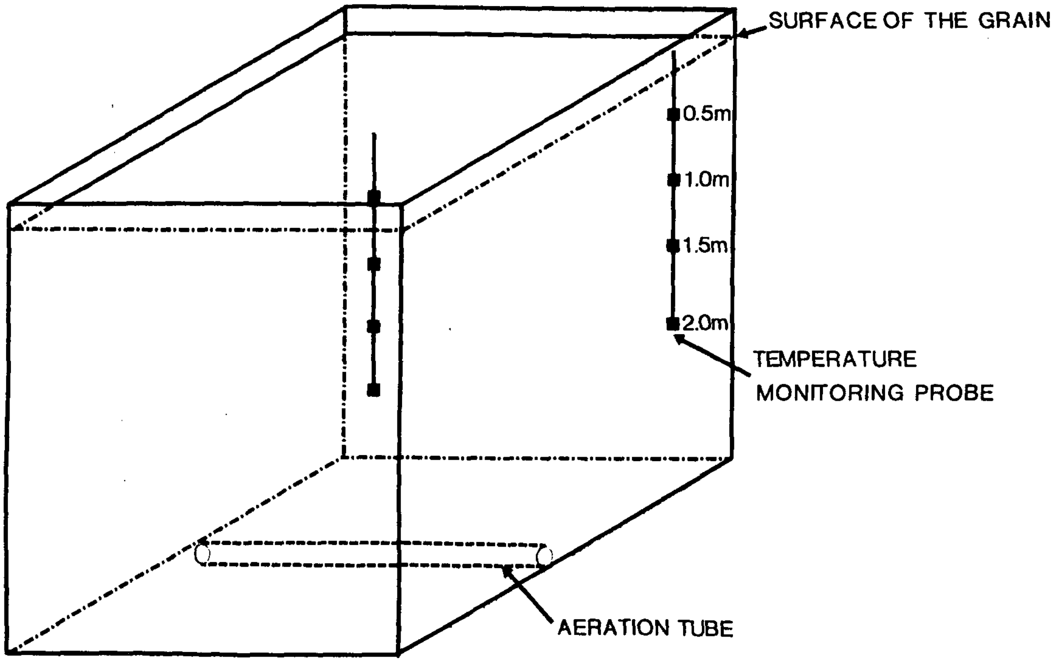


Fig. 6. Schematic diagram showing the position of the temperature probes in one of the six bins.

Fig. 7. Average maximum temperatures and range at the centre of 3 bins cooled using a 2 C differential thermostat

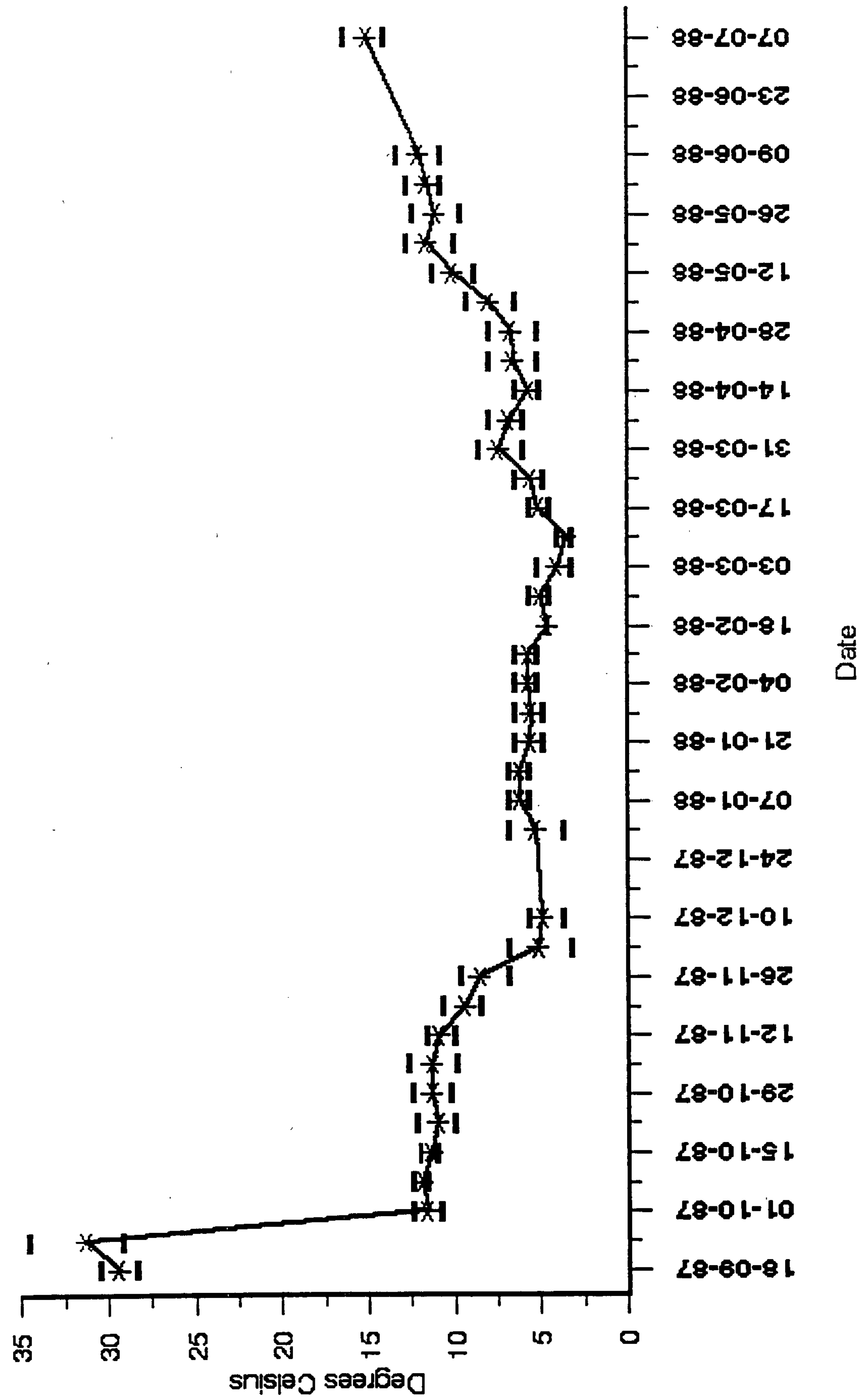


Fig. 8. Average maximum temperatures and range at the centre of 3 bins cooled using a 4 C differential thermostat

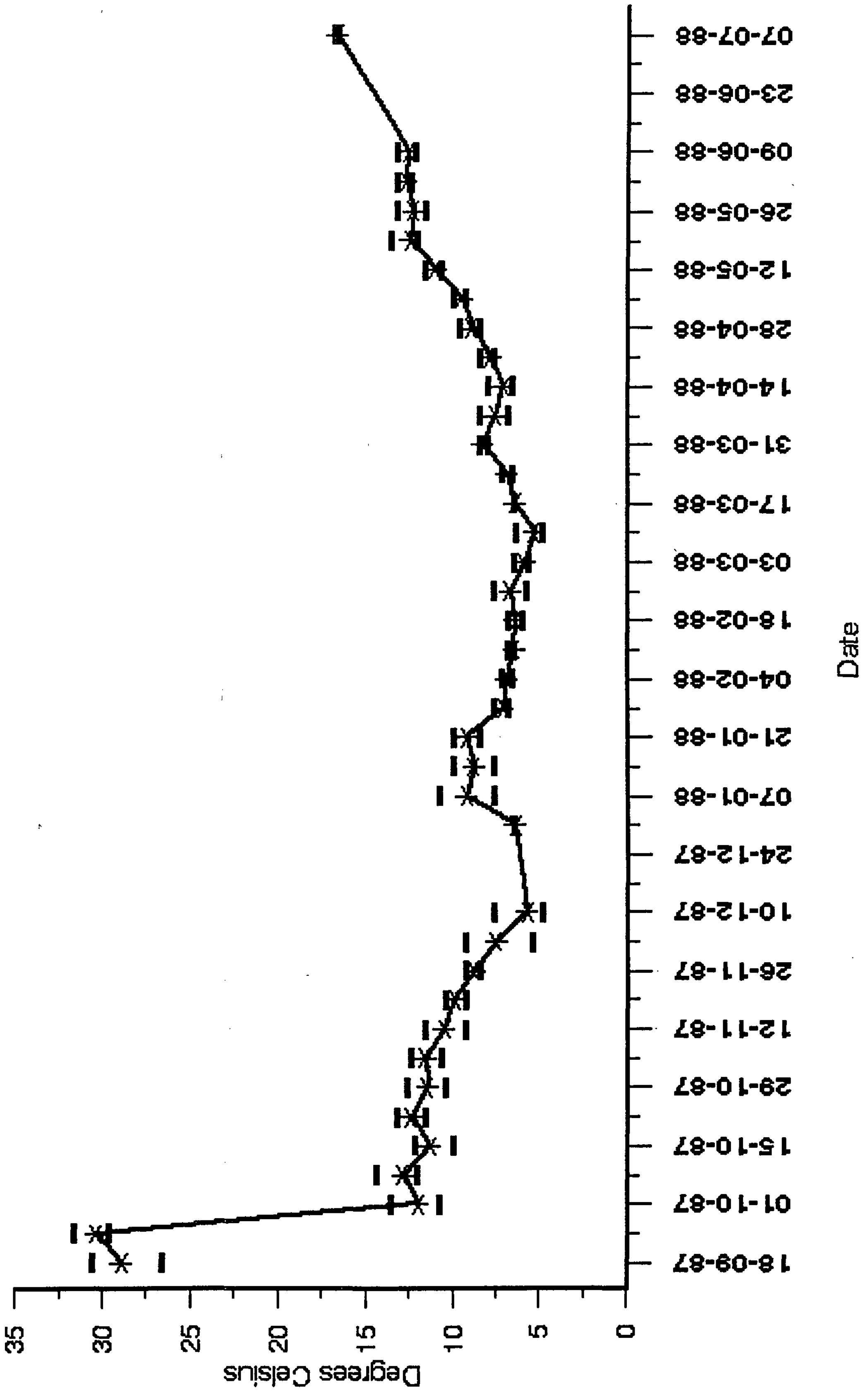


Fig. 9. Average maximum temperature and range at the periphery of 3 bins cooled using a 2 C differential thermostat

