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Further development of heat-based methods for disinfesting flour mills

by

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ABSTRACT

Following detailed studies at two mills, (volumes 3078 and 6600 m^3) a target temperature of 50°C and a total heating period greater than 40 hours is recommended for heat treatments. Commonly about half of this period will be required for the structure to approach target temperatures. Heating larger mills will take longer, and the scaling up of heating requirements may introduce other problems that could preclude the use of heat as a whole-site disinfestation strategy.

The survival data contained within this report indicates that there were many areas within the mill structures where insects could be expected to survive. This was due to design and construction material that prevented adequate temperatures being reached for a sufficient time.

A thermal model was developed to predict heating times of different structural components. Heat was provided by 18 kW electric fan heaters deployed on each floor, and 2.2 kW ducted fan heaters to selectively heat wall floor joints. In the concrete basement areas significant heat sinks were found. Laboratory tests on three common mill pests, the red and confused flour beetles (*Tribolium castaneum* and *T. confusum*) and the Turkish flat grain beetle (*Cryptolestes turcicus*) showed that treatment times of 7, 2, 0.5 and 0.3 hours are necessary to achieve kill at 47, 49, 51 and 53°C respectively. However, these have to be the temperatures actually experienced by the insects and do not take account of the shielding effect of local food residues, or building design. An insect death rate model has been incorporated into the thermal model of structures to facilitate the prediction of killing times. Using data gathered from temperature monitoring, a treatment assessment programme has been developed to permit real time process monitoring. This has incorporated the model for insect death rate within the structure, and so allows a prediction of insect mortality to show the progress of the treatment at each location.

The target temperatures were achieved for adequate periods within most machinery and air temperatures throughout the mills were raised to 50°C within 10-20 hours. In areas such as basement wall/floor joints, outside walls and windowsills, target temperatures were not achieved demonstrating that additional treatments such as spraying and inert dust application will be required as an adjunct to the heat treatment. A combination of insecticidal spraying and, where possible, diatomaceous earth formulation was applied to such locations prior to heating in both mill trials. It was apparent that mills with roller mills situated in the basement will experience difficulty in achieving a kill temperature within and beneath the machines.

The cost of heat treatments is likely to exceed those currently incurred for fumigation with methyl bromide.

SUMMARY

BACKGROUND

A previous project (HGCA Project Report 329, LINK project AFM93) investigated heat-based methods to develop a reliable alternative to methyl bromide for whole-site treatment of flour mills. Aspects investigated included sources for the provision of heat, methods of optimizing heat distribution and associated modeling studies, heat monitoring methods, effects of heat on a range of insect species, and the benefit of using various additional measures such as modified atmospheres or applications of chemically inert dusts in conjunction with heat. This project concluded that while the internal use of 18 kW heaters for smaller mills, supplemented by the use of additional heating for basement concrete wall floor joints and application of diatomaceous earth dust to problem areas, showed the potential success of a heat-based disinfestation procedure, more work was required to refine target temperatures and exposure times and to provide a ready means of assessing heating requirements.

For the flour milling industry the downtime and production loss arising from whole site treatments to combat pest problems has restricted control options to those which act most rapidly and effectively. This was the principal reason for adopting methyl bromide as the mainstay for a reliable annual whole-site treatment strategy. Heat is one of the few options offering a similar action but for heat treatments to be effective the problem is how to rapidly achieve an even distribution of temperatures high enough to kill pests but low enough to avoid damage to structural or electronic components. Residual infestations in deep-seated harborages in the basement or elsewhere are a particular problem.

The present project was launched to provide further data on insect mortality, heating requirements and distribution, and on potential costs, so that some general guidelines for heat disinfestations of mills could be established. The temperature range of 47-53°C was investigated against three common mills pests with particular emphasis on heating rates and the data incorporated into an insect death model. This was in turn integrated into a thermal model of mill structures that was developed in the first part of the project to estimate the speed at which different parts of structures may heat up and to identify those parts of the structure that may prove difficult to heat. Consideration was also given to supplementary heating of basement floors and heaters were developed for use in conjunction with perforated polythene ducting.

METHOD DEVELOPMENT

Heat provision and deployment

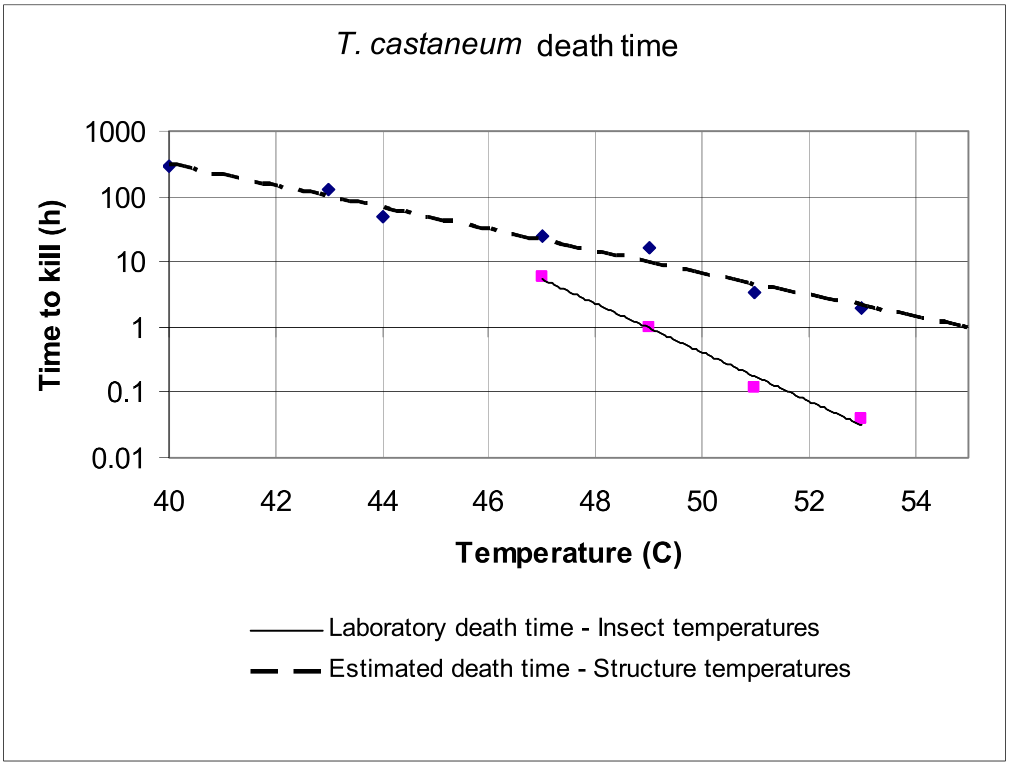
Simple methods are adequate for estimating heating requirements but these procedures do not show the speed of response of the structure. Overall treatment times depend on the slowest heating part of the structure. A thermal model is needed if extra heaters of different outputs are to be employed and to make efficacy predictions and comparisons with different heater deployments and other alternatives such as application of diatomaceous earth dust (DE). A thermal model of mill structures was developed in the first part of this project and used to estimate the speed at which different parts of structures may heat and to identify those parts of the structure that may prove difficult to heat beyond a certain point. Purpose-built 18 kW electric fan heaters, already in use under the trade name of 'ThermoNox' for heat-treating flour mills in Germany, were imported for trials work, and a heating strategy using these heaters for raising air temperatures, and lower power 2.2kw heaters connected to polythene ducting for raising the temperature of heat sink areas such as wall floor joints, was formulated. The heaters used in the trials, manufactured by ThermoNox in Germany, came with electrical distribution boards that could supply power to up to 15 units. The 2.2kW fan heaters were built as part of the project development work.

Development of real time process monitoring

The results of insect heating tests at CSL (see below) have been used to construct a model of insect death rate over the treatment temperature range. This model has been adapted to include the results of bioassays in mills under treatment and can be used to predict the death rate of the population at any given temperature (Fig. **i**). By integrating the death rate based on regular temperature observations from control points in the mill it is possible to predict the proportion of the population that has been killed at any time during a treatment. By integrating this model into the structure thermal model it has become possible to estimate killing times inside structures where temperature measurement is impractical. In the current mill trials, experimental temperature measurements were made using a hand held infra red thermometer (Omegascope Model OS530). A pc spreadsheet has been developed incorporating the death rate model making it possible to key temperature observations and obtain a prediction of insect mortality to show the progress of the treatment.

An instrument has been developed which combines these functions into a single hand-held tool. The progress of the treatment is displayed each time a temperature measurement is made. This information helps the operator to re-position heaters to optimise treatment uniformity and to confirm when a treatment has been completed. The instrument uses infra-red temperature measurement methods and has a key pad so that the operator can enter the identity of each measurement location. As well as storing the time, temperature and location information for the creation of a treatment report the processor uses the insect death model to calculate the current mortality at each monitoring point.

Figure i. Predicted times (dotted line) for kill of *Tribolium castaneum* in practical heat treatments



INSECT HEAT TOLERANCE

Rationale and methods

Three common beetle pests of mills, *Cryptolestes turcicus* (Grouvelle) (Turkish grain beetle or Flourmill beetle), *Tribolium castaneum* (Herbst.) (Rust-red flour beetle) and *T. confusum* Du Val (Confused flour beetle), were assessed for their heat tolerance. Initially temperatures in the range 49°C to 55°C were to be tested but since less than 5 minutes exposure at 53°C killed the insects, it was decided with this effective result to lower the test range by 2°C. The weight of the available literature suggested that of these species *T. castaneum* was the most tolerant of heat, and that the older larvae or pupae were the most tolerant stages.

Two hundred adults of each species were placed on a thin layer of food (whole wheat flour and yeast (ratio 20:1) in a plastic tank. This optimised the conditions for oviposition. The adults were left for 3 days at 30°C and 60% r.h. and then removed. This ensured that there would be enough larvae of the same age class for testing. After 19 - 21 days and 22 - 23 days respectively, 4th instar larvae and early pupae were separated from their food, ready for the heat exposures. These were carried out in a fan-assisted oven in a controlled environment room set at 25°C and 60% r.h. There were seven different treatment times with three replicates for each. Plastic Petri dishes were used for the exposures and controls and each had a thermocouple glued to the centre of the floor. To achieve rapid heating to the required temperature and minimise deaths during the heating-up period, only 0.5 g of 500 mesh sieved food medium was added, spread in a thin, even layer and covering the thermocouple. Pilot tests had shown that increasing the amount of food even to 1 g more than doubled the time to approach within 1°C of the target temperature.

The oven was heated to the required temperature and dishes were inserted on the middle shelf whereupon the stopwatch was started to record the time the sample took to reach target temperature. The dishes and their thermocouples were removed once the allocated time at the treatment temperature was completed. The dishes were placed in front of a fan which ensured that the dishes and their contents cooled rapidly. The thermocouples indicated the time samples took to cool down to 30°C. Typical temperature profiles are shown in Fig. **ii**. The treated samples were placed in tubes (25 mm wide x 75 mm high), with a nylon mesh top, for incubation at 30°C and 60% r.h. after treatment with an additional 10 g of sieved food. Tubes were examined daily for adult emergence.

Tribolium castaneum was tested alone at each temperature except at 47°C, when all three species were assessed together. *Cryptolestes turcicus* and *T. confusum* were tested together at the other three temperatures. The mortality data of each species at each temperature was plotted against each time interval using a probit programme (Version 7a, Central Science Laboratory, York UK). From the analyses, the times at each of the four test temperatures for 99% kill of each species are shown in Table **i**, together with the minimum times recommended for control of insect pests in a practical treatment. In these tests *C. turcicus* came out as the most tolerant of the three species, proving to be slightly more tolerant than *T. castaneum* at all test temperatures. This could have been due to the more cryptic behaviour of this pest together with its smaller size, enabling it to receive more protection by evaporative cooling from the thin layer of flour in the exposure dishes.

It must be remembered that the target temperatures for control must be reached at the point where the insects actually are in the structure, and that the presence of other material such as food residues will result in lower temperatures being experienced by the insect.

Figure ii. Laboratory exposures - Mean change in temperature over time in the treatment dishes during the heating and cooling phases to and from the four temperatures 47, 49, 51 and 53°C in a fan-assisted oven

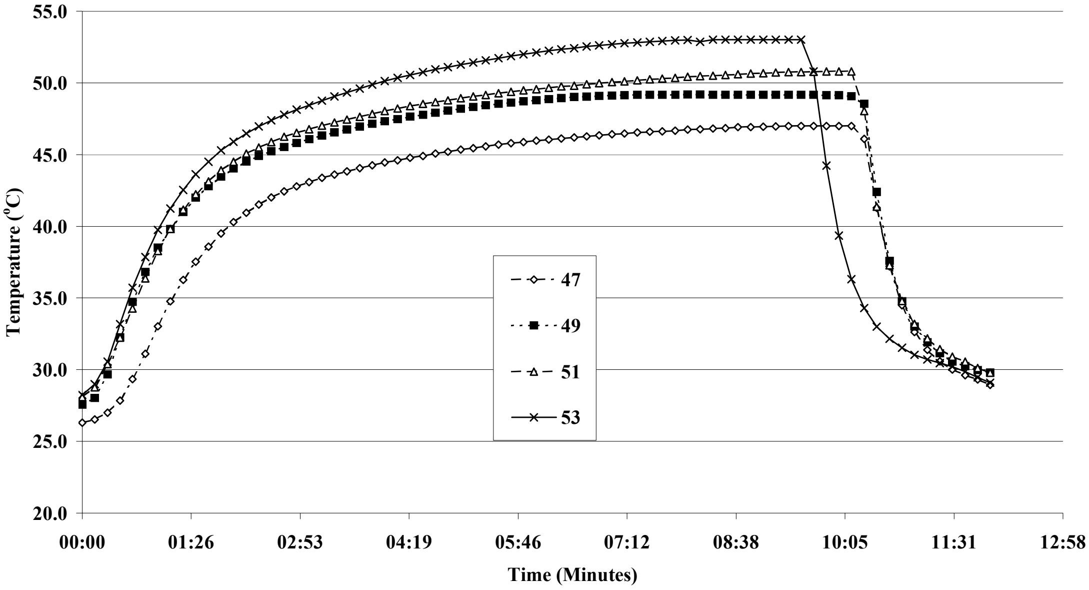


Table i. Laboratory exposures - LT$_{99}$ achieved after exposure of 4th instar larvae of *Cryptolestes turcicus, Tribolium castaneum* and *Tribolium confusum* in a fan-assisted oven

Temp. (°C)	LT$_{99}$ (Minutes)			Minimum exposure time for kill in practice (hours)
	C. turcicus	*T. castaneum*	*T. confusum*	
47	377.58	330.59	110.21	7
49	89.18	37.46	12.52	2
51	25.27	15.00	>4	0.5
53	14.44	2.58	>2	0.3

FIELD TRIAL SUMMARIES

Ramsgate

Building structure

The mill is housed in a $3078m^3$ Victorian brick built structure 23.2m long, 8.1m wide and 16.4m high. Outside walls range in thickness from 230mm to 450mm. Each of the five floors has single glazed windows. The ground floor is solid concrete and the roof of the building is of profiled steel sheet with bituminous felt weatherproofing. The intermediate floors are timber. The roller mills are located on the first floor and are driven by a line shaft running the length of the ground floor. The product lifts in this mill are by wooden cased elevators and steel chain conveyors

Heating plan

The calculated heating requirement for the whole building was 219kw with a 12ºC ambient, a 50ºC treatment temperature and 24 hour heating up time. Ten 18kw ThermoNox heaters were used together with fourteen 2kw wall floor heaters. The total heat input was 209kw. Four ThermoNox floor fans were used to improve the air circulation on the ground, first and third floors. Wall floor heaters and polythene ducts were deployed on all the upper floors and in part of the ground floor.

Power for the heaters was provided by a generator (64kw) and from the site power supply (144kw) via two distribution boards.

Dust application

The three types of dust applicators obtained by the CSL team were as follows:

1. ECO D700 hand duster
2. Flowmaster power duster (Model 1907, Root Lowell Company, Lowell, Michigan)
3. GPS “GASPOT” CO_2 powered applicator (works using small CO_2 cylinders)

Of these the hand duster was most effective when used to treat surfaces in a more complex structure where a general application was inappropriate. The power duster was useful for rapid treatment of large open structures such as grain stores where the spread of dust was not of major concern but was not ideal for application to dead spaces. The hand duster was used for application of dust to basement cracks and crevices in the Ramsgate trial in preference to the CO_2-powered unit which had been successfully employed to treat void spaces beneath machinery in earlier trials, because of the smaller amounts of dust required..

Key findings

The total electrical energy consumption during the 42 hour heating period was 28425.6 MJ. (7896 kWh or 9.24 MJ/m^3). Air temperature in each of the 5 floors was raised to 50ºC. after 14 h (ground floor), 15 h (1st floor), 24 h (2nd floor), 30 h (3rd floor) and 24 h (4th floor). Seventy five percent of the wall floor joint area was raised to lethal temperatures after 18 h. At the end of some ducts, in some corners and near floor fans where the polyducts were disturbed, lethal temperatures were not reached. Floor fans improved the distribution of heat and local rate of heat transfer to the structure. This was particularly important on the ground floor and on the 3rd floor where only one heater was used.

After 12 hours from the start of heating many insects emerged and began to die. After 26 hours few live insects were seen. The walls failed to reach lethal temperatures except in a few places but no insects were seen on the walls. Ceiling/wall joint temperatures reached lethal levels in the ground and first floor but failed to do so on upper floors. No insects were seen in these locations either. All floors except the concrete basement and all ceilings reached lethal temperatures within 30 hours. All timber and steel structures inside the mill heated to lethal temperatures within 30 hours. The mill cooled to below 30ºC six hours after the end of heating.

The bioassays confirmed that the timber floors and machinery were effectively treated but that the outer walls, window ledges and other sheltered locations provided a safe refuge where high levels of survival were observed. The stage IV larvae and pupae were confirmed as being the most heat tolerant. A few live insects were seen in a cool corner of the ground floor after treatment. None were seen in the rest of the mill during cleaning and re-assembly.

Tilbury

Building structure

The mill and flour bin base is housed in a 6600 m^3 reinforced concrete framed structure with brick infill external wall panels. Only the top floor has double glazed windows. The plant is supported on 5 levels but much of the intermediate timber floors are cut away allowing easy air exchange between floors. Much of the perimeter of the upper floors does not connect with the external wall so the wall floor joint is eliminated. The rolls stand directly on the ground floor which is solid concrete overlaid by woodblock. Product is moved throughout the plant by conventional pneumatic lifts and screw conveyors.

Heating plan

The overall heating requirement was calculated to be 351 kW. Heat was provided by eighteen ThermoNox 18.75 kw heaters and fifteen 2.2 kW wall floor heaters. Heat distribution was assisted by 5 ThermoNox floor fans and three 1.2m dia stirring fans. The maximum heat input rate of 370.5 kW was provided by a 500 kW generator. Power was distributed to the mill and the bin base area by separate distribution panels. Wall floor heating ducts were positioned where there was a wall floor joint. In three corner areas on three floors stirring fans were used in place of wall floor heaters. The total heat treatment time aimed for was 40h.

DE and chemical spray treatment

Previous experience and modelling has shown that some parts of the building can never be effectively heated to lethal temperatures. During an earlier project CSL have shown that DE is effective against adult insects at 30ºC and continues to be effective for weeks after the treatment and so will kill emerging adults not killed as eggs, larvae or pupae by the heat.

Several important areas of the mill were identified as test sites for this material. The cable duct below the rolls on the ground floor showed evidence of infestation and was treated with DE. The narrow space between a returns bin and the wall of the building was also treated with DE because there was no chance of heating this part of the structure to 50ºC. The GPS "GASPOT" CO_2 powered applicator was used for all applications of DE during this trial.

Chemical insecticide sprays were applied to doorways and lift access on the mill floors to prevent adult insects escaping from the heat. Ground floors below the bin bases were not heated so spray applications were made here to kill any insects falling from the bin base floor above.

Open and Closed Sifter comparison

It has been claimed that it is unnecessary to dismantle sifters to ensure an effective thermal disinfestations (Hans Hoffmeir, ThermoNox). Considerable time and effort could be saved if this is shown to be true. A comparison was made between open and closed sifters. All the sifters were taken apart and cleaned then four were re-assembled before the heating started. The fifth was left open. Bioassays and temperature sensors were placed in open and closed sifters. It was found that the unassembled sifters took ten hours less time to heat than the assembled ones, 28h compared with 38h, but that both were heated adequately during the 40h total treatment time.

Key findings

During the 40 hour treatment 56448 MJ (15680 kWh or 8.55 MJ/m^3) was consumed by the heaters. The average rate of heat input was 313 kW, 85% of the installed capacity.

Bioassay results confirmed that 40 hours was necessary to kill the insects in the machinery and that further improvements in kill in the fabric would result from extending the treatment time to 48 hours. Good agreement was found between the bioassay results and the insect death model based on temperature monitoring, confirming that temperature measurements during the treatment could be used to monitor the progress of the treatment at critical locations. Fully assembled sifters and purifiers were effectively treated in 38 hours. Unassembled sifters took only 28 hours to treat.

DE was shown to be very effective in killing adult insects where it was used under the roller mills. Its use in other parts of the structure where heating is difficult could improve the overall effectiveness of the treatment.

It proved impossible to heat the ground floor of the mill and most external walls to lethal temperatures. All the wooden upper floors and machinery in the mill building were heated to lethal temperatures. Ceiling fans were an effective replacement for wall floor joint heaters in the corners of the building where they were used but did not raise surface temperatures above the local air temperature. Wall floor heaters were shown to be mainly effective but limitations at corners where the polythene ducts have to bend were confirmed.

TRIAL TREATMENT CONCLUSIONS

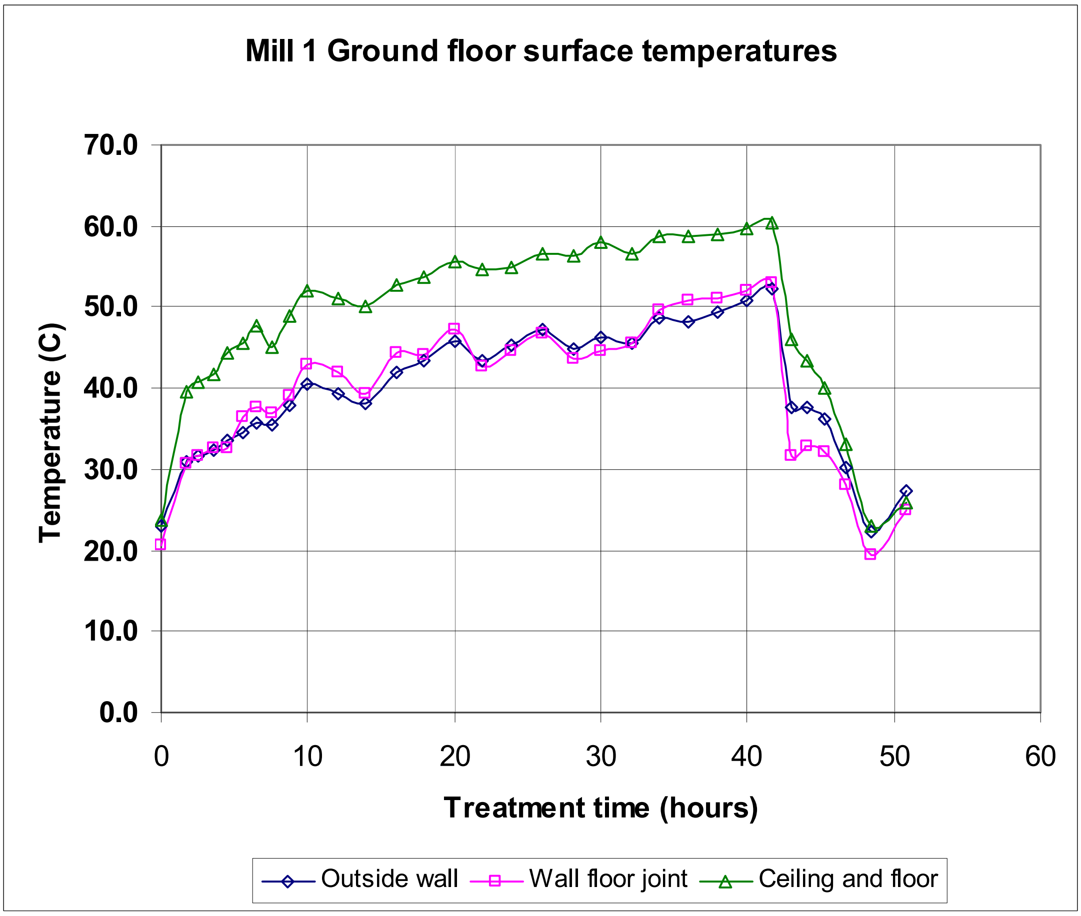
DE applications

It is recommended to use DE for ground floors and some wall floor joints.

It is clear that it will never be practical or economic to heat concrete ground floors to a level that will ensure 100% kill of any insects present there as can be seen from the temperature records from a mill basement shown in Fig **iii**.

DE is effective within a 40-hour treatment time at 25 – 30ºC and should be applied to ground floors in cracks, crevices and to dead spaces in voids or under plinths. It may also be advisable to apply dust to wall floor joint margins on upper floors to treat these parts of the structure. Supplementary treatments with DE could be applied during the course of a heat treatment when cool areas are detected as a result of routine monitoring.

Figure iii



Treatment time

The results from the bioassays confirm that a 40-hour treatment improved the kill rate over that obtained at 30 hours. It took about 20 hours to heat the structure at Tilbury to above 45ºC so, in this treatment, temperatures capable of killing insects within a finite time period (i.e. less than a day) were maintained for 20 hours. The treatment would have been more effective if such lethal temperatures had been maintained at some locations for a few more hours. Overall treatment times will depend on the speed of heating which in turn will depend on the cost benefit of using more heaters.

Costs

The cost of the Tilbury trial, including plant hire and labour, worked out at over twice that for a methyl bromide treatment at the site the previous year.

TECHNICAL DETAIL

GENERAL INTRODUCTION

The fumigant methyl bromide (MB), an ozone depleting compound listed under the Montreal Protocol (UNEP, 1998), has been phased out from general use in non Article 5 (developed) countries since January 2005. Although an alternative fumigant, sulphuryl fluoride, was registered for use in empty flour mills in the UK from July 2004, under the trade name Profume, the product is at an early stage of introduction and Dow are still working on dosing and marketing strategies to establish treatment reliability. With increasing pressures on safe chemical use a move away from total reliance on chemical control is obviously desirable and many physical techniques have been considered as MB alternatives. However, for structures there are limitations. The use of modified atmosphere (MA) techniques alone for space treatments is not practical because whereas buildings can be sealed sufficiently for fumigation, they cannot be sealed to the much higher standard required for MA applications. The UK winters are not cold enough to use the "freeze out" procedure proposed in Canada. The heating systems present in many northern USA and Canadian mills allow routine partial heat treatment with minimal set up time. These are absent from UK mills as a consequence of milder winters The UK climate does not offer the benefit of a regular hot season either, and MB has for many years been the fumigant of choice for the treatment of flour mills in the typically cool and humid conditions.

Before the advent of fumigants, heat treatments of flour mills were widely practiced, and sporadic use has continued with some food industry premises undergo regular heat treatment today (Sheppard, 1984; Heaps and Black, 1994). Improving performance by employing unit heaters and circulation of heat was described as early as the 1930's (Pepper and Strand, 1935), but has since been developed only locally and not systematically. Heating to 47°C or above results in rapid immobilisation and death of insect and mite stages within a few hours. The principal problem for heat disinfestation, though, is the planning of heating requirements and heat source deployment to obtain a uniform heat profile throughout the structure without causing high localised temperatures. This objective was tackled in a previous HGCA-sponsored LINK programme, AFM93, Alternatives to Methyl Bromide for Pest Control in Flour Mills, (Bell et al., 2004). In this study, much progress was made using a combination of heating strategies in conjunction with the use of inert dusts to treat areas difficult to heat such as voids and cracks, a procedure first tested in Canada (Fields et al., 1997). However, further refinement of the target temperatures and exposure times, temperature monitoring systems and heat distribution strategies, and verification of heat treatment management models, was required. The current project set out to address these issues.

CONSTRUCTION AND ASSESSMENT OF EQUIPMENT

In addition to model development and selection of appropriate monitoring equipment, the mill trials required the development of supplementary heating strategies. Thermal mats had been tested in the preceding Link programme, but had not proved sufficient to cope with heating wall/floor joints because of the presence of numerous obstacles. An new approach was required to supply heat to these areas, and the use of polythene-ducted heat seemed to be the most promising technique to develop further.

Wall floor heater and duct design.

Previous tests (HGCA Project Report No. 329, p.94) showed that positive ventilation of wall/floor joints can greatly improve the heat transfer between the air and the structure resulting in surface temperatures close to the average room air temperature. These sites in the building are likely to provide insect refuges so it is proposed to use local heating to raise the temperature of wall/floor joints above average air temperatures (Target 55 -60ºC) to ensure effective treatment. Relatively low power heaters can be used to raise the heating air from room temperature (target 50ºC) by about 10º to 60ºC. The heating element used in the heaters is a sheathed rod which operates at about 200ºC. The heater requires no control thermostat and operates continuously; temperature control is achieved by the thermostats in the main room heaters. An overheat cut-out is however incorporated to prevent damage if the air flow through the heater fails.

Work at NIAE during the early 1980s (Bailey, 1982) established a design process for perforated polythene ducts used in heating green houses. This program has been adapted to the design of wall floor heating distribution ducts. Hole spacing is varied along the length of the duct to give uniform heat output by allowing for changes in pressure and temperature of the heating air along the length of the duct.

A prototype heater was designed and tested with 6 and 9 meter long perforated ducts. A Helios inline vent centrifugal fan RR150 C delivering 0.189 m^3/s through a 250 mm dia duct 2.0 kW single phase electric heater was connected to a ‘T’ duct section attached to the polythene ducts. The ducts were deployed along a concrete wall floor joint and the temperatures and air flows were measured.