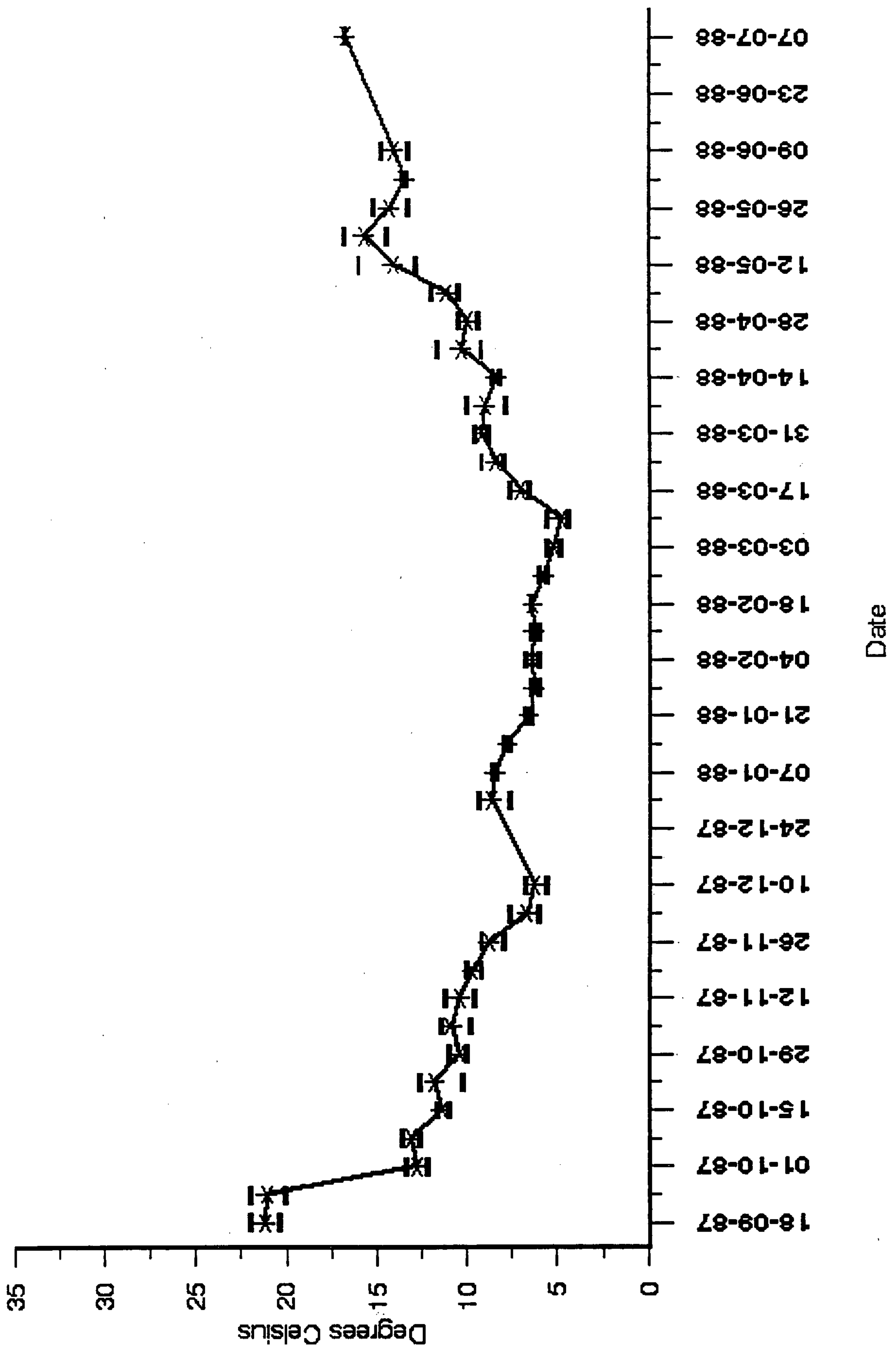
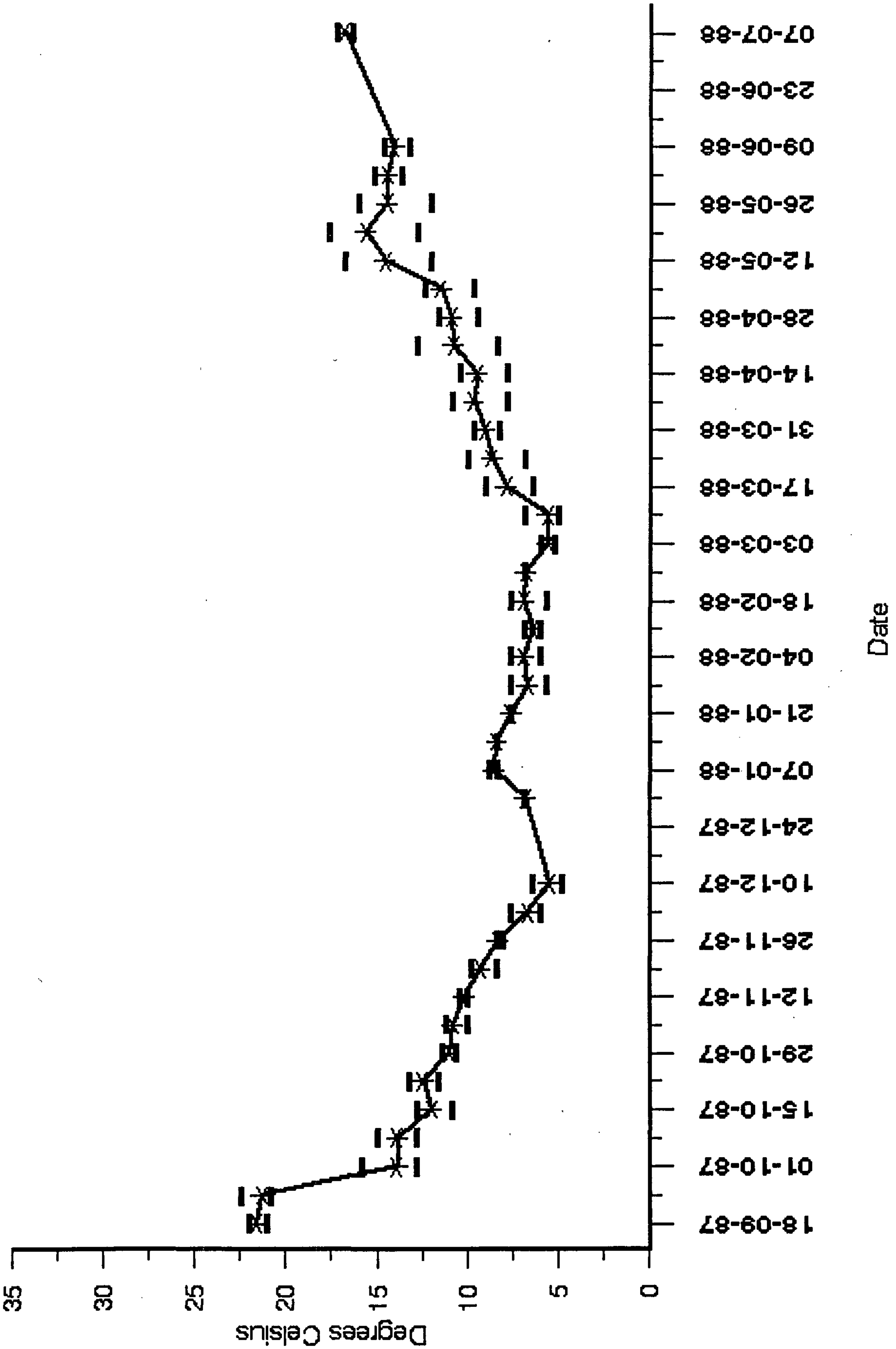


Fig. 10. Average maximum temperature and range at the periphery of 3 bins cooled using a 4 C differential thermostat



3. SURFACE TREATMENTS IN AERATED STORES

i) Introduction

The cooling of grain by ambient air does not guarantee control over the temperature of all the grain throughout the storage season. The temperature at the periphery of a bulk of grain will be influenced by the ambient temperature so that it will warm in the late winter and early spring. The upper surfaces of a bulk will also be exposed to solar radiation through the roof of the store and this can provide sufficient heat energy to raise the temperature of the grain by several degrees. Such warming at the periphery of a bulk could lead to the survival of insects and these survivors would be situated at a point where their detection would be easiest during an inspection by a prospective customer. Observations in the field tend to confirm that the survival of insects, particularly in the surface layers, does occur in the periphery of cooled bulks. Therefore, there may be circumstances when a storage strategy must include methods of controlling such surviving insects.

Two field trials have been carried out to examine one approach to dealing with surface infestations in cooled bulks. The objectives of the trials were :-

i) To control the infestation by means of localised and limited application of pesticide.

ii) To confirm that the effects of the treatment could be monitored by means of trapping techniques.

ii) **Experimental details**

The trials were carried out at two similar types of large grain store, both holding wheat. In both stores some of the grain had been in store for more than 12 months.

Store 1:-

The wheat was stored in converted aircraft hangars, with 5,000 tonnes in Hangar 1 and 10,600 tonnes in Hangar 5. The grain was contained by a metal walkway on one side and the outer wall of the hangar on the other. At each end it sloped down to floor level and the surface of the heap undulated gently with a general peak in the centre.

The grain had been aerated during storage and the temperatures throughout the bulks in both hangars ranged between 7 C and 11 C: below the minimum temperature at which _S. granarius_ can complete its life cycle.

An infestation of _S. granarius_ had been discovered by the store manager by means of pitfall traps inserted in the surface layers. Conventional spear sampling according to Intervention Board instructions had not detected any insects, nor were any found subsequently using this method.

Thirty-four traps were used by the store manager in Hangar 5 and forty-two in Hangar 1, but their exact locations were not recorded, as they were moved at intervals in an attempt to define the extent of the infestation.

Before the grain was treated, a monitoring exercise was mounted in order to assess the degree and extent of the infestation in both hangars. A combination of pitfall and probe traps was used, together with the collection and examination of spear samples. Traps were inserted into the surface of the grain according to the plans shown in Figs. 11 and 12. Probe traps were also inserted, 1.5 m beneath the surface, at the same points. In both hangars, a perimeter ring of pitfall traps were placed about 2m beyond the outer pitfall/probe combination. The assessment was carried out 5 times; once before treatment and then 4 times after treatment over a 6-week period.

At each assessment the temperature of the surface of the grain was measured at two sites along the peak of the heaps in each hangar. After the pre-treatment assessment, samples of grain were collected using a 200g gravity spear from the part of each bulk that the trapping had shown to be most heavily infested. The samples were collected from the surface and at a depth of 1.5 m. Fifteen samples were drawn at each depth from Hangar 5 and five from Hangar 1. The grain was sieved over a 2mm mesh and the sievings examined for insects. The sieved grain was incubated in the laboratory at 25 C and 70% r.h., to check for immature stages.

The pre-treatment trapping, together with the results of the store managers findings, were used as a guide to the extent of the infestation in each hangar. An area of the surface, somewhat larger than the infested area, was marked out for treatment. Etrimfos dust (Satisfar) was applied at the rate of 50g/m sq. using a large, 1.8mm sieve to spread the dust as evenly as possible. A double dose was applied to the top of the peak to counter the effects of the treated grain being dislodged down the slope. After the dust had been spread on the surface it was raked in using wooden or metal rakes.

Store 2:-

About 10,000 tonnes of barley was stored in a converted aircraft hangar. The surface of the grain was generally level but the heap sloped down to ground level at one end. During routine monitoring with pitfall traps, the storekeeper had discovered a localised infestation of S. granarius in about 15% of the surface layer of grain. The grain had been aerated during storage and was below 12 C, the minimum temperature needed by S. granarius to complete its life cycle.

A monitoring exercise was carried out using 33 pitfall traps located in and around the part of bulk shown to be infested by the storekeeper's results. These were checked at weekly intervals, starting 4 weeks before treatment and continuing for a further 6 weeks. Temperature sensors were placed in the grain at 11 points: at the surface, 0.5m and 1m depths. Temperatures were logged on data loggers on an almost continuous basis but the readings were converted to daily means. Temperatures were recorded over an 8-week period, starting 4 weeks before treatment. The layout of the store and the placement of the temperature sensors are shown in Figs. 13 and 14.

In addition to the trapping, 12 x 200g samples were collected with a sampling spear from the top 2.5cm of grain, in an area where the largest numbers of insects were trapped. These samples were sieved over a 2mm mesh to check for live insects and then incubated at 25 C for 6 weeks before being examined for progeny.