The air volume entering the fan was 0.189 m^3/s. The static pressure in the 'T' was 23 Pa. An air temperature rise of 9.4ºC was measured and each of the polythene ducts distributed this heat uniformly along their length. The 6 m polythene duct delivered 175 W/m and raised the wall/floor joint temperature by 4.3ºC from 16.5ºC to 20.8ºC with air at 32ºC. The air supply rate per meter of duct was 0.016 m^3/s. The 9 m duct delivered 117 W/m and raised the wall floor joint temperature by 3.7ºC from 16.4ºC to 20.1ºC with air at 32.6ºC. The air supply rate per meter of duct was 0.011 m^3/s. A single heater and duct can heat up to 20 m of wall floor joint.

LABORATORY STUDIES ON INSECT HEAT TOLERANCE

Three common beetle pests of mills, *Cryptolestes turcicus* (Grouvelle) (Turkish grain beetle or Flourmill beetle), *Tribolium castaneum* (Herbst.) (Rust-red flour beetle) and *T. confusum* Du Val (Confused flour beetle), were assessed for their heat tolerance under laboratory conditions of monitored rapid heating. Initially temperatures in the range 49°C to 55°C were to be tested but since an early test revealed that less than 5 minutes exposure at temperatures building to 53°C killed all the insects, it was decided with this effective result to lower the test range by 2°C.

The literature suggested that *T. castaneum* is more tolerant to heat than *T. confusum* (Fields, 1992) but there is some controversy over the most heat tolerant stage. Until recently this was unanimously thought to be the last larval instar or early pupal stage but Mahroof et al., (2003b) claimed that early instar larvae survived longer at high temperatures than older ones. However, exposures in mills by the same workers showed that 4th instar and pupae were most tolerant (Mahroof et al., 2003a). Initial test in the current programme confirmed that older larvae of the CSL strain were indeed the most tolerant stage.

Methods and preliminary results

Two age categories were prepared of *T. castaneum*, the most heat-tolerant UK insect mill pest. These covered all the developmental stages of the insect and therefore ensured that the most tolerant developmental stage would be present. The first category contained larvae stage IV and pupae at treatment time and were set up by placing 50 adults on 50 g of food (whole wheat flour and yeast (20:1)). These were placed in a controlled environment room at 30°C and 60% r.h. After two weeks the adults were removed and the contents were transferred to square nylon bags (100 x 100 mm), which were heat-sealed at the sides. 30-µm mesh was used as a precaution for the bags as this prevented contamination of the mill as it retained all stages of *T. castaneum* and any flour mites that may have been present in the food. These bags were returned to the same conditions for a further two weeks.

The target stages for the second age category were adults, eggs and 1st and 2nd stage larvae. These were set up by placing 50 adults in mesh bags of similar size, construction and number to the first age category. The bags were placed in similar conditions to age category one two weeks prior to the Ramsgate mill trial (See Ramsgate Mill section of Mill Heating report)

Preliminary mill trial results

The results at Ramsgate prior to analysis (Table 1) showed that there was always greatest survival with the 4th instar larvae and pupae. Higher numbers of adults were produced in the controls but the difference was disproportionately greater between the treated bags containing older and younger stages. Therefore it showed that 4th instar larvae were most tolerant and these were chosen for the laboratory tests.

Laboratory experiments

Two hundred adults of each species were placed separately on food (whole wheat flour and yeast (ratio 20:1) sieved through 180 µm mesh in a plastic tank (190 mm wide x 280 mm long x 170 mm deep) so that the flour mix formed a shallow layer in the bottom. Sieving the food through 180 µm mesh meant that it would be easy to collect the eggs. This optimised the conditions for oviposition. The adults were left for 3 days at 30°C and 60% r.h. and then removed. This ensured that there would be enough larvae of the same age class for testing. The food was sieved through 212 µm mesh so that all eggs would be retained while the food was removed. To obtain 4th instars and pupae, the initial flour with eggs was added to 150 g of sieved food (500 µm mesh) in a glass jar. The sieving with the 500 µm mesh ensured that the 4th instar larvae and early pupae were easy to separate from their food, which was done after 19 - 21 days and 22 - 23 days respectively, each species having a similar developmental rate at 30°C.

Oven exposures

The heat assessments were carried out in a 225 l fan-assisted oven (Model IPR225.XX1.5, Sanyo Gallenkamp plc., Loughborough, Leics., UK). The oven was in a controlled environment room set at 25°C and 60% r.h. Initial tests were conducted to monitor heating rate times in covered and uncovered Petri dishes on small amounts of food and to strike a balance between a rapid heating time and result consistency (Figs 1-3). For the main experimental runs each treatment or control replicate was set up on 0.5 g of sieved (500 µm apertures) *Tribolium* food with 30 4th instar larvae placed in a plastic Petri dish [50 mm diameter x 10 mm high with lid covered in nylon mesh (130

Table 1. Preliminary mill trial results - Emergence of *Tribolium castaneum* in 2 separate age categories from 50 g flour placed in nylon mesh bags after heat treatment at Ramsgate (for further details see Tables 11 and 12, p. 39-40)

		Adults, Eggs and 1st & 2nd instar Larvae	4th instar Larvae and Pupae
		Adult	Adult
Bag No.	Floor	Emergence	Emergence
Control		420	849
1 & 2	Ground	0	0
3 & 4		203	771
5 & 6		296	788
7 & 8		186	734
9 & 10	1st	103	334
11 & 12		1	15
13 & 14		0	6
15 & 16	2nd	0	3
17 & 18		252	471
19 & 20		124	473
21 & 22	3rd	1	22
23 & 24		4	17
25 & 26		0	19
27 & 28	Top	1	93
29 & 30		522	652
31 & 32		178	506
33 & 34		0	0

µm apertures)]. Each dish had a thermocouple [Type-T with a beaded tip and PTFE insulation (-50 to +250°C)] whose end was glued to the middle of floor of each Petri dish. There were seven different treatment times spaced at an interval of x √2 with three replicates for each (Table 2). Three replicate control samples were also used. A shelf midway up the oven (420 mm from the floor) was used and a position at the mid-left of the shelf gave the shortest time to the target temperature for the sample. (The fan was positioned midway up the right hand wall). Rapid heating to the required temperature was an important requirement for the predictive modelling that was to be used with the laboratory results to minimise deaths during the heating-up period. All three samples were treated in separate dishes at the same time.

The sequence for the treatment of each sample was as follows: The temperature of the oven was ascertained prior to the input of the sample by a further Type-T thermocouple, which was attached to the oven shelf adjacent to where the dishes were to be placed. The temperatures of the dishes and the oven were recorded on a chart recorder (MobileCorder Model MV230, Yokogawa Martron Ltd., Wooburn Green, U.K.).

The oven door was closed as the stopwatch was started to record the time the sample took to reach target temperature. Once the temperature was reached, the warm-up time was recorded and the removal time was calculated by adding the treatment time for the sample to the time when warm-up was completed. The dishes and their thermocouples were removed once the treatment time was completed. The door of the oven was closed immediately and the thermostat reset to allow it to heat up to the required temperature in preparation for the next sample. The dishes were placed in the draught from a fan (Model 1062, Pifco, Taiwan), which ensured that the dishes and their contents cooled rapidly. The thermocouples indicated the cooling down time for the sample, which was ended when the temperature dropped to 30^{o}C. It also signalled the start of the next treatment cycle, once the oven had reached its target temperature.

The treated samples were placed in tubes (25 mm wide x 75 mm high), with a nylon mesh top, for incubation at 30^{o}C and 60% r.h. after treatment. An additional 10 g of sieved food were added to ensure there was sufficient to allow the completion of the larval development. The tubes were monitored daily for adult emergence.

Tribolium castaneum was tested alone at each temperature except at 47^{o}C, when all three species were assessed together, as the length of exposure times meant that the test lasted two days. *Cryptolestes turcicus* and *T. confusum* were tested together at the other three temperatures. A combined mean heating time to experimental temperature, mean temperature during treatment and subsequent mean cooling time was calculated for all species. The mortality data of each species at each temperature was plotted against each time interval using a probit computer analysis (Version 7a, Central Science Laboratory, York UK). This produced a straight-line relationship between time and mortality, when both were converted by Log_{10} for the former and by probits for the latter. This allowed the prediction of the exposure time required to achieve a certain percentage of mortality, the lethal time (LT). In this case the LT for 50 (LT_{50}) and 99% (LT_{99}) mortality for each species were used. The goodness of fit for the relationship is shown by the closeness of the dotted lines either side of the straight-line relationship (Figs. 5 - 7).

Figure 1.

Change in temperature over time of whole wheat flour in a plastic dish with a solid lid on introduction to and after removal from a fan-assisted oven at 51°C

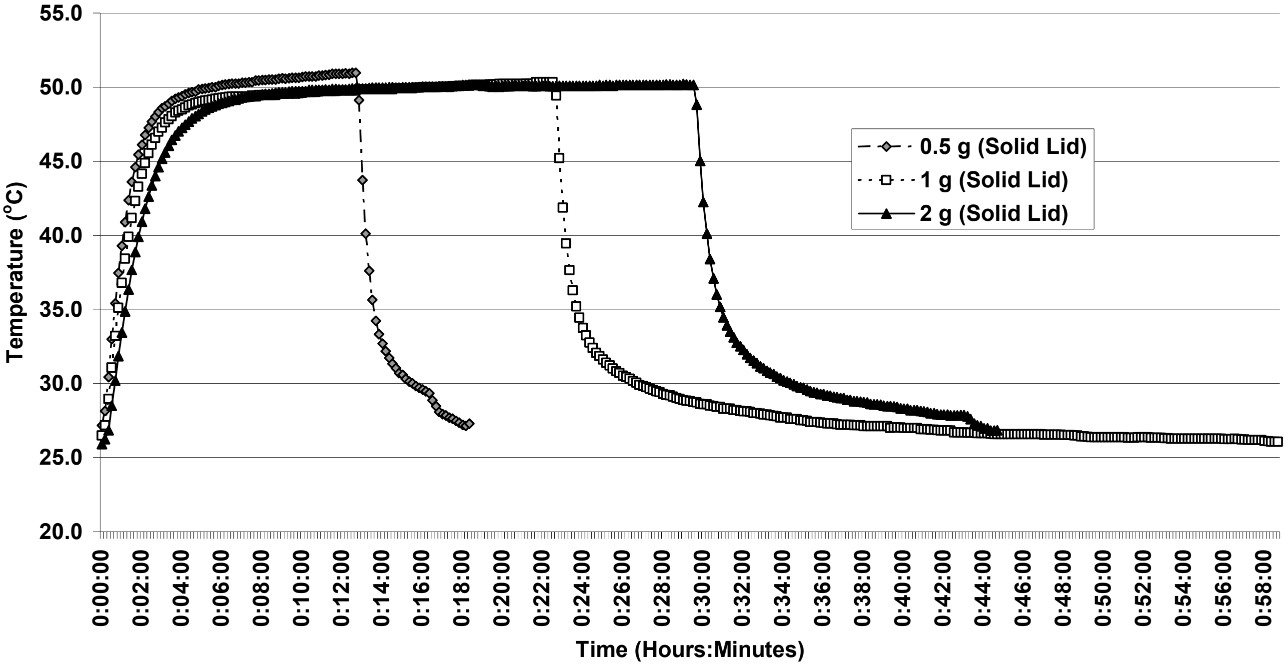
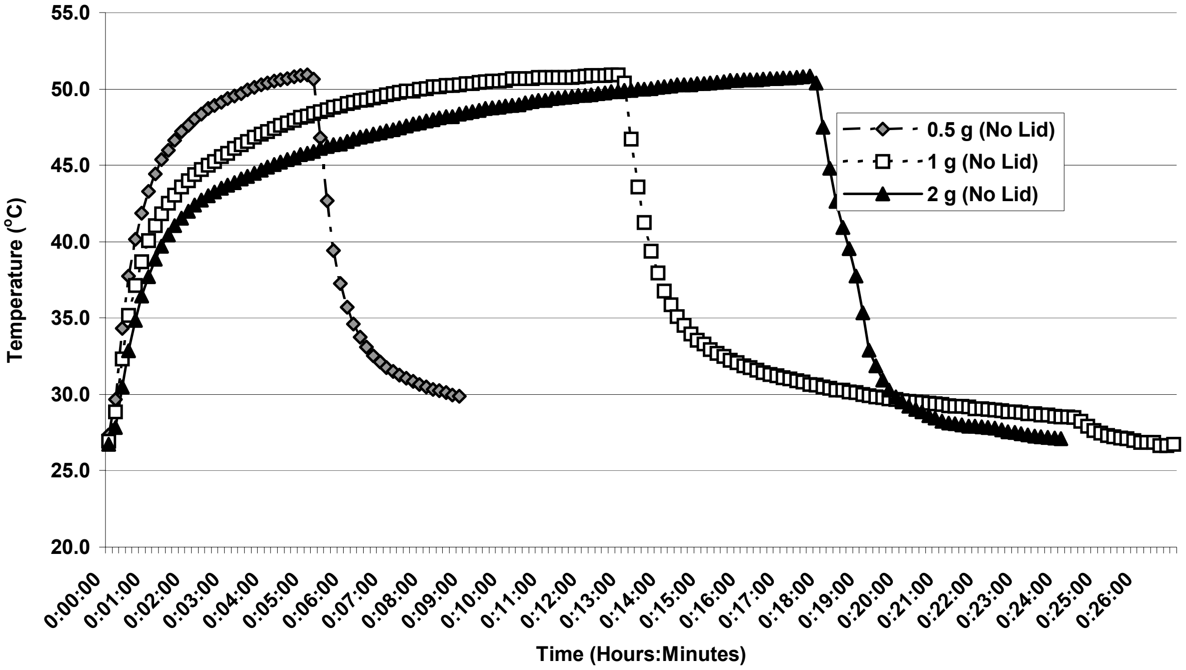
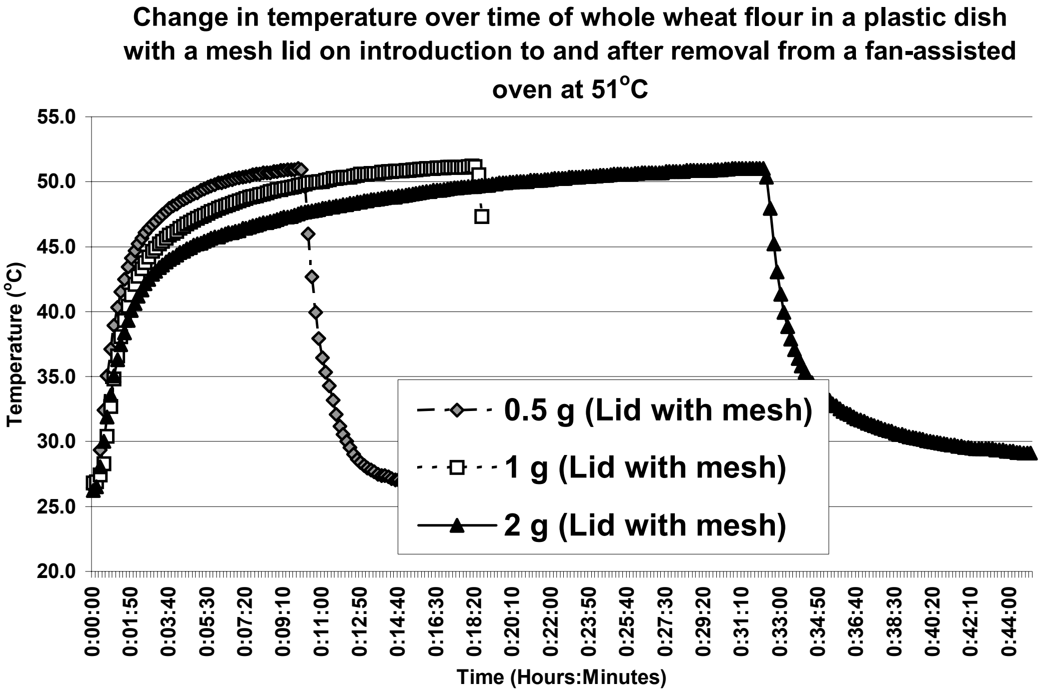


Figure 2.



Change in temperature over time of whole wheat flour in a plastic dish on introduction to and after removal from a fan-assisted oven at 51°C

Figure 3.



Results and discussion

Laboratory exposures

The heating profiles from the treatment dishes subjected to each of the oven temperatures are very similar (Fig. 4). Warm-up periods were quicker at the three higher temperatures but in all cases the rate of change decreased markedly after 40°C was passed; 66% of the warm-up period was spent between 40°C and the target temperature. There was no particular relationship between increased warm up times with increased temperature as might be expected (Table 1). This may be explained by the presence of flour in the treatment dishes. Although this was only 0.5 g it did have a buffering effect in the rate of heating when the covering on the thermocouple was uneven because it was difficult to keep the initial even distribution of flour while moving the dishes into the oven for treatment. There was less difference between cooling periods and the rate of change in temperature was uniform from all exposure temperatures (Fig. 4). There was a trend of increased mean cooling time with exposure temperature, as would be expected, but the mean difference between the highest and lowest temperatures was only 50 seconds (Table 1).

The target temperatures were well maintained by the oven during the treatment period (Table 3). The mean temperature was in all cases within 0.1°C of the requirement although there was some variation indicated by the range of temperatures mainly due to differences between the replicates in the warm-up periods at the lower end of the range. Generally the heating and cooling profiles fulfilled the requirements of the criteria for the model with rapid warming and cooling and the maintenance of a constant target temperature over the treatment period.

The results from heating the 4th instar larvae of the three beetles are found in Figs 5 to 7. Variation between the three replicates in mortality of *C. turcicus* and *T. castaneum* at each exposure time is shown by the divergence of the dotted lines on each side of the solid lines, though this was only particularly noticeable at 53°C. At this temperature, the warm-up time represented nearly half the total spent in the oven and this proportion increased as the exposure times decreased. Differences in warm-up times between the replicates would have a proportionately greater effect on the mortality at higher than at lower temperatures. There are no results for *T. confusum* at 51 and 53°C (Table 5 and Figure 7) because the high susceptibility of this species to these temperatures meant that 100% mortality was achieved in 3.45 and 1.25 minutes (plus warm-up) at 51 and 53°C respectively. It was therefore not possible to achieve enough intermediate data points in the short time period before 100% mortality was achieved. The results of this work agree with those found by Oosthuizen (1939) with the same insect stage in an incubator: 50 % mortality was seen after 8 and 4.42 minutes at 48 and 50°C respectively.

C. turcicus has shown the highest tolerance to heat of all the species over the temperature range (Table 5). There is certainly a markedly difference between *Tribolium* species in tolerance to heat, with *T. castaneum* three times more tolerant than *T. confusum*. Kirkpatrick and Tilton (1972) noted a similar difference in heat tolerance between the adults of these *Tribolium* species. This may be explained by the difference in developmental range (Table 6) with *T. castaneum* having a 5°C higher upper range. However this does not explain the increased tolerance of *C. turcicus* over the latter species as it has the same developmental range as *T. confusum* and even has a lower optimum developmental temperature. There are no supporting publications for the tolerance of *C. turcicus* to heat. An assessment of heat tolerance in adults of various stored product pests by Kirkpatrick and Tilton (1972) showed that a co-generic species, *C. pusillus* also had a high tolerance to heat, greater than that of *T. castaneum,* and its upper developmental threshold was also relatively low at 35°C (Davies, 1949). This heat tolerance may be a characteristic of the genus.

A small temperature difference at extreme temperatures can have a profound effect on the LT_{99}, which was appreciably longer at 47 than at 49°C for all species. This was also illustrated by the work of Beckett et al. (1998). LT_{99} from the exposure of 3rd instar larvae of *Rhyzopertha dominica* (F.) (lesser grain borer) to 46 and 47°C were 49 and 33 hours which is a reduction in exposure time of 16 h in 1°C.

The higher the target temperature, the greater the contribution of the heating-up time to the overall kill. This effect is difficult to capture in predictions of the exposure times required for extreme mortality levels by linear transformation statistical programmes such as probit. Nearly always, as can be seen from Figs 5-7, the exposure times predicted for 99% kill are overestimates, as judged by a lack of survivals at almost all exposures beyond probit 7 on the regression lines. As a result the LD_{99} can be taken to provide a reasonable estimate of the minimum time of exposure required for complete control.

Conclusion

To attain complete mortality of all stages of the commonest beetle pests of flour mills in the UK, based on the LD_{99} values for the most tolerant pest given in Table 5, the following exposures times are recommended for temperatures in the range 47-53°C:

47 °C: Max LD_{99} = 6 h 20 mins Min exposure time 7 h

49 °C: Max LD_{99} = 1 h 30 mins Min exposure time 2 h

51 °C: Max LD_{99} = 20 mins Min exposure time 0.5 h

53 °C: Max LD_{99} = 15 mins Min exposure time 0.3 h

These times apply only when the insects actually experience the stated temperatures and do not take into account the protective effect of local materials which may delay temperature rises. Temperature monitoring needs to take into account the rate of heating of such materials.

Table 2. Laboratory exposures -Maximum and minimum exposure times (minutes) used for each temperature

Temperature (°C)	Maximum	Minimum
47	360.00	28.00
49	60.00	7.30
51	25.00	2.13
53	11.19	1.00

Table 3. laboratory exposures - The mean time (minutes) (±S.E.) and range to reach the target temperatures, and the mean time (minutes) (±S.E.) and range for cooling from treatment temperature to 30°C

		Heating		Cooling	
Temperature (°C)	Number	Mean (±S.E.)	Range	Mean (±S.E.)	Range
47	21	8.28 (0.40)	7.00-10.00	1.21 (0.02)	1.10-1.40
49	42	6.24 (0.22)	5.10-8.40	1.40 (0.04)	1.10-2.00
51	42	8.55 (0.11)	8.40-9.40	1.47 (0.03)	1.20-2.20
53	42	7.39 (0.27)	6.00-8.50	2.11 (0.03)	1.40-2.30

Table 4. Laboratory exposures - The mean temperature (±S.E.) and range achieved during treatment time at target temperature

Temperature (°C)	Data Points	Mean (±S.E.)	Range
47	13540	47.0 (0.001)	46.6-47.4
49	5250	49.1 (0.004)	48.7-50.0
51	2680	50.9 (0.006)	50.2-51.4
53	1200	53.0 (0.009)	52.4-53.5

Table 5. Laboratory exposures - The LT_{50} and LT_{99} achieved after exposure of 4th instar larvae of *Cryptolestes turcicus, Tribolium castaneum* and *Tribolium confusum* in a fan-assisted oven

Species	Temperature (°C)	Time (Minutes)	
		LT_{50}	LT_{99}
C. turcicus	47	151.22	377.58
	49	22.51	89.18
	51	4.45	25.27
	53	0.50	14.44
T. castaneum	47	145.32	330.59
	49	18.20	37.46
	51	3.41	15.00
	53	0.28	2.58
T. confusum	47	52.34	110.21
	49	8.47	12.52

Table 6. Laboratory exposures- the temperature ranges for development and optimum for *Cryptolestes turcicus, Tribolium castaneum* and *Tribolium confusum*

Species	Temperatures	Optimum
C. turcicus a	17 – 37°C r.h.>40%	28°C and 90% r.h.
T. castaneum b	20 - 42°C	35-37°C and 70% r.h.
T. confusum c	20 - 37.5°C	32.5°C and 70% r.h.

a Lefkovitch, L. P. (1962)
b Howe, R. W. (1956)
c Howe, R. W. (1960)

Figure 4. Laboratory exposures - Mean change in temperature over time in the treatment dishes during the heating and cooling phases to and from the four temperatures 47, 49, 51 and 53^{o}C in a fan-assisted oven

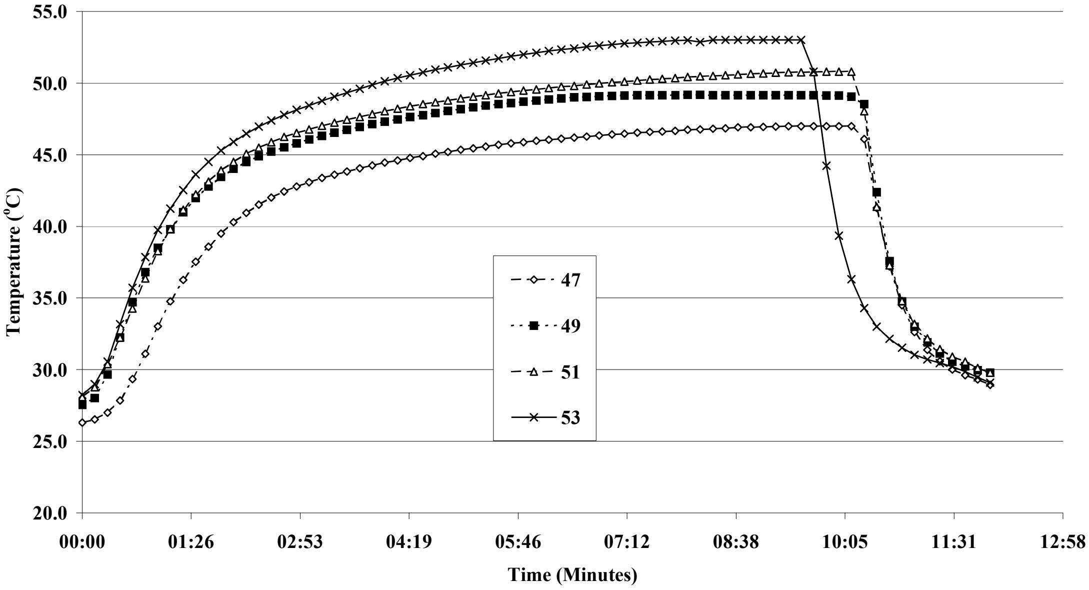


Figure 5. Laboratory exposures -The relationship between mortality and time for 4th instar larvae of *Cryptolestes turcicus* at 47 (purple line and open squares), 49 (blue line and Xs), 51 (green line and crosses) and 53°C (olive line and triangles) (Probit 7.3 = 99% mortality)

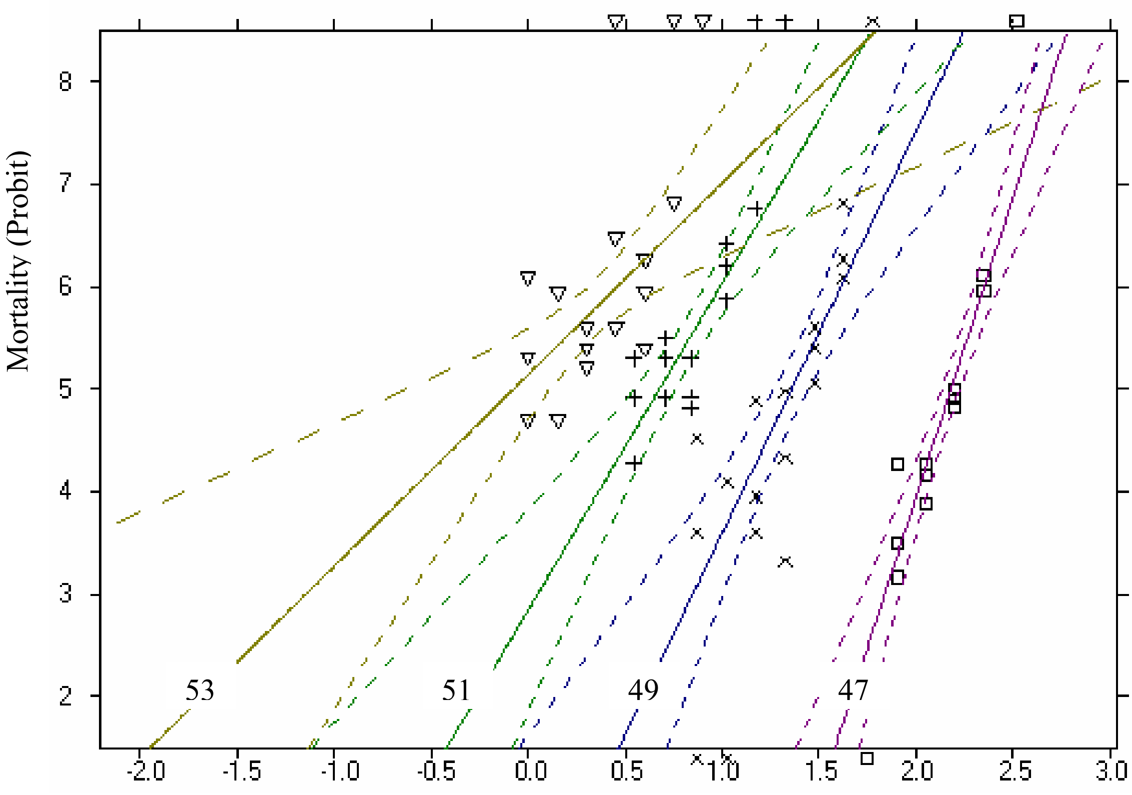


Figure 6. Laboratory exposures- the relationship between mortality and time for 4th instar larvae of *Tribolium castaneum* at 47 (purple line and open squares), 49 (blue line and Xs), 51 (green line and crosses) and 53°C (olive line and triangles) (Probit 7.3 = 99% mortality)