The grain was treated as in Store 1 but pirimiphos-methyl (Actellic) 2% dust was used. An area approximately half as big again as the extent of the known infestation was treated with 50g of dust/sq.m. The dust was raked into the surface after application.

iii) **Results**

Store 1:-

Pre-treatment, Hangar 5 was more heavily infested than Hangar 1 but in both cases the infestation was centred around the top of the central peaks. No insects were found in the outer ring of pitfall traps with the exception of single weevils in some traps between the peak and the walkway or wall in Hangar 5. These insects may well have been moved down the slope by the action of the samplers walking on the grain. The areas treated with insecticide were adjusted in the light of these results.

The traps were replaced in the grain 10 days after the dust had been applied and were then examined after 4 days. Further post-treatment trapping was carried out at three intervals over the next 8 weeks. The numbers of S. granarius found in the traps both before and after treatment, together with the temperature of the surface layers of grain, are given in Table 13. A visual indication of the distribution of the insects in Hangar 5 is given in Fig. 15. There was a marked reduction in the numbers of insects caught in traps following the application of the dust and no insects were detected during the final two assessments.

Throughout the trial, only 2 dead S. granarius were detected in a probe trap. A total of 4 weevils were found in the 15 surface spear samples collected in Hangar 5. No *S. granarius* were detected in any other spear samples despite the spearing being confined to the areas that the trapping results indicated were the centre of the infestation. None of the samples produced progeny after incubation.

Store 2:-

The storekeeper's assessment of the infestation, using between 66 and 71 traps, examined on a daily basis, caught an average of 5 insects/trap. About 33% of the traps caught insects, with a maximum number of 20 *S. granarius* in a single trap.

The results of the more detailed trapping exercise carried out before and after treatment are given in Table 14. Fig. 16 gives the mean temperature readings over the 4 weeks before and after treatment. The temperatures at 0.5 and 1m remained relatively constant at about 6 C but the surface temperature fluctuated between 3 and 9 C in respose to changes in ambient conditions.

No live insects were found in the spear samples but a total of 10 *S. granarius* adults were found after incubation.

iv) Discussion and conclusions

Although up to 22 adult weevils were collected in a single trap over a seven day period at Store 1 and 20 during one day at Store 2, the level of infestation must be regarded as light. Routine spear sampling over several months did not reveal insects and intensive spear sampling around the areas most heavily infested, produced only two *S. granarius* at Store 1 and none at Store 2.

The results from Store 1 suggest that pitfall traps were much more effective than probe traps in detecting weevils. Only two adult *S. granarius* were found in one probe trap throughout the trial. The apparent lack of efficacy of the probe traps under these conditions must seriously limit the information collected about weevil populations beneath the surface. As the intensive spear sampling did not reveal any insects at depth, the population must have been below the threshold of detection of this method.

The low temperature of the grain must have reduced insect activity and hence trapping efficiency. However, pitfalls still provided an effective means of detecting the weevils moving in the surface layers and of indicating the levels of infestation.

The treatments with etrimfos or pirimiphos-methyl dust produced a dramatic reduction in the level of insects detected by trapping. Two weeks after treatment at Store 1 and 1 week afterwards at Store 2, the numbers of insects found in the traps had fallen to almost zero despite a temperature of around 5 C. At such temperatures the action of pesticides is slow and insects may require many days exposure before dying (Wilkin, 1988). It is possible that some of the lethal effects of the treatment can be attributed to the low temperature, nevertheless, the populations at both stores had remained relatively stable for several weeks under similar conditions. Therefore, the majority of the reduction in numbers of insects can probably be attributed to the insecticide. However, the inability to monitor small populations beneath the surface does allow the possibility that the insects were repelled by the insecticides and migrated to lower levels in the bulk. This seems unlikely as the grain was always cooler beneath the surface. In any case, the grain at both stores was held for more than 6 months after the treatment and, even during the summer months, no insects were detected by the storekeeper. All grain was eventually sold without the customers raising any complaint of infestation.

The cost of the treatment at Store 1 can be estimated at about £290-00 (assuming labour at £5-00 per hour). This compares with the cost of fumigation of at least £10,000. The costs of the treatment at Store 2 were about half, although the cost of fumigation would have been about the same as at Store 1.

Surface treatments with an insecticide would appear to offer a low-cost alternative method of dealing with localized infestation. The method reduces the ammount of pesticide used to less than a tenth of the amount needed if the entire bulk was treated. Pesticide residues in the surface layers are likely to be about the same as those produced by complete admixture but when the grain is moved, treated and untreated grain will be mixed so that the overall level of residue will be much lower. However, further work is needed, particularly to assess the effects of this type of treatment against a wider range of species, including pesticide resistant strains.

These trials demonstrate the effectiveness of trapping methods to detect insects in bulk grain but they also illustrate some of the difficulties associated with these methods. Throughout the experiment, conventional sampling with a spear did not reveal any insects so, by those standards the bulk remained uninfested. However, once insects were detected there were strong feelings on the part of the owners of the grain, that action must be taken to control the pests. This attitude could lead to an escalation in the tonnage of grain that is treated with insecticides or fumigants. At the very least this could add to the costs of storage.

The results show that surface applications of pesticides to grain can provide a good method of dealing with localised infestations that are able to survive control by cooling. The method is, therefore, worthy of more development, particularly in relation to its use as part of an integrated storage strategy.

Table 13. Total number of adult <u>Sitophilus granarius</u> found in pitfall traps at Store 1, together with the surface temperature of the grain (C), when this was recorded.

Trapping interval	Total insects (surface temp. C) Hangar 1	Hangar 5
7	2	2
4	24	51
2	14	43
5	18	16
3	8	8
4	10	20
4	0	9
4	0	53
2	14	61
6	15	14
7	5 (7.5)	154 (7.5)
Etrimfos dust applied		
14	1 (5.0)	0 (4.5)
7	0	0
20	0 (7.5)	0 (6.0)
15	0 (6.0)	0 (6.0)

Table 14. The numbers of adult <u>Sitophilus granarius</u> caught in 33 pitfall traps examined at weekly intervals at Store 2.

Total catch per week	% Traps with insects	Maximum catch per trap	Average trap catch
48	42	12	3.4
72	45	24	4.8
64	36	23	5.3
27	45	4	1.8
Pirimiphos-methyl dust applied			
No further insects found in traps over a 4 week period.			

Fig. 11 The arrangement of pitfall and probe traps in the surface of the grain in Hangar 1.

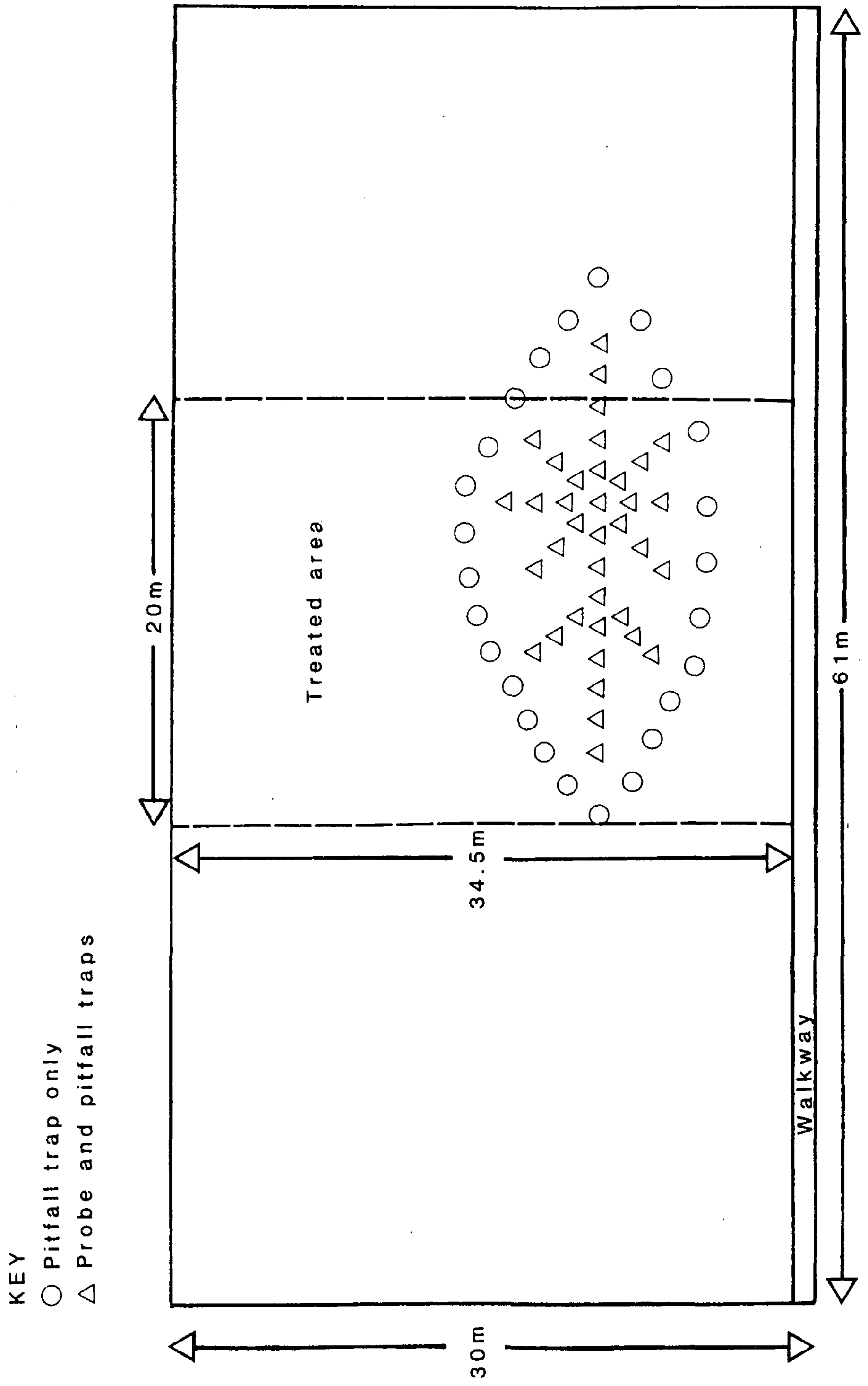


Fig. 12 The arrangement of pitfall and probe traps in the surface of the grain in Hangar 2.

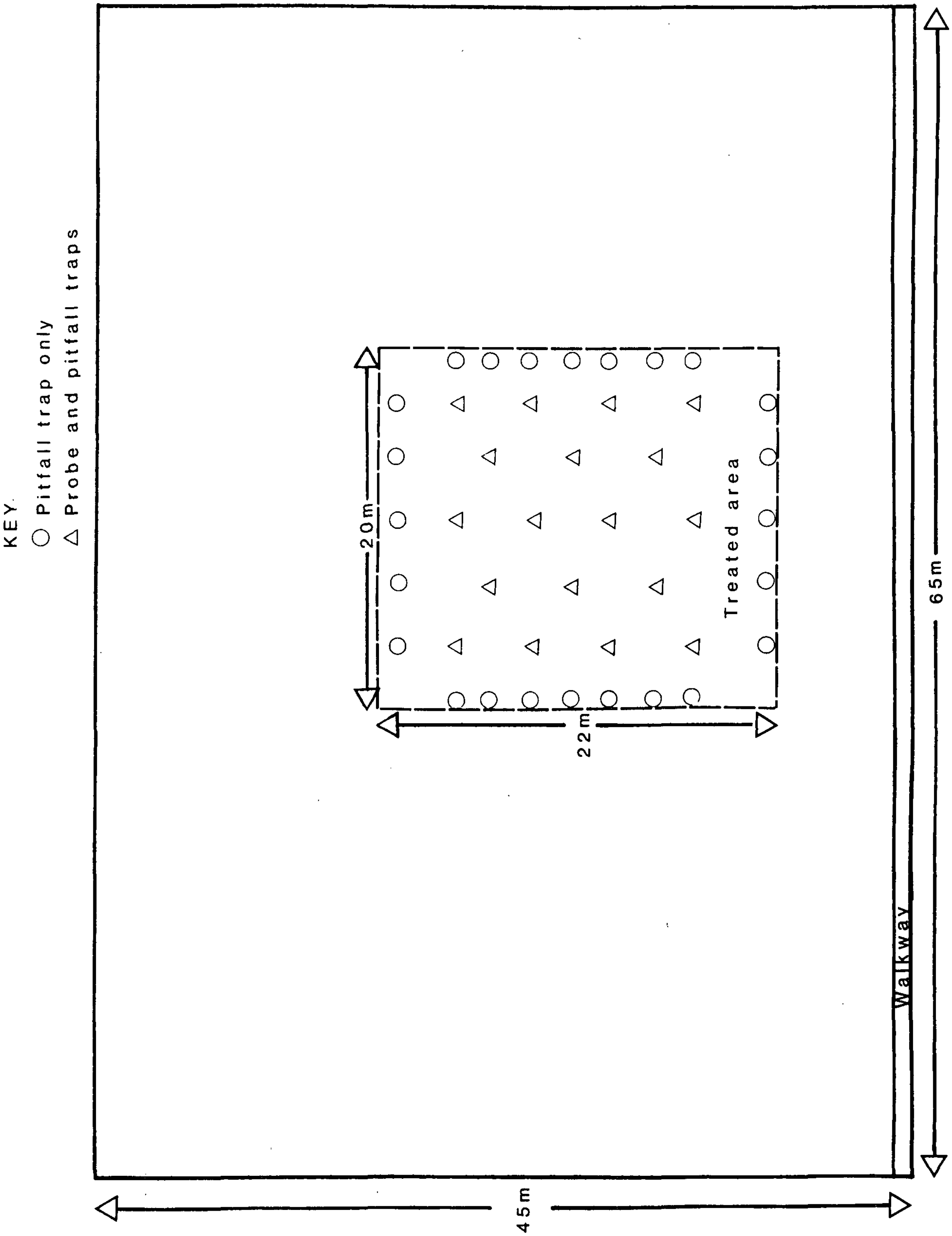


Fig. 13. General layout of Store 2, showing the infested area.

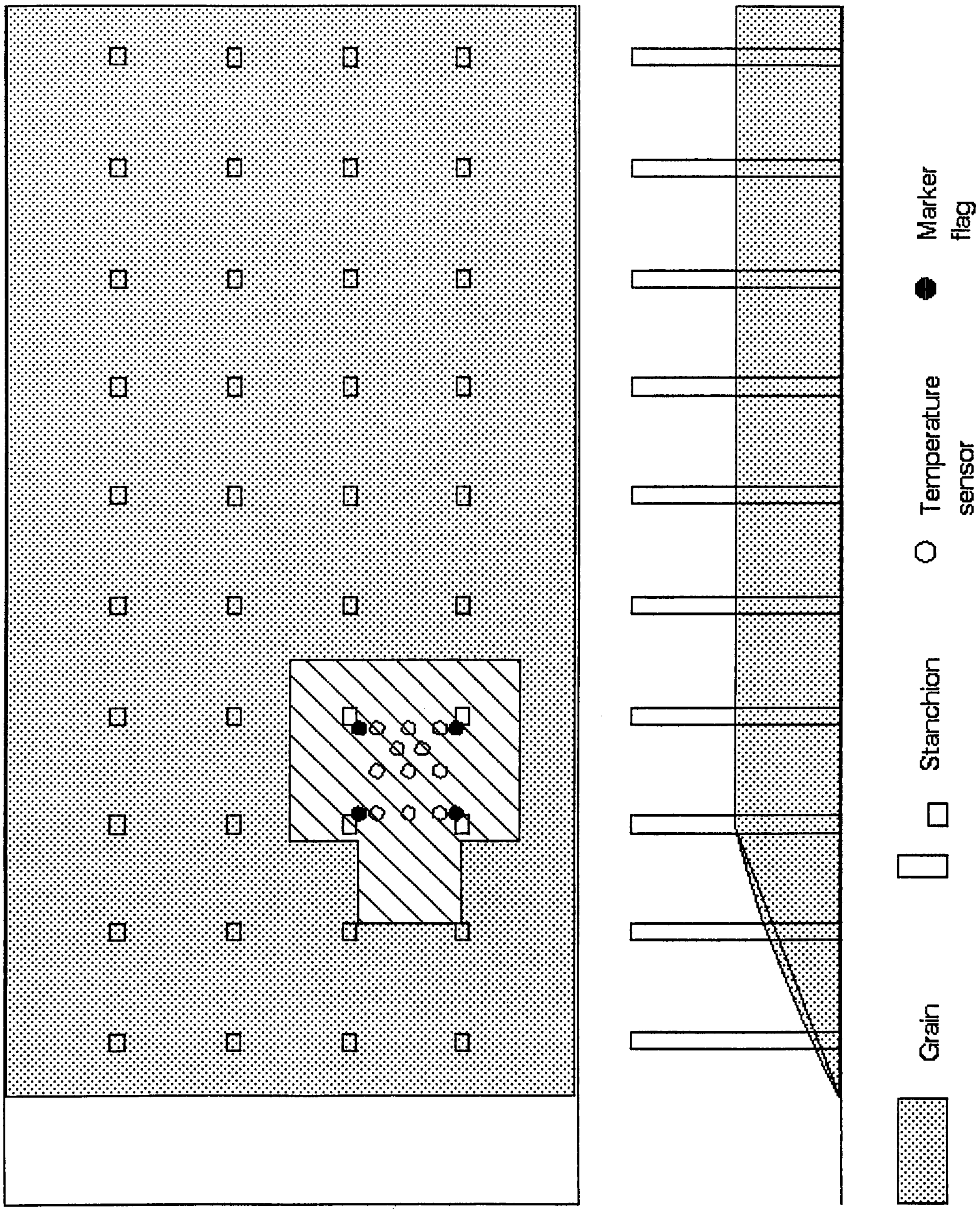


Fig. 14. Area of grain surface treated with pirimiphos-methyl and the placement of temperature sensors

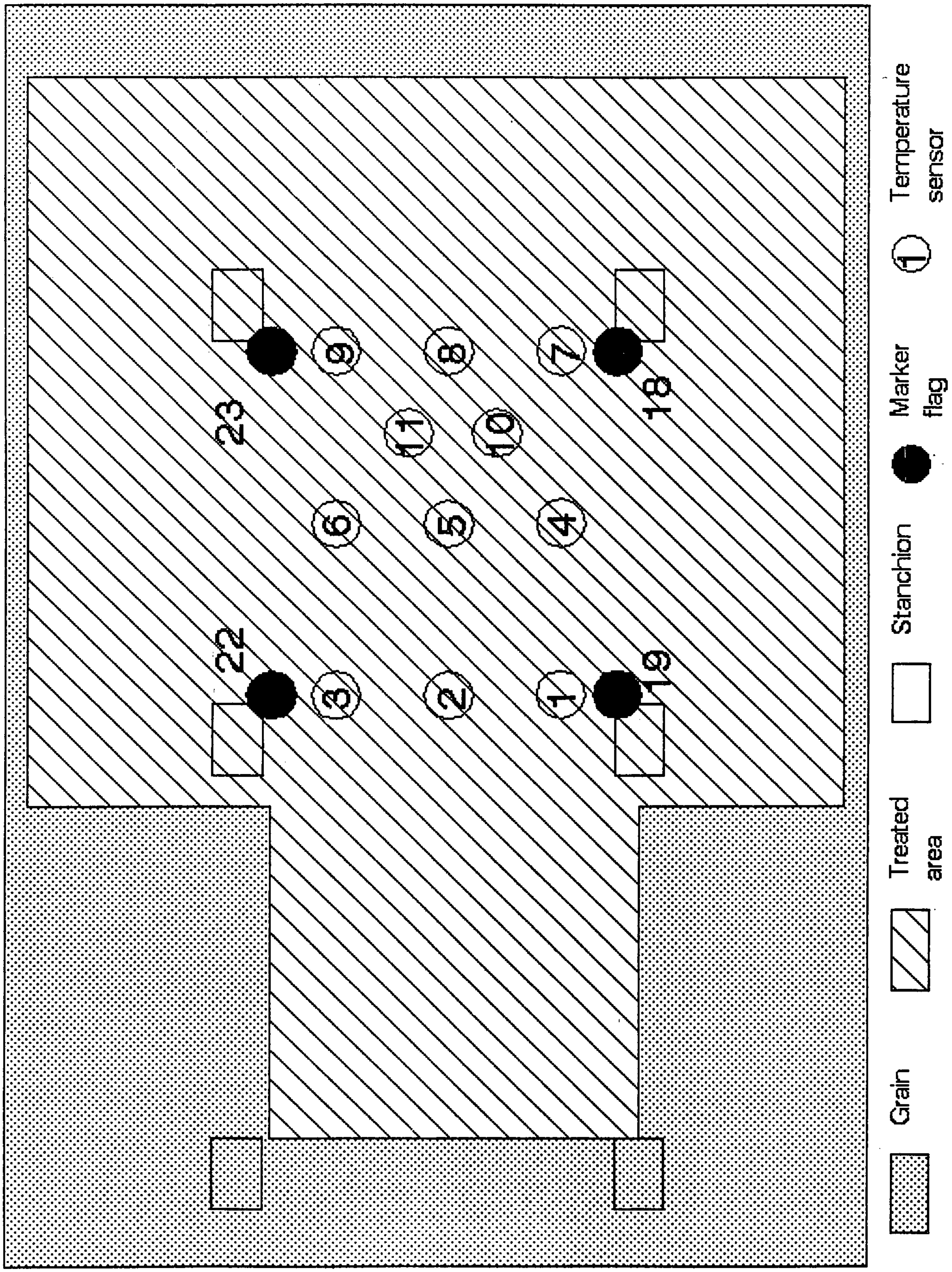


Fig. 15 The distribution of <u>Sitophilus granarius</u> catch in pitfall traps during 1 week in the surface of the grain in Hangar 1.