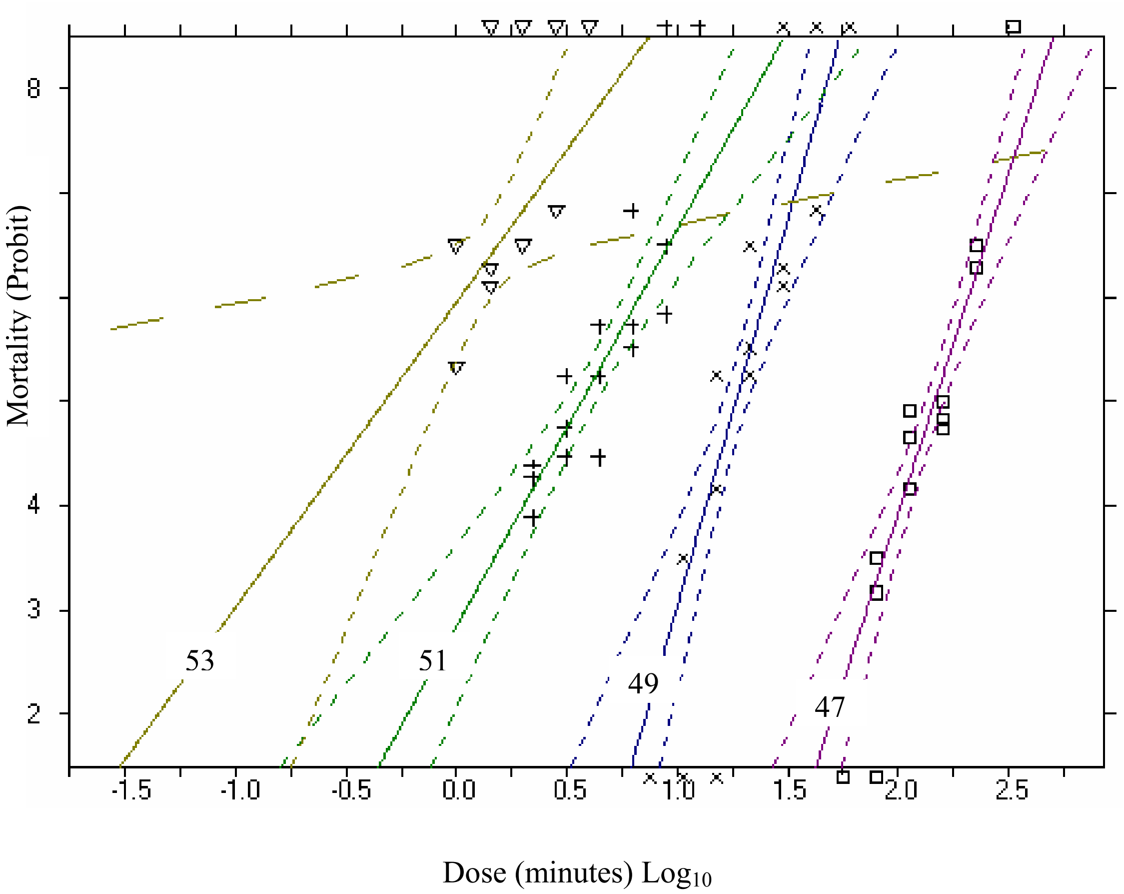
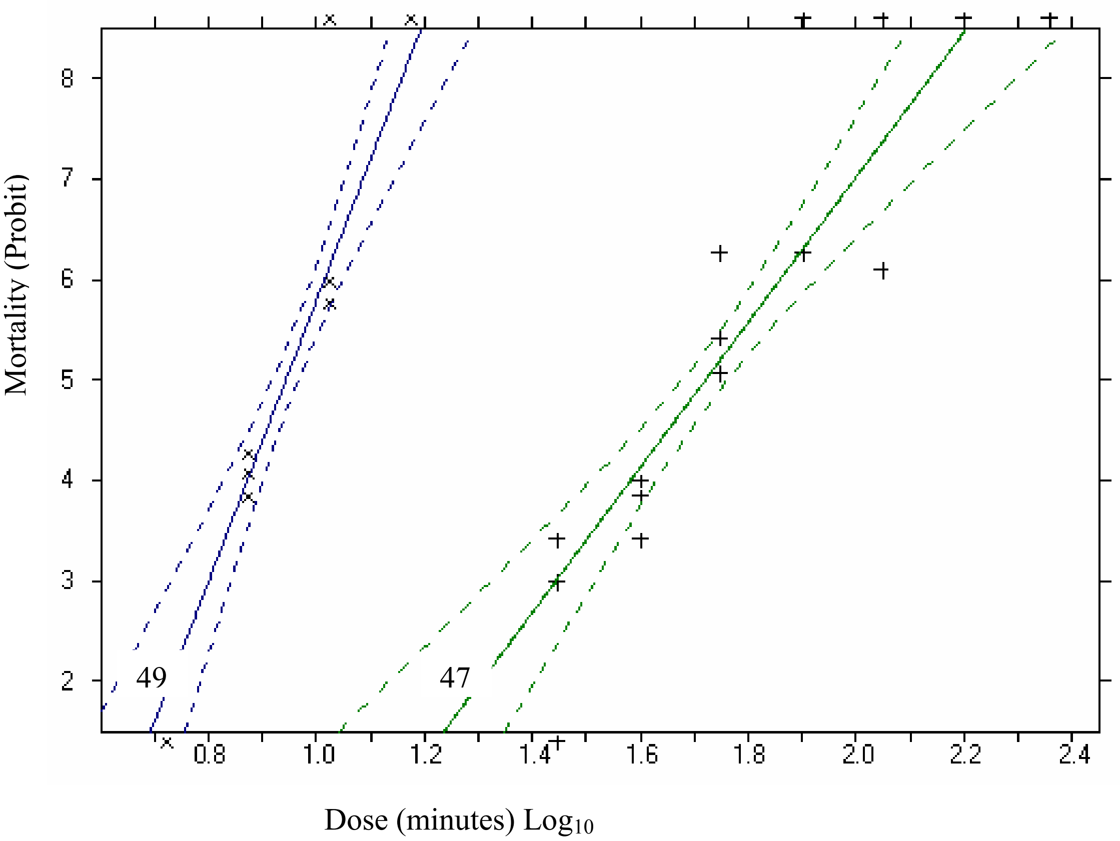


Figure 7. Laboratory exposures - The relationship between mortality and time for 4th instar larvae of *Tribolium confusum* at 47 (green line and crosses) and 49°C (blue line and Xs) (Probit 7.3 = 99% mortality)



DEVELOPMENT OF REAL TIME PROCESS MONITORING

Temperature measurements of various surfaces within the mills investigated have been made using a hand-held infrared thermometer (Omegascope Model OS530). These observations were keyed into a pc spreadsheet incorporating an insect death rate model that had been constructed from the laboratory data presented in the previous section and from the results of bioassays taken from various mills. The progress of the treatment is displayed on the pc for each location.

An instrument has been developed which combines these functions into a single hand-held tool. The progress of the treatment is displayed each time a temperature measurement is made. This information helps the operator to re-position heaters to optimise treatment uniformity and to confirm when a treatment has been completed.

The instrument uses infrared temperature measurement methods and has a keypad so that the operator can enter the identity of each measurement location. As well as storing the time, temperature and location information for the creation of a treatment report the processor uses the insect death model to calculate the current mortality at each monitoring point.

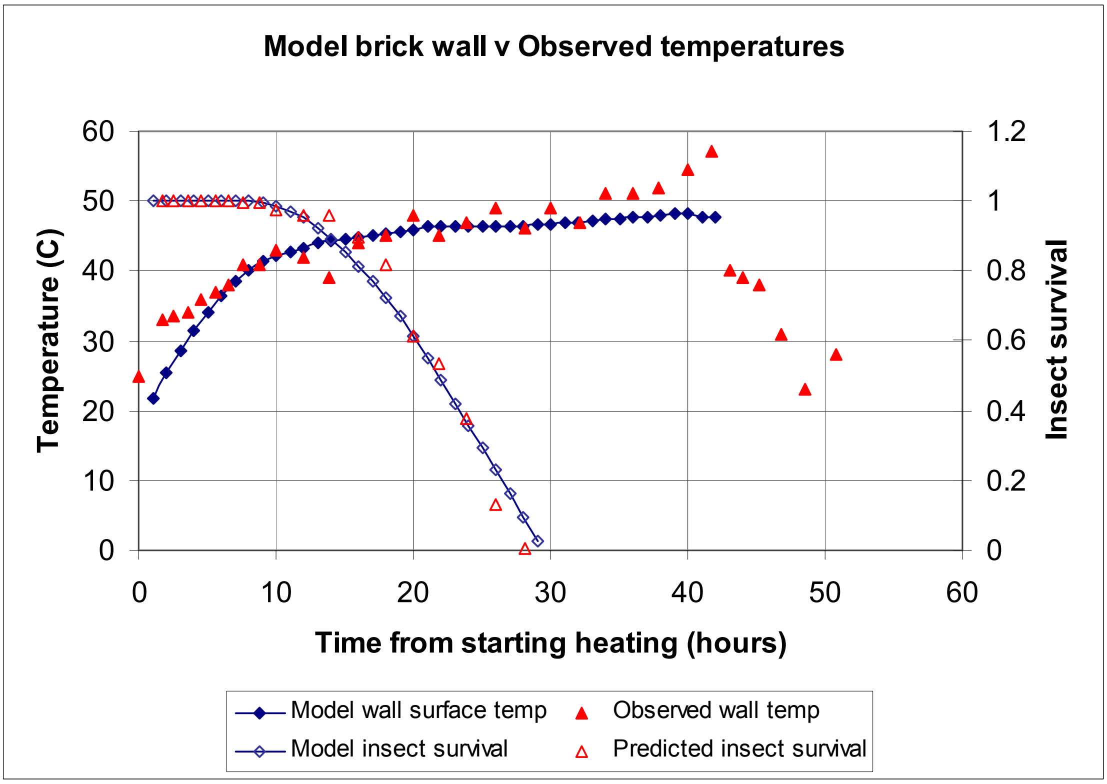
Thermal model validation

The thermal model of mill structures that was developed in the first part of this project from basic principles (Ede, 1967; Anon, 1987) has been used to estimate the speed at which different parts of the structure may heat and to identify those parts of the structure that may prove difficult to heat. By integrating the insect death model into the thermal model it has become possible to investigate killing times inside structures where temperature measurement is impractical.

Simple methods are adequate for estimating heating requirements but these procedures do not show the speed of response of the structure. Overall treatment times depend on the slowest heating part of the structure. The thermal model can be used to compare the effect of extra heaters with other alternatives like DE.

The thermal model uses thermo physical properties of the building components (Anon, 1970) and convective and radiative surface heat transfer coefficients to calculate the heating response of each type of building element bounding a heating zone. By adjusting the surface heat transfer coefficients, the model surface temperature predictions can be made to match the observed surface temperatures. When a match is found it can be assumed that the heat transfer coefficients used are representative of the actual process. The comparison chart also shows good agreement between the modeled insect death and that obtained by applying the insect death model to the observed temperatures (Fig. 8).

Figure 8. Comparison between observed and modeled surface temperatures and the results of applying the insect death model to these surface temperatures (In right hand scale 1 = 100% survival)

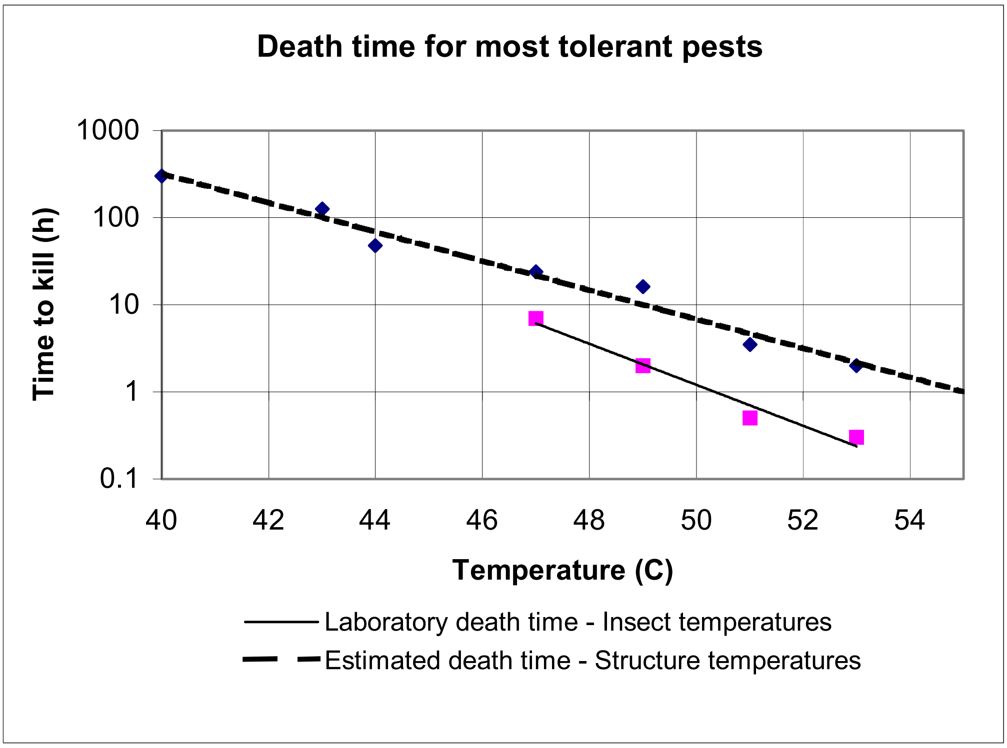


Modelling of insect death rates

Death rate model

The results of insect heating tests at CSL have been used to construct a model of insect death rate over the treatment temperature range. This model has been adapted to include the results of bioassays in mills under treatment and can be used to predict the death rate of the population at any given temperature (Fig. 9). By integrating the death rate based on regular temperature observations from control points in the mill it is possible to predict the proportion of the population that has been killed at any time during the treatment.

Figure 9. Killing time (logarithmic scale) and temperature for the most tolerant pests: Laboratory observations on three species and estimates based on bioassay response in mill trials. The dotted line shows the model prediction used in trial result analysis.



The insect death rate can be estimated from the killing time results:

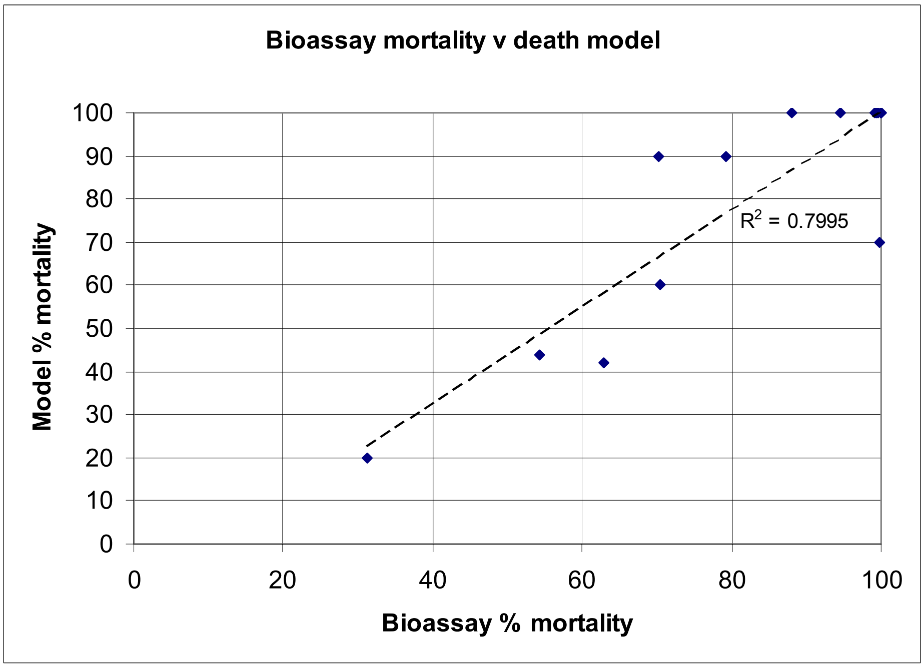
$dr = 430.72 * (t - 40)^{-1.802}$

dr fraction of the population dying in 1 hour

t average insect temperature in the range 40 to 55°C

The model predictions and the results of the bioassay have been compared where appropriate temperature records exist (Fig.10). The variability in these results highlight the importance of small variations in temperature over a few centimetres and the protection afforded by the food in the bioassays.