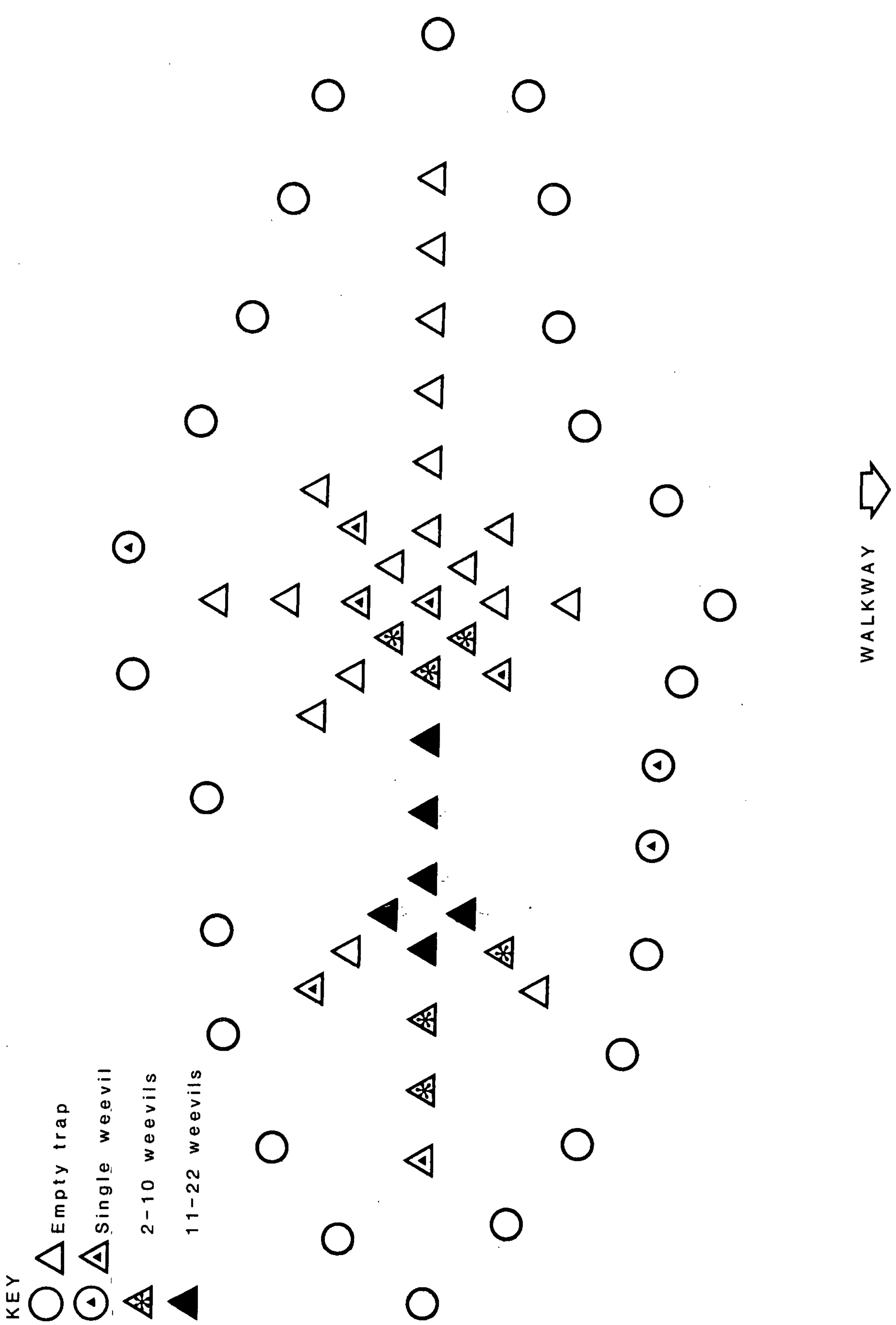
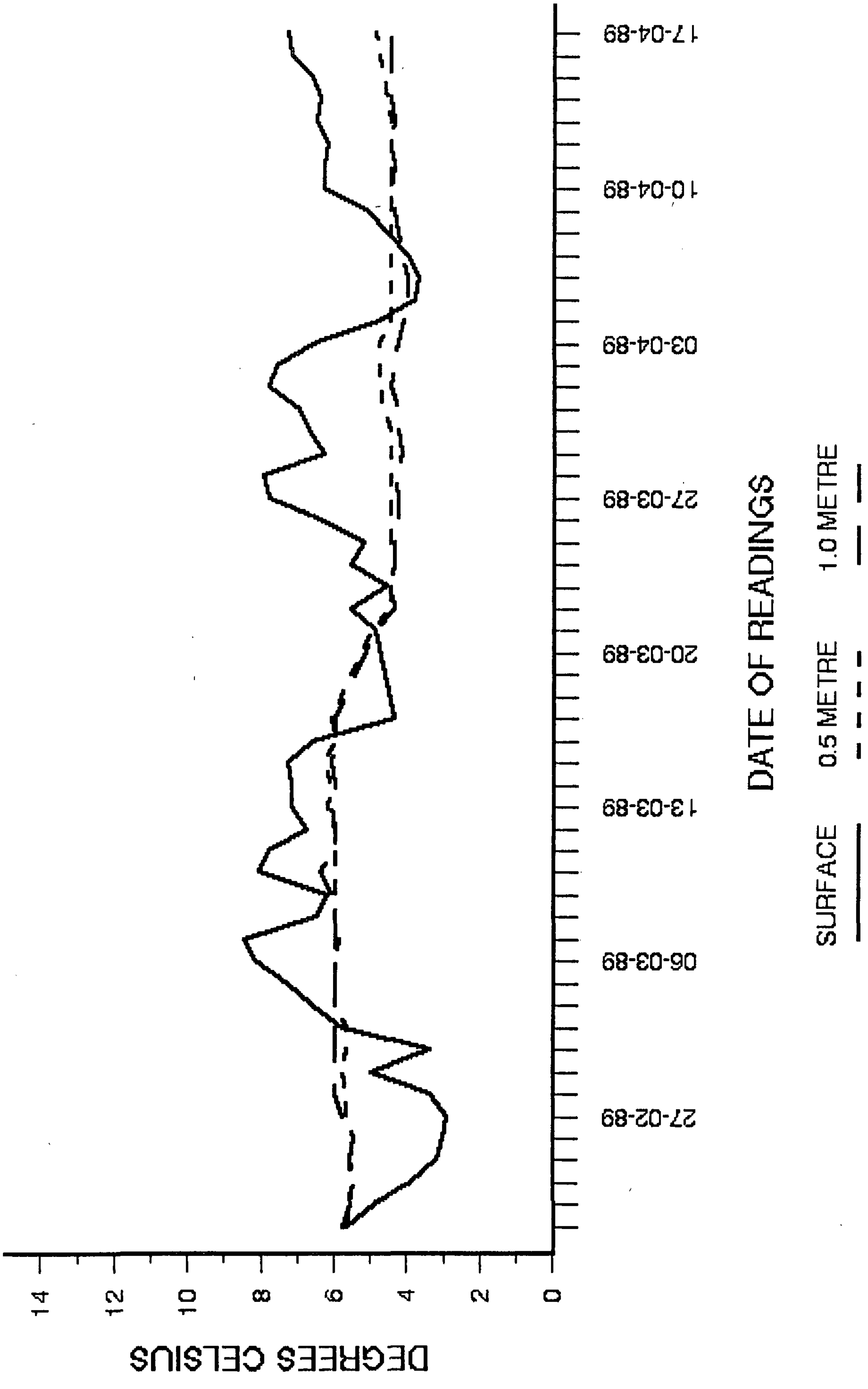


Figure 16. Mean daily temperatures in the grain over an 8 week period



4. THE COST OF AERATION AT COMMERCIAL STORES

i) Introduction

Data from the large-scale trial provided some insight into the costs of operating aeration systems. However, these results may only apply to small, shallow bulks of grain when the fans are controlled by differential thermostats. In order to gain more information on costs of cooling larger, deeper bulks of grain with manual control of aeration, records of fan use were collected from some commercial stores.

Ideally, the data should also have included some estimate of the cooling performance of the manually controlled systems. This was not possible as none of the stores had clear records of starting temperatures when aeration commenced, nor were temperature records or loading details from the bulks sufficiently comprehensive to allow accurate analysis. The information does, however, give a general indication of the range of temperatures that were achieved after a certain number of fan hours.

ii) Selection of stores

Stores were chosen on the basis of the availability of clear records of fan use and that an adequate aeration system was used. A number of sites were located with nearly identical aeration systems, all with aeration systems intended to deliver 10 cu m/h/t. Grain was stored in uneven heaps on the floor at depths ranging from 3 to 10 m. The size of the heaps ranged between about 5,500 to 20,000 tonnes. The design of the aeration system at each store was very similar, with air delivered to the grain via vertical supply ducts drawing air from the exterior at roof level. On either side of the grain heap were plenum chambers supplied by the vertical ducts and from the plenum chambers a number of supply ducts ran beneath the grain.

iii) Collection of data

Records were acquired from 18 stores on 5 sites between 1984 and 1989. The sites were situated on the South Coast, in East Anglia, in North Lincolnshire, in Herefordshire and in Shropshire. Daily records of fan running hours were acquired. Sometimes these just noted the number of hours run, but often also included the time at which the fans were switched on and off. Details were also collected of the capacity of the store, either potential or exact; the total power output (Kw) of the fans and the depth of the grain. No exact figure could be obtained for the latter as the grain heaps were uneven to some extent at all the stores.

In all cases it was impossible to collect comprehensive data covering the entire period. None of the stores were full each year between 1984 and 1989 so there are gaps in the data. Also, in some cases the grain remained in store for more than one year, so that it may well have started the second season at a relatively low temperature, This should have reduced the number of hours of fan running needed in the second season.

It was noted that in at least one store, the fans were turned on after working hours, sometimes between 9 and 10 in the evening, presumably to make best use of the cool night air. This would have incurred some cost in overtime payments.

The number of hours of fan operation between August and April each year were calculated, this being the normal storage season, as was the number of watts required to aerate each tonne of grain and the Kwh used for each tonne.

As already noted, lack of information about the proportion of the store filled and hence the number of temperature sensors exposed to ambient temperatures, reduced the value of the temperature records. Nevertheless, data from two stores from the same year are presented to give some indication of the prevaling temperature ranges.

One store (E1) was visited and airflow measurements were made using a hot wire anemometer and these showed air was being delivered at close to the estimated rate of 10 cu m/t/h.

iv) Results

The number of kw hours and the hours of fan runing are given in Table 15 and the temperature records for the two stores where this information was collected, is given in Table 16.

The results show that the stores needed between 0.9 (E4) and 3.8 (D1, 2, 3) w/t to deliver 10 cu m/h/t through grain depths of 6.5 - 10 m. These figures compare with estimates given in part 6 of this report (Bartlett, ADAS Silsoe Pers. Comm.) of 2 - 4.7 w/t to pass 7 - 10 cu m/h/t through 10 m of grain.

The hours of aeration in one "storage season" varied between 79 and 555. This compares with the estimate of 139 h to pass 1 cooling front through the grain or 417 to pass 3 fronts through, when using 10 cu m/h/t.

The power required to aerate the grain bulks can be calculated at between 0.17 and 1.29 kw x h/t (mean 0.4) for a "storage season". At 6p/Kwh, allowing for the fans having a nominal efficiency of 66 %, the cost would be about 1.6 - 11.7 p /t (Mean 3.6p/t)

Comparison of the temperatures achieved showed no great difference between the two stores, but at one the fans were operated for twice as long as at the other.

v) Conclusions

The large variation in hours of aeration and consequently cost from season to season and site to site, is probably a consequence of variation in the manual control. It may also relate to the individual storekeeper's own ideas on how best to operate an aeration system.

The data collected probably gives a good indication of the range of values that occur in well managed, commercial stores. The results suggest that the variation between stores at a single site was as great as that found between sites. No clear evidence of geographic location or seasonal effects were significant factors. Variation between different sites may be accounted for by varying management techniques. Variation between stores on one site may be due to a number of reasons:-

a. one store cooler than another,

b. one store loaded earlier,

c. one store containing more grain than another.

Despite the variations in the number of hours that the fans were run, no clear advantage in temperatures achieved could be seen between the two stores where temperature data were extracted. This suggests there is scope for a more standard approach to the use of aeration systems and that using automatic differential thermostats could help with this process. This, in turn, would lead to electricity savings on some sites and probably in more effective cooling on others. It is likely that aeration could be carried out soley at night and in this case, with automatic control, it would be appropriate to convert to day/ night tarrif, when the electricity cost would drop to about 2p/ kwh, by two - thirds.

Table 15. A comparison of energy costs for aerating 18 stores on 5 sites at 10 cu m/h/t between 1984 and 1989

Site	store	date	h	tx 1000	ht(M)	kw	w/t	kwh/t
A	1	10.87-2.88	117	11	10	22.4	2.04	0.24
		9.88-11.88	166	11	10	22.4	2.04	0.34
	3	8.88-11.88	229	11	10	22.4	2.04	0.47
	4	8.88-11.88	254	11	10	22.4	2.04	0.52
	5	10.87-2.88	86	5.5	10	11.2	2.04	0.17
		9.88-11.88	166	5.5	10	11.2	2.04	0.34
B	1	9.87-2.88	93	18.3	10	28.2	1.5	0.14
		11.88-2.89	70	18.3	10	28.2	1.5	0.11
	2	10.87-3.88	95	17.8	10	28.2	1.5	0.15
		9.88-2.89	225	18.4	10	28.2	1.5	0.34
C	1	9.88-2.89	160	9.5	8-9	32.2	3.3	0.54
	2	8.88-11.88	143	9.3	8-9	28.2	3.0	0.43
	3	10.87-4.88	125	9.4	8-9	34.2	3.6	0.46
		18.88-3.89	80	9.4	8-9	34.2	3.6	0.29
	4	8.88-2.89	234	9	8-9	28.2	3.1	0.73
	5	8.88-10.88	79	9.1	8-9	28.2	3.1	0.24
D	1	9.84-3.85	321	8.5	7.9	34.2	3.8	1.29
		9.85-2.86	112	8.5	7.9	34.2	3.8	0.45
		7.88-1.89	84	8.5	7.9	34.2	3.8	0.34
	2	9.84-3.85	238	9	7.9	34.2	3.8	0.90
		9.85-2.86	112	9	7.9	34.2	3.8	0.42
		7.88-1.89	84	9	7.9	34.2	3.8	0.32
	3	10.84-3.85	163	9	7.9	34.2	3.8	0.62
		9.85-2.86	112	9	7.9	34.2	3.8	0.42
		7.88-1.89	87	9	7.9	34.2	3.8	0.33
E	1	8.88-4.89	520	15.6	6.5	18	1.2	0.60
	2	9.88-4.89	463	7	6.5	7.4	1.1	0.49
	3	10.87-3.88	305	15.3	6.5	18	1.2	0.36
		10.88-4.89	422	15.3	6.5	18	1.2	0.50
	4	10.87-3.88	166	18	6.5	18	0.9	0.17
		8.88-4.89	555	19.7	6.5	18	0.9	0.50

Table 16. Aeration hours and grain temperatures at 2 commercial stores aerated at 10 cu m/h/t during 1988

Site/store	Max.temp C E1	 C1	Min temp C E1	 C1	Hs blown E1	 C1
Aug	14.8	14.9	6.7	8.7	12.5	34.8
Sep	14.5	14.4	6.1	9.9	80.3	98.6
Oct	13.4	13.5	9.3	8.9	122.8	114.8
Nov	9.9	12.9	2.2	4.3	376.3	174.5
Dec	9.3	-	3.3	-	405.8	-
Jan	9.0	9.5	3.1	3.0	443.8	195.5
Feb	8.0	-	3.7	-	485.8	-

5. TRAPPING INSECTS IN COMMERCIAL STORES

Sampling pest beetle populations in grain has traditionally been carried out by using a gravity spear or vacuum sampler to collect grain samples and then sieving the sample to remove any insects. This method has recently been shown to be relatively inefficient in detecting low densities of insects compared to the use of static traps such as probe traps (Barak and Harein, 1982; Lippert and Hagstrum, 1987) or the combined use of probe traps and pitfall traps (Cogan et al, 1985).

Insect traps within grain do not provide reliable quantitative data in relation to numbers/kg as the numbers of insects in a trap will depend on factors such as temperature and the spatial relationship of the trap to the infested area. Infestations are unlikely to be spread evenly within the grain bulk. Traps do, however, determine those species present and, for the purposes of this integrated strategy, provide the most sensitive means of detecting the distribution and movement of the insects in bulk grain. Despite these advantages the user can be left with the problem of interpreting trap catches in terms of the need for control action or possible commercial repercussions arising from a particular level of catch.

The calibration of pitfall and probe traps is a major technical undertaking and may ultimately be found to present insoluble problems. However, an examination of field data was undertaken to verify the performance of the traps, as found during the laboratory trial, in relation to their field use.

Both pitfall and probe traps are now used extensively in commercial grain stores, primarily in bulk, floor stores. The two types of trap are also recommended for use in intervention stores for the detection of beetle pests (Storekeepers Manual, IBAP). This widespread use allowed observations to be made at a number of commercial grain stores in which the performance of traps could be compared to conventional sampling methods.

Data on the relative detection abilities of insect traps and conventional sampling methods was obtained from both the period when the traps were first evaluated plus that gained during this trial. Fifteen commercial grain stores were monitored by Central Science Laboratory, Slough, for beetle pests, using a total of 480 pitfall and 354 probe traps. Most of the monitoring was carried out by store personnel but visits were made to the stores to collect data and to ensure that standard operating procedures were being adhered to.

During the period of observation, all infestations that occurred in the stores were first detected by the pitfall and/or probe traps rather than conventional sampling. All the major U.K. beetle pest species were detected by the traps and detection occured up to one year before insects were found by spear sampling. Representative data from 5 stores are presented in Table 17.

The results indicate that both pitfall and probe traps regularly detected the major beetle species. However, spear sampling failed to detect 2 of the 3 species and only 1 in 50 sampling locations detected O. surinamensis compared with 1 in 4 for the pitfall and probe traps.

These results show that the traps used in the strategy are a reliable indicator of the beetle pests present and function as such in commercial stores. They also suggest that pitfall and probe traps are capable of detecting insects in grain at population densities far below the lowest practical level of detection for spear sampling, ruling out any direct comparison between the results given by the two techniques. In practical terms, a few insects detected in traps offer important early warning of a problem and allow time for the implementation of control measures.

Table 17. Percentage traps (or sampling locations) used in 5 commercial bulk grain stores which detected the major U.K. grain beetle species.

STORE LOCATION	SAMPLING PERIOD	*O.sur.*			*C.ferr.*			*S.gran.*		
		PIT	PRO	SPR	PIT	PRO	SPR	PIT	PRO	SPR
CAMBS	IX-XII	31	28	0	0	9	0	63	28	0
KENT	IV-IX	32	20	0	8	10	0	-	-	-
SUFFOLK	II-IV	15	29	5	5	5	0	20	21	0
SUFFOLK	III-IV	12	16	4	0	4	0	0	4	0
SUSSEX	VIII-XII	-	-	-	0	7	0	-	-	-
MEAN PERCENT		24	23	2	3	7	0	24	25	0

Key : PIT=Pitfall trap ; PRO=Probe trap ; SPR=Gravity spear. Sampling period is indicated by months I-XII.

6. CALCULATIONS TO DETERMINE THE EFFECTIVENESS OF COOLING SYSTEMS

i) Introduction

Calculation of the time taken to cool grain and its effect on insects is an important part of this integrated control strategy. Cooling is affected by geographical location, time of year and climatic variation between years. The biological effects of cooling will depend upon the species of insect present, their speed of reproduction, their cold hardiness and the length of time the grain can be held at a given temperature. The size of a bulk should have relatively little effect, except on insulation properties, as the power of the fans is adjusted accordingly.

Atmospheric relative humidity has in the past been considered to be an important consideration in the use of ambient air cooling. Fans were often controlled by a humidistat which only turned them on when the r.h. was below 75 %. This practice has the effect of limiting the number of hours that cooling fans can run as the normal pattern of diurnal temperature and humidity is for r.h. to rise as temperature drops at night.

All the above factors have been considered in the following calculations showing the effects of geographical location, seasonal variation and the ability of different airflow rates to control insects.

ii) **Aeration rates**

The minimum time required for a fan to pass enough air to cool a given volume of grain can be calculated in one of two ways:-

1. based on the ratio of air to cooling front velocity, where:-

Time (h) = 580 x depth of grain (m)/3600 x air velocity (m/sec).

2. based on the fact that approximately 600 volumes of air are required to cool 1 of grain (Jouin, 1965).

These two methods give similar results (McLean, 1980). However, in grain storage practice air is not evenly distributed and it is normal to assume 800 - 1000 volumes of air are required to cool 1 of grain (Poichotte, 1977). It has been usual to recommend airflow rates of 4-10 cubic feet per minute per tonne (cfm/T), so rates of 4, 6, 8, 10 cfm/T are considered here. In addition, a rate of 2 cfm/T has been included, as being commonly encountered in commercial stores.

Assuming 1 tonne of grain occupies 50 cu ft; the number of hours aeration for these 5 airflow rates was first calculated.

Thus h = (1000 x 50)/(a x 60), where h = hours to pass a cooling front and a = airflow in cfm/T.

Airflow-cfm/T	2	4	6	8	10
m3/h/T	3.4	6.8	10.2	13.6	17
h aeration	417	208	139	104	83

iii) Meteorological considerations

The above calculation on cooling time offers only a general guide to the number of hours of fan operation needed before the cooling effect will have passed through the entire bulk. In practice, ambient temperatures may be above those of the grain for at least part of the 24 hour daily cycle. Therefore, the actual period needed to cool grain is greatly extended over the calculated number of fan hours.

Weather is a notorious variable, so a series of calculations of actual cooling times have been made using meteorological data for Exeter and Wattisham. Wattisham in Norfolk is in the heart of the grain growing area, and Exeter in the south west, so could be expected to have a warmer climate and therefore to undergo slower cooling. In addition to records based on 20 year compiled data, a warm autumn and a warm winter, based on those in which few hours were spent at low temperatures, were selected for each site (Exeter: the warm autumn of 1963 and the warm winter of 1974-5; Wattisham: the warm autumn of 1984 and the warm winter of 1974-5.)

Records were acquired which show the hours spent each day below 15 C, 10 C and 5 C. Thus to calculate how long it would take to pass a 15 C front through grain, for a given start date, it was merely necessary to add up the hours below 15 C until the number of hours indicated for a particular airflow was exceeded. This calculation gave the date of the cooling front and therefore how many days were taken to achieve it.

Three sequential cooling fronts were considered in this manner: 15, 10 and 5 C. Four dates of starting aeration were selected: 1 July, 1 August, 1 September and 1 October. The results of the calculations are given in the following Tables.