Figure 10. Comparison of bioassay results with the insect death rate model



APPLICATION OF COMPUTER MODELS

Killing times inside structures

Many building materials have small cracks in which insects may hide to escape the heating process. Outside walls will have a temperature gradient from treatment temperature (50ºC) on the inside to average ambient air temperature on the outside. The model can be used to investigate how far into the structure insects will be killed during a normal treatment period. Alternatively areas known to be infested can be specifically targeted with locally higher surface temperatures to ensure treatment goes deep enough into the fabric. Table 7 shows the predicted killing time in a 350 mm and 750 mm thick brick wall floor joint when a 60 W/m^2 wall floor heater is used to boost the surface temperature in the angle of the joint.

Steel is a good conductor of heat so where steel plates cover masonry any space between the masonry and the steel will reach treatment temperature. A more difficult situation occurs where bulk flour is against a heated steel plate (eg in a flour bin). Flour is a good insulator and the layers near the steel plate will quickly warm up but any insects present will be able to move away to cooler areas through the flour.

Table 7. Heat penetration of structures, Time to deliver a lethal heat dose at various depths in a range of building structures (hours)

Distance from inside surface (cm)	1	2	3	4	5	10
750mm brick wall floor joint	14	15	17	20	22	41
350mm brick wall floor joint	16	18	22	26	33	
Solid concrete ground floor	25	28	32	36	40	
Timber upper floor heated both sides	11	11				
Solid concrete upper floor heated both sides	15			16		17

Table 8 shows the killing times at various positions in flour in a steel bin heated from the outside predicted from using the thermophysical properties of flour established by Mohesenin (1980) and Bozikova (2003).

Table 8. Heat penetration rates into flour in two different containers

Heat penetration into bulk flour in a steel bin:

Distance from bin wall (cm)	1	2	3	4	5	6	7	8
Killing time (h)	13	15	19	24	29	36	42	49

Heat penetration into flour sacks (300mm thick) from both sides:

Distance from sack wall (cm)	1	3	5	8	15
Killing time (h)	13	19	23	27	29

Prediction of structure heating rates

Speed of treatment is critical in commercial applications. Insect death only starts when the temperature exceeds 40ºC. The structure can accept heat rapidly at the start of the heating process and at this stage there is little chance of overheating any sensitive parts of the building. Maximum heat input at this stage will shorten the warm-up time. Extra heater capacity increases the equipment costs and is only effective if there is good heat transfer to the building surfaces – rapid air movement, particularly over slow heating structures like concrete floors. There is little scope for reducing treatment time once the building has heated up.

The model has been used to calculate the time taken from the start of heating for the building surfaces to reach 40ºC with different heater capacities (Table 9).

Table 9. Time to heat to 40ºC (hours)

Heater capacity*	70%	100%	150%
Concrete ground floor	16	8	6
Brick wall (750mm thick)	14	7	4
Timber floor (heated from both sides)	8	3	1.5
Concrete floor (heated from both sides)	10	5.5	3
Average room air	6	2	0.5

* 100% capacity represents the normal heating design

DESCRIPTION OF TRIALS

The aim of the mill treatments was to demonstrate that commercially acceptable insect control can be achieved using heat in combination with, where appropriate, diatomaceous earth (DE) and insecticidal sprays. Treatments were designed to take no longer than a commercial methyl bromide fumigation which is normally 40 - 48 hours. The monitoring program was designed to expose weakness in the treatments by choosing locations where heating was expected to fail. Surface temperature records were taken at all monitoring locations at intervals throughout the treatment and these records were complimented by bioassays containing all stages of *Tribolium castaneum*.

Where possible DE was applied in locations where heating predictions showed that it would be unlikely that lethal temperatures could be achieved. Insecticidal sprays were applied to access points (e.g. stairwells) where insects might escape from the heat treatment.

Heating for the treatments was provided by 18 kW ThermoNox air heaters. These heaters are designed to heat up and then control room temperature at 50ºC. The heating elements operate at less than 200ºC to avoid risk of dust ignition. The air flow from these heaters is 1.04 m^3/s and the average air speed leaving the heater is 12.78 m/s.

Heating requirements were based on the steady state heat loss through the structure and an allowance for the heat stored in the structure to raise its temperature to 50ºC. Because the buildings are not sealed an allowance for heat loss due to air exchange was also included.

Effective heating of structures requires good heat transfer from the heating air to the structure surface. Surface resistance to heat transfer is significantly lower when there is active air movement over the surface. ThermoNox floor fans give enhanced heat transfer by blowing air directly down on to the floor. These fans extend the range of influence of the air heaters by ensuring good air circulation and return of cool air to the heater.

Wall floor joints have been identified as a problem to heat. Wall floor heaters have been developed to deliver hot air directly into the wall floor joint by means of perforated polythene ducts. Each fan heater delivers 0.19 m^3/s at 23 Pa and the 2.1 kW heater raises the air temperature by 9.4ºC. Each heater can service up to 20 m of wall floor joint. These heaters can produce a thermal cordon round the edge of the floor preventing insects migrating to cool harbourages at the wall floor joints.

The success of commercial treatments is difficult to establish in the short term. The level of infestation before treatment is difficult to quantify and the evidence of any live insects immediately after a treatment would be considered a failure. The only true measure of success is the length of period between successive treatments. Methyl bromide fumigation treatments normally produce an inter-treatment period of a year or more. The Ramsgate treatment produced an inter treatment period of 280 days. This represents 5.6 generations of *Tribolium castaneum* at average conditions of 25C and 60% r.h. (Howe, 1956).

The only short-term measures of success available are temperature monitoring during the process and the survival of bioassays at critical monitoring points in the mill. The temperature history of monitoring points is difficult to compare so an insect death model has been applied to these records to calculate the time taken to kill the population or estimate what fraction of the population has died by the end of the treatment. These results are presented on floor plans of the two mills so that the distribution of potential survivors can be seen. These floor plans, plans 1-5 for Ramsgate and 6 to 11 for Tilbury, are presented in the Appendix attached to this report.

Mill heating trial at Ramsgate

Building structure

The mill is housed in a 3078m^3 Victorian brick built structure 23.2m long, 8.1m wide and 16.4m high. Outside walls range in thickness from 230mm to 450mm. Each of the five floors has single glazed windows. The intermediate floors are timber. The rollers are located on the first floor and are driven by a line shaft running the length of the ground floor. The product lifts in this mill are by wooden cased elevators and steel chain conveyors

The ground floor is solid concrete and the roof of the building is of profiled steel sheet with bituminous felt weatherproofing.

Heating plan

The calculated heating requirement for the whole building was 219 kW with a 12ºC ambient and a 50ºC treatment temperature and 24-hour heating up time. Ten 18 kW ThermoNox heaters were used together with fourteen 2 kW wall floor heaters. These were deployed as set out in Table 10. The total heat input was 209 kW. Four ThermoNox floor fans were used to improve the circulation of the air on the ground, first and third floors. Wall floor heaters and polythene ducts were deployed on all the upper floors and in part of the ground floor.

Power for the heaters was provided by a hired generator (64 kW) and from the site power supply (144 kW) via two distribution boards. The heating period for the whole-site treatment was set at 42 hours.

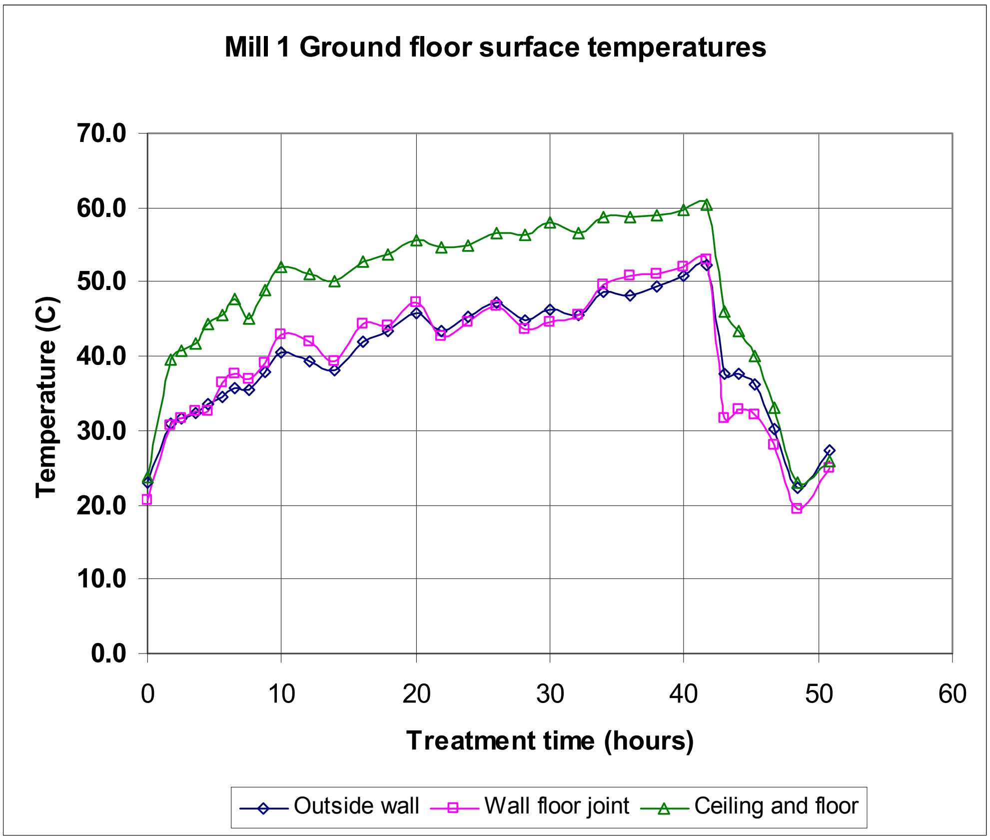
Temperatures achieved

The average surface temperatures on the ground and first floor of the Ramsgate mill during the treatment are shown in Figs 11 and 12. The total electrical energy consumption was 28425.6 MJ. (7896 kWh or 9.24 MJ/m^3). Air temperature in each of the 5 floors was raised to 50ºC. after 14 h (ground floor), 15 h (1st floor), 24 h (2nd floor), 30 h (3rd floor) and 24 h (4th floor). All timber and steel structures inside the mill received a lethal heat dose within 30 hours. All floors except concrete ground floor and all ceilings received a lethal heat dose within 30 hours.

Table 10. Heater deployment by floor at Ramsgate

Location	Steady State kW	Installed Heaters kW	Number of 18 kW heaters	Number of 2.1 kW heaters	Floor fan
Ground floor	73.35	76.2	4	2	2
Floor 1	28.24	42.3	2	3	1
Floor 2	28.45	24.3	1	3	
Floor 3	39.02	24.3	1	3	1
Floor 4	49.95	42.3	2	3	
Total	**219.01**	**209.4**	**10**	**14**	**4**

Figure 11. Structure heating of the ground floor at Ramsgate



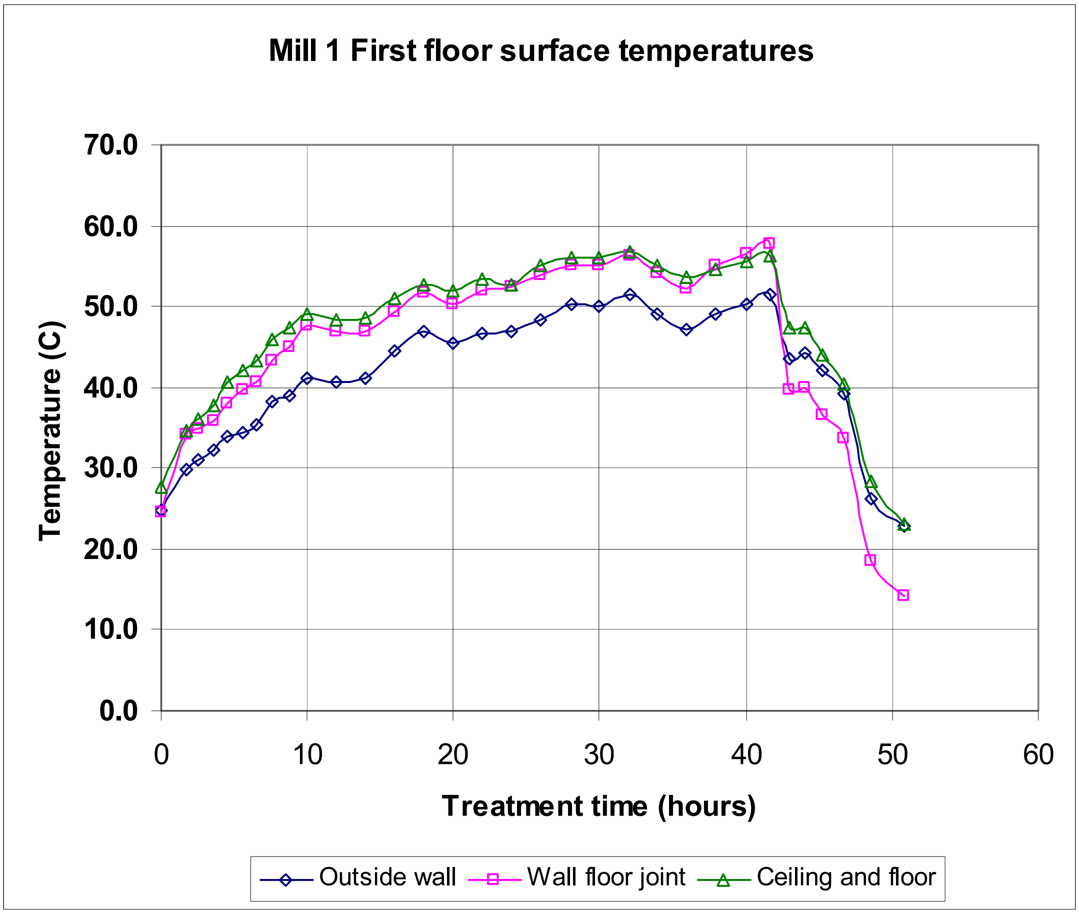
About 75% of the wall floor joint area received a lethal heat dose after 18 h. At the end of some ducts, in some corners and near floor fans where the polyducts were disturbed a lethal dose was not delivered. Ceiling/wall joint temperatures reached lethal levels in the ground and first floor but failed to do so on upper floors. The walls failed to reach lethal temperatures except in a few places.

Floor fans improved the distribution of heat and local rate of heat transfer. This was particularly important on the ground floor and on the 3rd floor where only one heater was used.