Date at which 15 C was achieved

start	2	4	6	8	10cfm
1.7	4-18.8	14-24.7	8-16.7	6-12.7	5- 9.7
1.	5-12.9	19-25.8	11-17.8	9-13.8	7-11.8
1.9	24-30.9	11-17.9	7-12.9	6- 9.9	5- 7.9
1.10	18-21.10	9-12.10	6-8.10	5-6.10	4-5.10

Date at which 10 C was achieved

start	2	4	6	8	10 cfm
1.7	9.10-20.11	28.9-11.10	19-29.9	9.9-21.9	17.8-21.9
1.8	15.10-26.11	30.9- 4.10	25.9-9.10	23.9-3.10	18-22.9
1.9	11.10-28.11	1.10-7.11	27.9-14.10	25.9-9.10	23.9-3.10
1.10	6.11- 2.12	19.10-15.11	13.10-9.11	10.10-3.11	8-30.10

Date at which 5 C was achieved

start	2	4	6	8	10 cfm
1.7	11.12-22.2	10.11-4.1	30.10-8.12	29.10-6.12	20.10-5.12
1.8	13.12-23.2	12.11-16.1	30.10-8.12	29.10-6.12	21.10-5.12
1.9	14.12-26.2	12.11-17.1	30.10-9.12	29.10-6.12	21.10-5.12
1.10	20.12-5.3	20.11-24.1	6.11-1.1	31.10-11.12	30.10-6.12

For the 15 C front, the longest periods of cooling were derived from data based on the 20 yr records. The longest periods of cooling to 10 C were derived from data based on the warm winter of Exeter and the longest periods of cooling at 5 C were derived from data based on the warm autumn at Exeter.

iv) Biological considerations

a) Cooling fronts

In order to predict the effects of cooling on insects, the following assumptions have been made:-

1. that the temperature of grain drops sharply stepwise,

as each cooling front passes through the warmest area. Thus initially, the warmest grain would be at 30 - 35 C and optimum for reproduction of the 3 commonest British grain beetles: S. granarius, O. surinamensis and C. ferrugineus.

2. The temperature would then drop to 15 C, at which only one species; S. granarius can complete its life cycle. The second cooling front would reduce the temperature to 10 C, whereupon the 3 species would die only very slowly.

3. Finally, the 3rd cooling front would drop the temperature to 5 C and maintain it there until Spring. During this final phase, the death of the insects would be more rapid.

b) 15 C front

While the first cooling front passes through the grain, the insects will reproduce rapidly at an optimum rate and the maximum infestation will occur in the slowest cooling areas. The calculations are based on the activities of a gravid female. Thus it was necessary to compile the data on life cycle times, oviposition rates and pre-oviposition times for the three species as shown below:-

	S. granarius.	O. surinamensis.	C. ferrugineus
t (days)	26	17	21
t2 (days)	144	-	-
p (days)	3-8	5	2
e	1	7	6

Given;
t = optimum time (days) for development from egg to adult
t2= time for development from egg to adult at 15 C
p = adult maturation time (pre - oviposition)
e = no. of eggs laid per female per day
d = population development time (i.e. cooling period)

Sources;-
Eastham and Segrove,(1947);Eastham and McCully (1943);Richards (1947)-S. granarius
Howe,(1956);Back and Cotton (1926) - O. surinamensis
Smith (1963);Smith (1965);Rillett (1949) - C. ferrugineus

Thus, knowing the days available for rapid breeding at optimum temperatures until the cooling front arrives, it is possible to calculate if the insects can complete their development in this time and if so,how many progeny will be produced. This allows the following equations to be constructed:-

1. If $d < t$,then no adults produced

2. If $d > t$ and $d < (t+p+t)$, then only F1 (1st generation) produced, with $n = (d-t)e$

3. If $d > (t+p+t)$ and $d < (t+p+t+p+t)$, then F1 and F2 (2nd generation) produced. The numbers produced will equate to $n = (d-t)e + (m.m + m)/4 \times e.e$; where $m = d-(t+p+t)$

The F2 term is derived from the sum of $[(d - (t+p+t)) e/2e]$, where the summation is for each day from $(t + p +t)$ to d

These basic formulae can be used to calculate the theoretical potential for population development using data from the earlier calculations on rates of airflow, start dates and geographical and climatic variation. The results of such calculations are shown in the following Table.

Insects developing during the 15 C front

Start	2	4	6	8	10cfm
S. granarius					
1.7	9- 22	-	-	-	-
1.8	10- 16	-	-	-	-
1.9	0- 4	-	-	-	-
1.10	-	-	-	-	-
O. surinamensis					
1.7	126- 1319	0- 49	-	-	-
1.8	133- 322	7- 56	-	-	-
1.9	49- 91	-	-	-	-
1.10	7- 28	-	-	-	-
C. ferrugineus					
1.7	84-342	0- 18	-	-	-
1.8	90- 126	0- 24	-	-	-
1.9	18- 54	-	-	-	-
1.10	-	-	-	-	-

The consequences of the cooling times were that no development of insects of any species occurred, during progress of the first front, at airflows of 6-10 cfm/T in any year or either location. Burges and Burrell's (1964) prediction that S. granarius would only develop at airflows of less than 4 cfm/T was confirmed. In fact this species failed to develop at 2 cfm/T, providing aeration was started in October.

However, O. surinamensis and C. ferrugineus were often able to develop at 4 cfm/T, when aeration was started in July or August, although only the former developed at 2 cfm/T, when aeration was started in October.

For all these calculations it was assumed that the aeration start date coincided with the filling of the store.

c) 10C front

At 15 C, only S.granarius can continue to complete its development. Therefore, for this species there is a further period in which they can develop, albeit at considerably sub-optimal conditions before the second, 10 C, front passes through the grain. We assume here that there is no mortality of immature insects caused by this drop in temperature.

Therefore, to calculate the numbers of S. granarius developing during the 10 C as well as the 15 C front the actual time of the second front is converted to "biological time units" equivalent to days of the first cooling front:-

i.e. d2 x t/t2, where t = optimum development time and t2 = development time at 15 C.

Thus d = d1 + (d2 x t)/t2 and this value gives the total population development time available the following values for S. granarius development by the time the 10 C front passes through the grain:-

start	2	4	6	8	10 cfm
1/7	21-46	3-12	0-3	-	-
1/8	16-26	0-8	-	-	-
1/9	1-13	-	-	-	-
1/10	0-1	-	-	-	-

Additional S. granarius completed their development at 2 cfm/T, regardless of start date. Smaller numbers also developed at 4 cfm/T when aeration was started in July or August and even at 6 cfm/T when starting cooling in July.

d) 5 C front and population decline before unloading.

When the grain cools to first 10 and then 5 C, the insects will no longer be able to breed and so the population will begin to decline. The plot of percentage population mortality against time is sigmoid, so mortality varies with time and is not constant. It has been found appropriate to plot probit mortality against untransformed time to produce a straight line and facilitate analysis of mortality (Evans, 1983).

Unpublished mortality data has been produced at Slough at 6 C for the strains of all 3 species of insect used in the large scale experiment and, at 10 C for O. surinamensis and S. granarius, but not C. ferrugineus. Evans (1983) has produced data at 9 C, for Australian strains but his estimated death rate at this temperature is quicker than that obtained at Slough at 6 C. C. ferrugineus has therefore been omitted from estimations of mortality at 10 C.

Mortality at 10 and 5 C was estimated using the following values and formulae:- Probit mortality = 5 + slope (d- ET 50)

	10 C		5C		
	slope	ET50	slope	ET 50	(Days)
S. granarius	0.009	223	0.015	138	
O. surinamensis	0.008	257	0.019	113	
C. ferrugineus	-	-	0.026	115	

These calculations give the following values for survival of the F1 and F2 insects that developed during the various aeration regimes that have been considered. The values represent the numbers of progeny produced from a single female and surviving until 1 April the following year.

start date	Aeration rate in cfm 2	4	6	8	10
S. granarius					
1.7	13- 33	1- 7	0- 1	-	-
1.8	10- 20	0- 5	-	-	-
1.9	1- 9	-	-	-	-
1.10	0- 1	-	-	-	-
O. surinamensis					
1.7	66- 829	0- 20	-	-	-
1.8	72- 202	6- 23	-	-	-
1.9	25- 59	-	-	-	-
1.10	1- 19	-	-	-	-
C. ferrugineus					
1.7	51- 251	0- 8	-	-	-
1.8	51- 90	0- 10	-	-	-
1.9	10- 39	-	-	-	-
1.10	-	-	-	-	-

These data show that, in no case where cooling was too slow to prevent the development of further insects, was storage at low temperature capable of eliminating the infestation.

v) Grain dampening during cooling

a) Calculations

The weight of water per cubic metre of the ventilating air (m1) was first calculated from psychrometric charts at the temperatures of the 3 cooling fronts and assuming relative humidities of 90 % and 100 % The effect on r.h. of the fan heating the air by 1 C was also taken into account. Next the weight of water/cu.m in air in equilibrium with the grain at 70% r.h.(m2) and the difference between this and the incoming air was calculated. This weight was assumed to be the maximum amount of water available to wet the grain. The weight of the volume of air (v) required to pass one cooling front through 1 tonne was derived from the specific volume of air (s) at the temperature of the cooling front (also using a psychrometric chart) so that:-

amount of water deposited = (m1-m2) x v/s

The water added to 1 tonne of grain was calculated assuming the moisture was distributed evenly and the % m.c increase was then calculated assuming the grain to be initially at 15 % m.c. This gave the following values:-

	r.h. of air	
	100%	90%
15 C front	0.57	0.43
10 C front	0.40	0.27
5 C front	0.30	0.18
Total	1.27	0.98

It is unlikely that this moisture would be deposited evenly but equally, it is unlikely that the moisture would be deposited in a small area around the duct. For example, if dampening was confined to a 1m layer around the duct in a 10 m deep bin, then increases of 10 x those calculated might occur. However, under practical conditions the calculated values are unlikely to be reached as, because of r.h. fluctuations, this layer would dry as quickly as it dampened. No increases of this sort have been found in practice (see below and large scale results). The possibilities of dampening are greater with grain at much lower moisture contents, such as malting barley.

There are other reasons why grain dampening is unlikely:-

1. Grain m.c. comes into equilibrium with air at an r.h. BELOW the theoretical value so that not all the available water is deposited.

2. As the cold air blown into the bin meets the warm grain, its temperature changes to that of the grain, so its r.h. is further reduced (Sutherland _et al_, 1971). For example, using air between 5 C and 15 C; a 5 C difference between saturated air and the grain it meets, is sufficient to ensure its r.h. will be lowered to 70%.

3. Farm scale experiments at Slough over 15 years have shown insignificant moisture increases or even marginal drying.

b) Moisture content changes in farm scale experiments

Over a 10-year period a series of experiments have been carried out at the Laboratory in which about 20-tonne lots of grain or oilseed were aerated with ambient air. The results in the following Tables show the moisture content of grain or rapeseed at various depths at the start and at the completion of the experiments.

1. Rapeseed ventilated at 17 cu M/h/T

	Experiment 1			Experiment 2	
Depth	Sep '75	Mar '76	Apr'77	Oct'77	May'78
sur	7.9	9.0	7.3	9.9	8.6
0.3	7.9	7.4	7.0	9.2	8.5
0.6	7.9	7.2	7.4	9.1	8.3
0.9	8.0	7.3	7.1	8.9	8.2
1.2	8.0	7.4	7.5	8.8	8.1
1.5	7.8	7.4	7.5	8.6	7.9
1.8	7.9	7.3	7.5	-	-
hours of fan running	0	500	1120	0	932

2.Wheat ventilated at 11 cu M/h/T

a. Differential thermostat (2 C)

	Experiment 1		Experiment 2		Experiment 3	
	Nov '82	Apr'83	Sep '83	May '84	Sep '84	May '85
sur	16.5	15.7	15.0	14.0	14.3	14.1
0.5	15.6	15.1	14.7	14.3	14.0	13.8
1.0	14.9	14.9	14.4	14.1	13.9	14.0
1.5	14.8	14.5	14.2	14.0	13.9	14.0
2.0	14.7	14.0	14.2	14.3	14.6	14.4
2.5	14.6	14.0	14.4	14.5	14.8	14.8
3.0	14.4	14.6	14.3	14.6	14.3	15.1
hours of fan running	0	279	0	276	0	611

b. Manual operation

	Experiment 1		Experiment 2		Experiment 3	
	Nov '82	Apr '83	Sep '83	May '84	Sep '84	May '85
sur	16.5	15.3	15.0	13.7	15.3	14.6
0.5	15.0	15.0	14.6	14.6	14.7	14.4
1.0	15.2	15.1	14.4	14.4	14.5	14.3
1.5	15.8	15.4	14.5	14.5	14.5	14.2
2.0	16.1	14.0	14.4	14.5	14.5	14.7
2.5	15.2	13.6	14.4	14.5	14.1	14.9
3.0	11.4	14.2	14.5	13.4	14.0	14.7
hours of fan running	0	347	0	338	0	661

In general, the moisture content of the wheat or rape seed was unaffected by the aeration. The only case where a significant, local increase in moisture was detected was with the wheat in Experiment 1. Here, the grain at 2m was exceptionally dry at the start of aeration and had gained 2.8% moisture after 347 hours of aeration.

vi) Calculation of power requirements and costs

The power (w) was calculated from:-

w = [airflow (cu m/sec/tonne) x total pressure (N/sq.m)] /fan efficiency (ratio). The resulting temperature rise (t) was given by:-

t = w/tonne/ [1.2 x airflow]

The velocity pressure was taken as 135 N/sq.m = 15 m/sec and the efficiency as 65% in all cases.

Static pressures were estimated using relations developed by Matthies and Petersen (1974) for the pressure loss through the crop and duct work resistances based on ASHRAE.

The duct layout assumed was:-

Duct	centres	width	depth	cover free area
3m deep	3.0	0.3	0.3	5%
10 m deep	4.0	0.45	0.5	5%

The crop parameters were:-

density; 1.3 cu m / tonne, resistance coefficient; 2.2, void volume ratio; 0.39 and particle equivilent diameter; 3.9.

The costs required to pass each cooling front through the grain were obtained by multiplying aeration hours required for the 5 rates, by Kw required for 2 grain depths; 3m, typical of farm stores and 10m, appropriate for commercial stores. The costs per Kwh assumed day/night tariffs and were taken as 2p for night ventilation and 6p for fan operation during the day and night.

	cfm/T	2	4	6	8	10
w/tonne	3m	0.24	0.59	1.07	1.68	2.68
	10m	0.57	2.00	4.73	8.19	12.74
t rise C	3m	0.21	0.25	0.31	0.36	0.43
	10m	0.5	0.9	1.4	1.8	2.2
cost/T/front at 2p	3m	0.2	0.25	0.30	0.35	0.41
	10m	0.48	0.83	1.31	1.70	2.11
cost/T/front at 6p	3m	0.6	0.74	0.89	1.05	1.23
	10m	1.43	2.50	3.94	5.11	6.34

vii) Conclusions

i. Based on the climate in E. Anglia and the warmer South West over the last 20 years, airflows of 6 - 10 cfm/ T were adequate to prevent the development of the 3 main stored products beetles, irrespective of the date aeration was commenced (The small numbers of S. granarius developing at 15 C when aerating in July can probably be ignored due to the large safety margins used in the calculations).

ii. At airflows of 6 - 10 cfm, 10 C could have been achieved by early November and 5 C by early December.

iii. An airflow of 4 cfm/t was adequate when the store was loaded and aeration started in September or October but in the warmer months, opportunities for aeration were less and some infestations could have developed.

iv. At 4 cfm/t, 10 C could have been achieved in mid November and 5 C by mid January.

v. Where inadequate aeration allowed insects to develop, the periods at which the grain was held at 5 C before sale in the spring were inadequate to eliminate the infestation.

vi. At the succesful aeration rates, it would cost 0.9 - 1.2 p/t for each of the cooling fronts in a 3m deep bin or 4 - 6 p/t in a 10 m deep bin. (at 6 p/Kwh.)

vii. If aeration were carried out at night only, using a day/night tariff the above costs would be reduced to one-third.

viii. The liklihood of important m.c. increases in grain at about 15 % m.c. is very low.

7. VALIDATION - COMPARISON OF EXPERIMENTAL RESULTS WITH CALCULATED VALUES

In order to show that the results of the calculations made in Part 6 and the data from the trials are applicable to practical grain storage, the experimental results from part 2 (observed) are compared with the calculated values from part 6 (expected). This allows the seasonal and geographical variations to be taken into account.

i) Fan hours and temperatures

The actual number of hours for which the fans run while cooling the grain in the experiment, compared with those which were estimated to be necessary to give a temperature of below 5 C, are given in the table below. For the experimental results, the minimum number of fan hours were achieved using the 4 C differential thermostat and the maximum hours using the 2 C thermostat. The minimum value given in the calculations assumes an airflow rate of 6 cfm/tonne, the maximum using 4 cfm/tonne. This sort of variation might arise if the design was attempting to achieve 5 cfm/tonne.

The number of days taken to achieve first 15 C, then 10 C, and then 5 C at the centre of the experimental bins have also been compared with the calculations. For the experiment, the range given includes all 6 bins, while for the calculations, the range includes both the seasonal and geographical variations examined.

	Cumulative hrs fan running		Days from start of aeration	
Cooling Front	observed	expected	observed	expected
<15 C.	34-58	135-208	2-5	6-12
<10	111-422	278-416	42-63	13-48
<5/6	181-516	417-624	70-77	37-142

The actual fan hours run and the days to achieve 15 C are much lower than the calculated values. This could be accounted for by the coincidence of the start of the experiment with the first really cold nights of the year. Scale may also have played its part as airflow in the farm scale bins was fairly even and there was no great disparity between longest and shortest cooling areas.

The second front took a little longer than the maximum expectation to pass through some bins, presumably due to the mild winter. The third front was achieved within the very wide expected range but the temperature rose briefly thereafter.

For the last two fronts, the hours run using a 4 C differential continued to be much lower than expected, while the hours run using the 2 C differential, were within the expected range.

ii) Insect numbers

As expected, there was no experimental evidence of the insects increasing their numbers, despite the 10 days at the start of the trial when no aeration was used. However, in practice, the insects died much quicker than expected. Although no calculations were made for subsequent survival of the initial infestation, they must have spent 24-94 days at 10 C, while the time taken for 50% of them to die in the lab. was 227-257 days, depending on species. The calculations suggest that over 90 % would have survived. Similarly, the 67- 146 days storage at 5 C before theoretical unloading on 1 April, compares with 50 % survival time in the lab. after 113 - 138 days exposure to 5 C. Therefore, more than 50 % could have survived.

As the theoretical survival values were obtained using the same strains as in the farm scale experiment, other factors must be responsible for the inconsistency. The most likely is acclimation; that is the initial rate of cooling, which was very quick in the large scale experiment, but which was carried out at 1 C per day in the laboratory, to find the maximum possible survival. In addition, the insects in the large scale experiment, experienced lower temperatures than 5 C, for limited periods. The practical results suggest that laboratory data and calculated values give a very optimisic indication of insect survival in aerated grain.

Overall, the calculations always assumed conservative values; cooling times and fan running hours were longer than the values determined by experimentation. Estimated insect survival times were also longer than occured in practice but problems associated with the detection of the last few surviving insects could have influenced these results. As the experiment took place during an exceptionally mild winter and warm spring, the data from the practical trials produced by this project should be safe and not unduly optimistic. Nevertheless, it would be desirable to find a more accurate way of assessing the survival time of the insects.

8. OVERALL CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

The results, from both the laboratory experiments and the calculated values for cooling time and insect survival, confirm that the concept of the storage stategy was sound. It worked under extreme conditions and would not appear to be unduly restricted by climatic or geographic considerations.

The large scale experiment showed that automatic control of aeration using differential thermostats was effective and was able to reduce grain temperatures to 5 C by December. The 4 C differential was 3 times cheaper than the 2 C differential. However, the larger differential allowed grain temperatures to drift upward in mid winter. A disadvantage of the relatively small, farm-scale bins is that they lack the insulation properties of larger bulks and thus may give a pesimistic view of time the grain will spend at sub-5 C temperatures. It would be an advantage to try out the regime in a far larger bulk of grain, where lower temperatures may prevail for longer.

The initial aeration stimulated a migration of _O. surinamensis_ and _C. ferrugineus_ to the grain surface, where most insects were subsequently found, and where they would be accesible to treatment. The surface treatments in commercial stores were succesful in dealing with _S. granarius_ infestations but in the large-scale experiment this species did not migrate to the surface. Future research should examine the combination of aeration with surface treatment.

The strains of the 3 insect species used in the large-scale experiment, all died out before the grain was sold. However, these results need to be confirmed in other seasons and using field strains of insects that may have a greater tolerance to cooling. Under practical conditions, grain may be cooler at the start of storage, so that the insects' acclimation is much more gradual and they may survive longer. In addition, no account was taken of mites during this part of the programme. They are, however, important pests and the effects of this type of storage strategy on mite populations is worthy of investigation.

While the trappings gave a clear picture of the insects' activity, the results need careful interpretation and it was not possible to relate trap catch to the number of insects per kg. Further work is needed to compare results from conventional sampling with trap catches.

Field trials demonstrated that local applications of pesticide to grain can provide a cost-effective method of dealing with an infestation that is not readily controlled by cooling. Further work is needed to integrate this approach with the current strategy and also to examine the effects of limited treatments on the resistance status of the insects.

Calculations of cooling speed and insect development showed the aeration technique was likely to be effective in most years and in different regions providing the appropriate airflow rate was employed. The use of airflow rates below 4cfm, increases the chances that insects will develop. Also low rate of airflow reduce the likelihood that any insects in the grain will be killed by cooling. The main shortcomings of the calculations were that they suggested that insect would survive the periods at 5 C, while the practical results suggested otherwise. More work needs to be done to find a model of insect survival that more closely matches large-scale observations. This model should also include mite development and survival.

The costs of aeration in the large-scale experiment were low but the fans used were much larger than was necessary. In future, it would be advantageous to use fans of appropriate size, so accurate cost comparisons can be made.

The results obtained in this project have immediate application. Many storekeepers holding grain from harvest for more than 5 months could apply the results to their store and achieve insect-free grain at a very low cost. However, the success of the strategy is reliant on the use of automated fan control that is not restricted by a humidistat, and the use of adequate airflow rates. The regular monitoring of pest populations with pitfall and probe traps must also form part of the strategy. The adoption of the strategy should also allow storekeepers to reduce their reliance on pesticides.

There are still serious limitations on the strategy described in this paper. It is unlikely to be effective with infested grain that is stored for less than 5 months. There must also be doubts over its suitability for malting barley and other cereals stored at moisture contents of below 14.5%. It is hoped that future work will address at least some of these limitations, so allowing the application of the strategy to be extended.

Acknowledgements

The authors wish to thank the following people for their participation in the various parts of this exercise:-

Grain handling: B. E. Llewellin and numerous sandwich students.

Insect assesements: Miss M. Wakefield

Outloading sampling: Ms B. Tigar, C. van Wyk

Analyses: Dr. J. Muggleton, A. Prickett

Met. data: Dr J. Brownscombe, Miss S. Lee, Agromet, MAFF, Reading.

Engineering data: D. Bartlett, ADAS, Silsoe

Photography: M. Brown

Moisture content determinations: Mrs S. Henderson, Miss K. Amos.

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