After 12 hours from the start of heating many insects emerged and began to die. After 26 hours few live insects were seen.

The mill cooled to below 30°C six hours after the end of heating.

Figure 12. Structure heating of the first floor at Ramsgate



Diatomaceous Earth Treatment

The day before start of the heat treatment the basement of flour of the mill was treated with diatomaceous earth (Silico Sec, Agrinova Gmbh, Mulheim, Germany) after the floor was cleaned and sprayed with insecticide. The target was not total coverage but the treatment of any harbourages and cracks in the lower walls, wall/floor joins and the floor itself. It was not possible to apply DE dusts to treat all dead spaces under the conveying system. The application was made with a hand-driven duster (Echo D-700, Kioritz Corporation, Japan) and a total of 40 g was used. It was applied to act as an initial control factor to prevent reinfestation from peripheral harbourages after the heat treatment.

Bags containing various developmental stages of the red flour beetle *T. castaneum* were placed in the mill on the following day, at the start of the heating process (Table 11). The bags were removed at the end of the trial after the two days of heating and cooling, and were returned to the laboratory the following day. All the bags were opened and transferred to glass jars (60 mm diameter x 120 mm high) after a count and removal of adults. The jars were then placed at 30^{o}C and 60% r.h. until all the adults had emerged.

Table 11. Bag number and position within the mill during heat treatment

Bag no.	Floor	Location
1 & 2	Ground	Entrance lobby on metal beam above position 86
3 & 4		Window ledge to left of position 97
5 & 6		Recess near floor above position 102 and below 101
7 & 8		Window ledge near corner and position 91
9 & 10	1st	In corner near position 59
11 & 12		On high wood rafter above position 61
13 & 14		Behind top of clock near position 65
15 & 16	2nd	On high shelf above position 41
17 & 18		On window ledge by position 44
19 & 20		On corner of bench behind screens above position 49
21 & 22	3rd	On wall bracket near corner and position 23
23 & 24		Just above floor in corner near position 31
25 & 26		On perforated platform above middle sifter
27 & 28	Top	On ledge above fire exit sign over door
29 & 30		On window ledge near position 15
31 & 32		On high girder between stairs and corner (position 9)
33 & 34		On brush shelf to left of position 7

The counts are shown in Table 12. They show that larvae stage IV and pupae are the most tolerant stage. The heat treatment was effective at treating the timber floors and all the machinery. There was gave little or no control at locations around the periphery of the building. Live insects were seen in a cool corner of the ground floor after treatment. None were seen in the rest of the mill during cleaning and re-assembly.

The bioassays confirmed that the timber floors and machinery were effectively treated but that the outer walls, window ledges and other sheltered locations provided a safe refuge where high levels of survival were observed. The stage IV larvae and pupae were confirmed as being the most heat tolerant developmental stage.

Table 12. Adult mortality and emergence of *Tribolium castaneum* in 2 separate age categories after heat treatment from 50 g flour placed in nylon mesh bags and their location within the Mill

		Adults, eggs and younger larvae			Larvae stage IV and pupae	
Bag no.		% Adult mortality*	Adult emergence	% Reduction in emergence	Adult emergence	% Reduction in emergence
Control		2.0	420	-	849	-
1 & 2	Ground	100	0	100	0	100
3 & 4		0	203	52	771	0
5 & 6		0	296	30	788	0
7 & 8		0	186	56	734	0
9 & 10	1st	20.4	103	76	334	61
11 & 12		100	1	99.8	15	98
13 & 14		100	0	100	6	99
15 & 16	2nd	100	0	100	3	99.6
17 & 18		5.2	252	40	471	44
19 & 20		21.9	124	70	473	44
21 & 22	3rd	100	1	99.8	22	97
23 & 24		100	4	99	17	98
25 & 26		100	0	100	19	98
27 & 28	Top	100	1	99.8	93	89
29 & 30		0	522	0	652	23
31 & 32		5.1	178	58	506	40
33 & 34		100	0	100	0	100

* % Mortality (Treated mortality corrected for control mortality)

Mill heating trial at Tilbury

Building structure

The mill and flour bin base is housed in a 6600 m^3 reinforced concrete framed structure with brick infill external wall panels. Only the top floor has double-glazed windows. The plant is supported on 5 levels but much of the intermediate timber floors are cut away allowing easy air exchange between floors. Much of the perimeter of the upper floors does not connect with the external wall so the wall floor joint is eliminated. The rolls stand directly on the ground floor which is solid concrete overlaid by woodblock. Product is moved throughout the plant by conventional pneumatic lifts and screw conveyors.

Heating plan

The overall heating requirement was calculated to be 351 kW. Heat was provided by eighteen ThermoNox 18.75 kW heaters and fifteen 2.2 kW wall floor heaters. Heat distribution was assisted by five ThermoNox floor fans and three 1.2 m dia stirring fans. The deployment of heaters and fans is summarized in Table 13.

Table 13. Heater and fan deployment by floor at Tilbury

Location	**Calculated heating requirement kW**	**Installed heater capacity kW**	**Number of 18.75 kW heaters**	**Number of 2.2 kW heaters**	**Number of fans**
Ground floor (rolls)	75.16	100.35	5	3	2FF
Spout floor	30.38	41.90	2	2	1SF
Purifier floor	32.12	41.90	2	2	1SF
Sifter floor	43.58	39.70	2	1	1SF
Cyclone floor (top)	69.05	62.85	3	3	
Total	**250.29**	**286.70**	**14**	**11**	**2FF 3SF**
Bin base	100.92	83.80	4	4	3FF
Overall total	**351.21**	**370.50**	**18**	**15**	**5FF 3SF**

FF = ThermoNox floor fan SF = Stirring fan

The maximum heat input rate of 370.5 kW was provided by a 500 kW generator. Power was distributed to the mill and the bin base area by separate distribution panels.

Wall floor heating ducts were positioned where there was a wall floor joint. In three corner areas on three floors stirring fans were used in place of wall floor heaters.

DE and chemical spray treatment

Previous experience and modeling has shown that some parts of the building can never be effectively heated to lethal temperatures. During an earlier project tests at CSL have shown that DE is effective against adult insects at 30ºC and continues to be effective for weeks after the treatment (Bell et al., 2004) and so will kill emerging adults not killed as eggs, larvae or pupae by the heat.

Certain areas of the mill were treated with diatomaceous earth (Silico Sec, Agrinova Gmbh, Mulheim, Germany) after the cleaning was completed. The target was not total coverage but the treatment of any obvious harbourages with a dose of 5 g/m^2. On the ground floor the cable duct and supporting plinth below the roller mills on the ground floor showed evidence of infestation and was treated with DE. Hatches were opened in the tops of the plinths for the roller millsand the DE was injected through these. The dead space behind the holding bin that went from the top flour to the first floor was treated because there was no chance of heating this part of the structure to 50ºC, though this proved difficult as various materials such as polystyrene sheets had been put in there to fill the gap. However every effort was made to inject DE into any crack that was found. The application was made with a carbon dioxide (CO_2)-driven duster (GPS 'Gaspot', Killgerm Chemicals Ltd, West Yorkshire, UK) with a 5 mm application tube. This was easier to use than the hand-driven duster (Echo D-700, Kioritz Corporation, Japan) which had been employed at the Ramsgate mill trial. Although not ideal for small applications in open spaces the CO_2-driven duster did limit the amount of dust thrown into the air as compared to the hand-driven applicator.

A population of adult *Tribolium* sp. was observed under the roller mills and their movement ceased after a few hours with heating. This was only a qualitative observation on the effectiveness of the DE as its effect could not be quantified because no bioassays were used to check the efficacy of the treatment.

Before the heat treatment, chemical insecticide sprays were applied to doorways and lift access on the mill floors to prevent adult insects escaping from the heat. Ground floors below the bin bases were not heated so these were sprayed with insecticide to kill any insects falling from the bin base floor above.

Open and closed sifter comparison

It has been claimed that it is unnecessary to dismantle sifters to ensure an effective thermal disinfestations (Hans Hoffmeir, ThermoNox). Considerable time and effort could be saved if this is shown to be true. A comparison was made between open and closed sifters. All the sifters were taken apart and cleaned then four were re assembled before the heating started. The fifth was left open. Bioassays and temperature sensors were placed in open and closed sifters.

Temperatures achieved

Figs 13 and 14 show the surface temperatures measured on the ground and sifter floor during the treatment. Whereas on the ground floor no surface reached a temperature of 50°C during the treatment, floors and ceilings of the first floor and upwards through the mill to the floor of the top floor reached 50°C by the end of the first day of heating.

Figure 13.

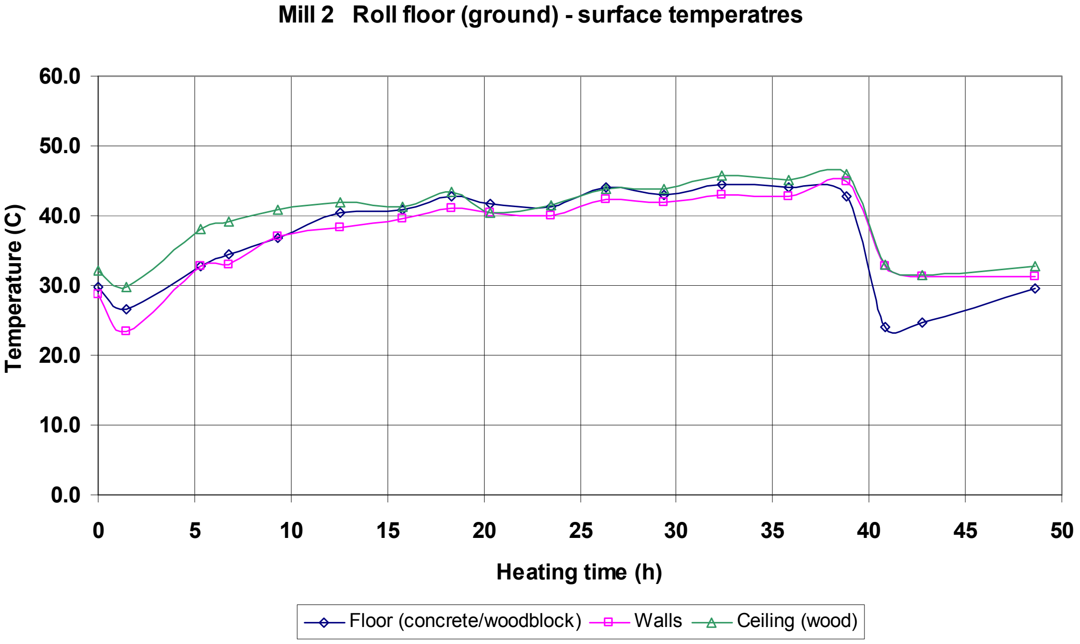
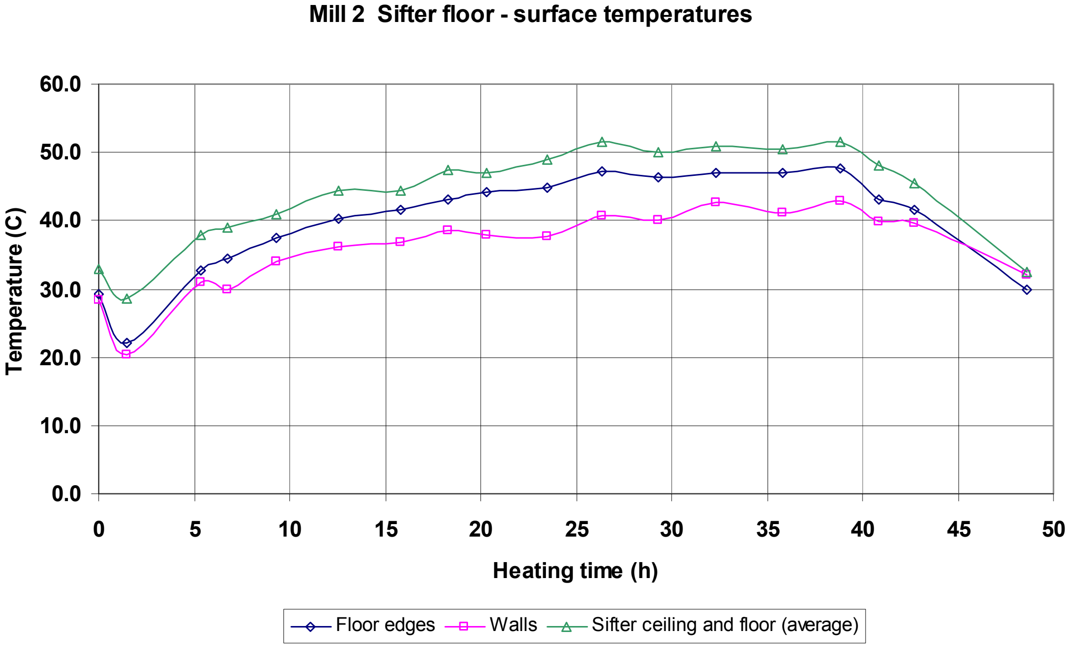


Figure 14.



Results for the insect bioassay

The control results are shown in Table 14. All the comparisons between the laboratory and site control bags showed no significant difference ($p>0.05$). This meant that they could be combined for each comparison and a mean was produced for all ten bags. The results from the treated bags show that an adequate number of each developmental stage would have been available for testing in each of the treated bags.

Table 15 shows the results for the treated bags and a mean has been produced for percentage mortality and percentage emergence reduction at each position. There was not much difference in the emergence reduction between the floors. The important factor was the position of the samples on the floors and the time of the samples' removal. Of those removed after 30 hours only H in the dismantled sifter on the 3rd floor and T on a pipe near an inside wall on the ground floor had emergence reduction over 90%. The samples in the reassembled sifter on the 3rd floor and in the that were taken out at 30h (sample J) showed much high levels of survival, indicating that is was best to leave the sifters dismantled for treatment. Samples I and K left in the dismantled and reassembled sifters for the full treatment time showed no survival. The temperature records for the sifters showed clearly why survivals were recorded (Fig.15). Therefore the 40-hour exposure was shown to be required. Even with this exposure only 7 positions throughout the mill gave a complete reduction in emergence and these were all within machinery.

Table 14. The mean number of adults present (±S.E.), the mean number of adult emergence post-heat treatment (±S.E.), and the mean number of pupae and larvae present at treatment (±S.E.) in the control bioassay bags kept at CSL and taken to the ADM Mill at Tilbury

Sample	**At Treatment**				**Post-Treatment**
	Adults	Pupae	IV Larvae	Total Immature	Adult Emergence
Control (Lab)					
A	398	344	376	720	667
B	420	336	291	627	637
C	381	331	254	585	625
D	527	368	202	570	602
E	524	338	227	565	616
Average (±S.E.)	450 (31.4)	343.4 (6.5)	270 (30.3)	613.4 (28.8)	629.4 (11.0)
Control (Site)					
A	438	405	290	695	665
B	325	378	248	626	702
C	426	376	415	791	718
D	439	329	267	596	641
E	423	293	277	570	608
Average (±S.E.)	410.2 (21.5)	356.2 (20.0)	299.4 (29.7)	655.6 (39.8)	666.8 (20.0)
Combined Av. (±S.E.)	**430.1 (19.1)**	**349.8 (10.1)**	**284.7 (20.6)**	**634.5 (24.2)**	**648.1 (12.4)**

Any locations with cracks or dead spaces where there is a high probability of survival such as around the periphery of the building or adjacent to a heat sink such as the concrete structure of the building should be a target area for diatomaceous earth (DE). An application before the trial would be beneficial as the insects are active and more likely to take on the dust. This rapid movement and displacement from their locations due to the heat also shows areas of treatment with DEs that are obvious targets for application during the trial and should be recommended for all future heat treatments.

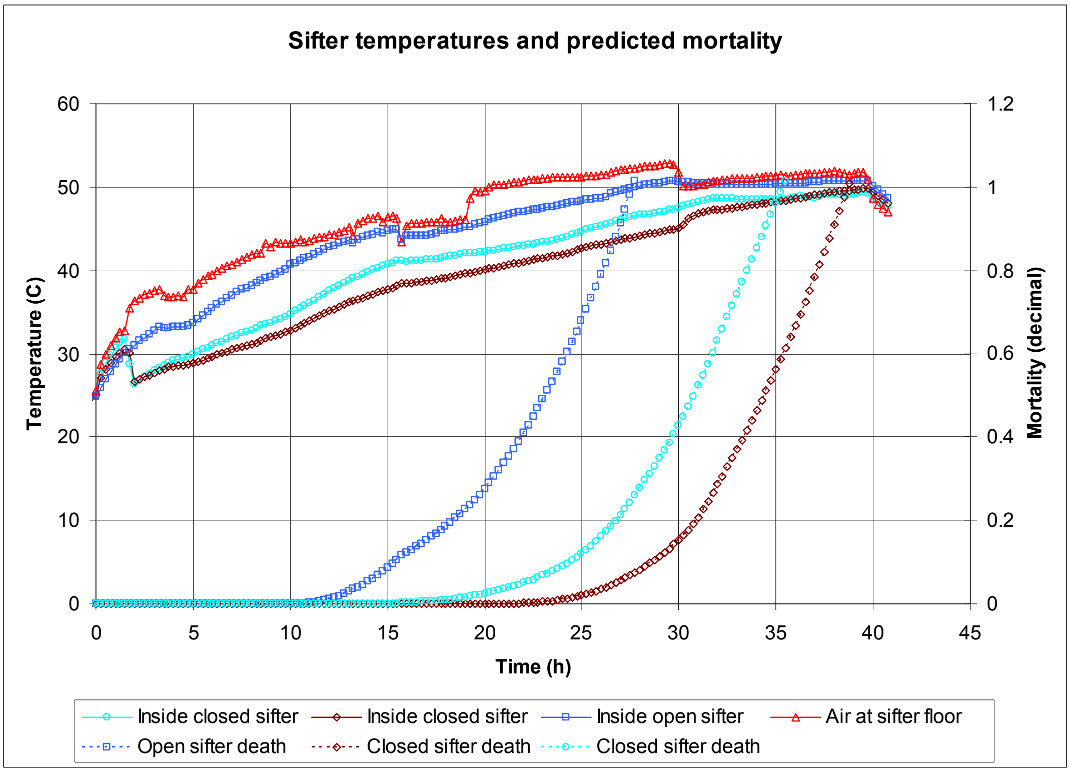
Table 15. Percentage adult mortality and percentage mean emergence reduction from the bioassay bags placed in the ADM Mill, Tilbury after heat treatment

Floor	Position	Sample	Exposure time	% Adult mortality	Mean % adult mortality	% emergence reduction	Mean % emergence reduction
4th	A	1	40	100	100.0	100.0	100.0
		2	40	100		100.0	
	B	3	40	100	100.0	99.8	99.6
		4	40	100		99.4	
	C	5	40	100	100.0	87.3	88.0
		6	40	100		88.7	
	D	7	30	100	100.0	84.4	79.3
		8	30	100		74.2	
3rd	E	9	40	0	0.0	69.1	70.1
		10	40	0		71.0	
	F	11	40	53.4	76.7	65.9	55.9
		12	40	100		45.8	
	G	13	40	100	100.0	59.1	69.7
		14	40	100		80.2	
	H	15	30	100	100.0	94.6	94.6
		16	30	100		94.6	
	I	17	40	100	100.0	100.0	100.0
		18	40	100		100.0	
	J	19	30	33.4	48.3	59.3	62.9
		20	30	63.2		66.5	
2nd	K	21	40	100	100.0	100.0	100.0
		22	40	100		100.0	
	L	23	40	39.5	38.0	56.8	58.2
		24	40	36.4		59.6	
	M	25	40	89.3	82.6	66.2	70.2
		26	40	75.9		74.2	
	N	27	30	100	100.0	70.2	62.7
		28	30	100		55.1	
	O	29	40	100	100.0	99.8	99.2
		30	40	100		98.5	
1st	P	31	30	100	100.0	64.7	69.2
		32	30	100		73.8	
	Q	33	40	100	100.0	95.2	85.4
		34	40	100		75.6	
	R	35	40	0	0.0	100.0	100.0
		36	40	0		100.0	

Table 15. (Continued)

Floor	Position	Sample	Exposure time	% Adult mortality	Mean % adult mortality	% emergence reduction	Mean % emergence reduction
Ground	S	37	40	53.4	76.7	51.2	54.4
		38	40	100		57.6	
	T	39	30	100	100.0	100.0	99.4
		40	30	100		98.8	
	U	41	40	100	100.0	100.0	100.0
		42	40	100		100.0	
	V	43	30	100	100.0	33.0	31.2
		44	30	100		29.3	
	W	45	40	33.4	48.3	99.5	99.8
		46	40	63.2		100.0	
Bin Bottoms	X	47	40	100	100.0	100.0	100.0
		48	40	100		100.0	
	Y	49	40	39.5	38.0	68.7	70.5
		50	40	36.4		72.4	

Figure 15. Open and closed sifter comparison: Temperature profiles and predicted insect mortality (two monitoring positions in closed sifter, one only in open sifter)



Conclusions

- All the wooden upper floors and machinery in the mill building received a lethal heat dose.
- It proved impossible to heat the ground floor of the mill and most external walls to lethal temperatures.
- Bioassay results confirmed that 40 hours was necessary for the heat treatment and that further improvements in insect control would result from extending the treatment time to, say, 48 hours.
- Good agreement was found between the bioassay results and the insect death model based on temperature monitoring, confirming that temperature measurements can be used to estimate local treatment end points.
- Temperature records and computed insect mortality inside the open and closed sifters shows that fully assembled sifters can be treated within the 40-hour heating period.
- Fully assembled sifters and purifiers were effectively treated in 38 hours. Unassembled sifters took only 28 hours to treat.
- DE was shown to be very effective in killing adult insects where it was used under the roller mills. Its use in other parts of the structure where heating is difficult could improve the overall effectiveness of the treatment.
- Ceiling fans were an effective replacement for wall floor joint heaters in the corners of the building where they were used. Wall floor heaters were shown to be mainly effective but were limited in corners where the ducts have to be realigned.
- During the 40-hour treatment 56448 MJ (15680 kWh or 8.55 MJ/m^3) was consumed by the heaters. The average rate of heat input was 313 kW, 85% of the installed capacity.

Recommendations

1. Use DE for ground floors and some wall floor joints

It is clear that it will never be practical or economic to heat ground floors to a level that will ensure 100% kill of all insects present there.

DE is effective within a 24-hour treatment time at 30ºC or above and should be applied to ground floors and wall/floor joint margins on upper floors to treat these parts of the structure.

Supplementary treatments with DE could also be applied during the course of a heat treatment when cool areas are detected as a result of routine monitoring.

2. Treatment time

Initial preparations for a heat treatment can be made while the mill is still running and heating can commence after shutdown as soon as cleaning operations permit. In the current trials a 40-42 hour heating period was followed by an 6-8-hour period for cooling and reassembly prior to restarting the mill.

It took about 20 hours to heat the Tilbury structure to 40ºC so, in this treatment, lethal temperatures were maintained for 20 hours. The results from the bioassays confirm that the 40-hour treatment improved the kill rate over that obtained at 30 hours. The treatment would have been even more effective if lethal temperatures had been maintained for a further few hours.

It is recommended that future treatments should be based on the maintenance of lethal temperatures for at least 24 hours and preferably 30 hours. Overall treatment times will depend on the speed of heating which in turn will depend on the cost benefit of using more heaters.

PROSPECTS FOR COMMERCIAL IMPLEMENTATION

The trials at Tilbury and Ramsgate provided the opportunity to assess the likely costs and commercial charges of carrying out treatments to these mills using this or a very similar specification, or in similar type/size of mill buildings elsewhere.

The actual costs incurred and paid for at both mills, have been added to the estimated commercial charge for the actual amount of labour used/required, all as detailed below in Table 16.

Table 16. Heat treatment costs

Actual costs incurred	**Tilbury**	**Ramsgate**
Generator hire:	£1690	£1028
Thermonox heater hire	£5969.50	£3620
Electricians labour	£240	-
Total	£7899.50	£4648
Other costs		
Labour **Tilbury** Preparation – 3 men x 3 days (inc application of DE) Treatment – 3 men x 40 hours (2 on duty at any one time) Removal of equipment from mill – 3 men x 8 hours **Ramsgate** Preparation – 2 men x 2 days (inc application of DE) Treatment - 3 men x 40 hours (2 on duty at any one time) Removal of equipment from mill – 2 men x 8 hours *Total estimated labour charge for above (plus or minus 20% depending on hourly rate)*	£7500	£5000
Transport costs – 2 vehicles, total 500 miles at £0.40 per mile	£200	£200
Subsistence	Approx £300	Approx £300
Total of other costs:	£8000	£5500
Total Costs:	**£15,900**	**£10,168**
Profit on commercial treatments In a commercial treatment the actual costs alone are not the totality of the charge made by contractors as company overhead and profit charges must be taken into account. These are generally set at about 5/10% of the total cost.	£800/£1600	£500/£1000
Estimated total commercial treatment charge for heat treatment on the basis of this trial and specification:	**£16,700 - £17,500**	**£10,620 - £11,148**
For comparison the charge for methyl bromide fumigation of this mill by the Contractor in 2004 was:	**£7840**	**£4710**

Economic assessment

It can therefore be seen that the adoption of heat as an alternative strategy to methyl bromide as a whole site treatment method for flour mills incurs a significant cost increase. It is unlikely that costs alone would be the principal obstacle to the adoption of heat as a control strategy, the overriding factor will always be the extent to which practical results at each site can build confidence in the likely efficacy of the heat treatment process and its supporting measures.

Concluding remarks

- The milling industry has been very supportive of the project and has expressed active interest in considering the use of heat as an important component of intergrated pest control treatments in flour mills.
- Heat alone will not provide a satisfactory treatment but only in combination with insecticide (spray) and desiccant dust (diatomaceous earth), the latter for use in plinths and voids.
- A heat application with a target temperature of 50°C will need to be maintained for over 40 hours to allow time for an even distribution of heat (+/- 1-2°C) to be achieved thoughout the mill structure for a sufficient time to kill pests.
- As the work carried out has been limited to mill sizes below 7,000m3, the scaling up of this work to larger mills is untested.
- Success of the heat treatment will be dependent on the building, its design and construction.
- Future uptake will depend on the cost and perceived effectiveness of heat treatments compared with available alternatives. The reduced availability of methyl bromide for mill fumigation may further alter the balance in favour of heat.
- At least one service provider is equipped to deliver mill heat treatments.

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APPENDIX

Charts 1-11 are result summaries as shown on plans for each floor of each mill. In charts 1-5 for Ramsgate, bioassay results are shown in blue and the mortality of adult, eggs and stages I & II, Stage IV and pupae are shown below the location description. Temperature monitoring results have been analysed using the death model. Numbers greater than 1 are the estimated time (hours) to kill 100% of the population. Figures less than 1 show the fraction of the population estimated to have survived by the end of the treatment. The shape of the label indicates where on the structure the measurements were made.(see key)

In charts 6-11 for Tilbury the bioassay results are shown in red. The sample identification letter is followed by the percentage mortality (all life stages). Some of the samples were removed after 30 hours of heat treatment and this is also indicated in the label. Temperature monitoring results are shown in blue and black. The blue identifiers show those locations were the death model predicts insect survival. The figure shown is the percentage mortality. The black identifiers show the locations where the death model predicts 100% mortality before the end of the treatment. The figure is the number of hours to achieve 100% mortality.

Chart 1. Ramsgate ground floor

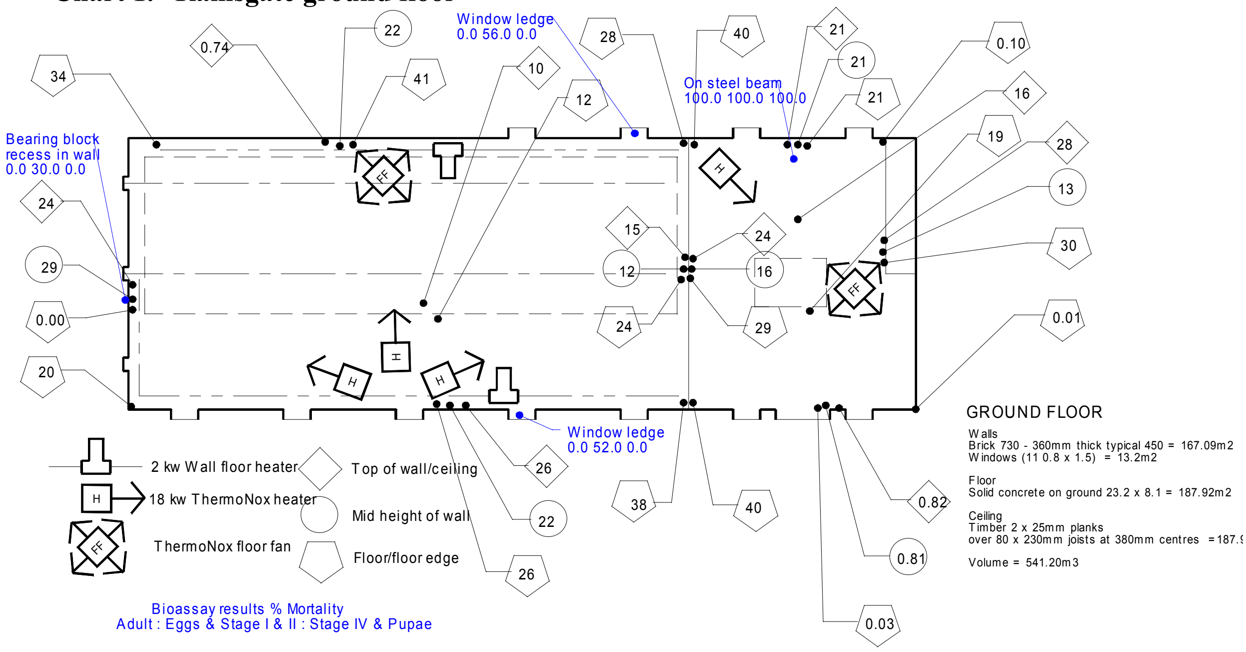
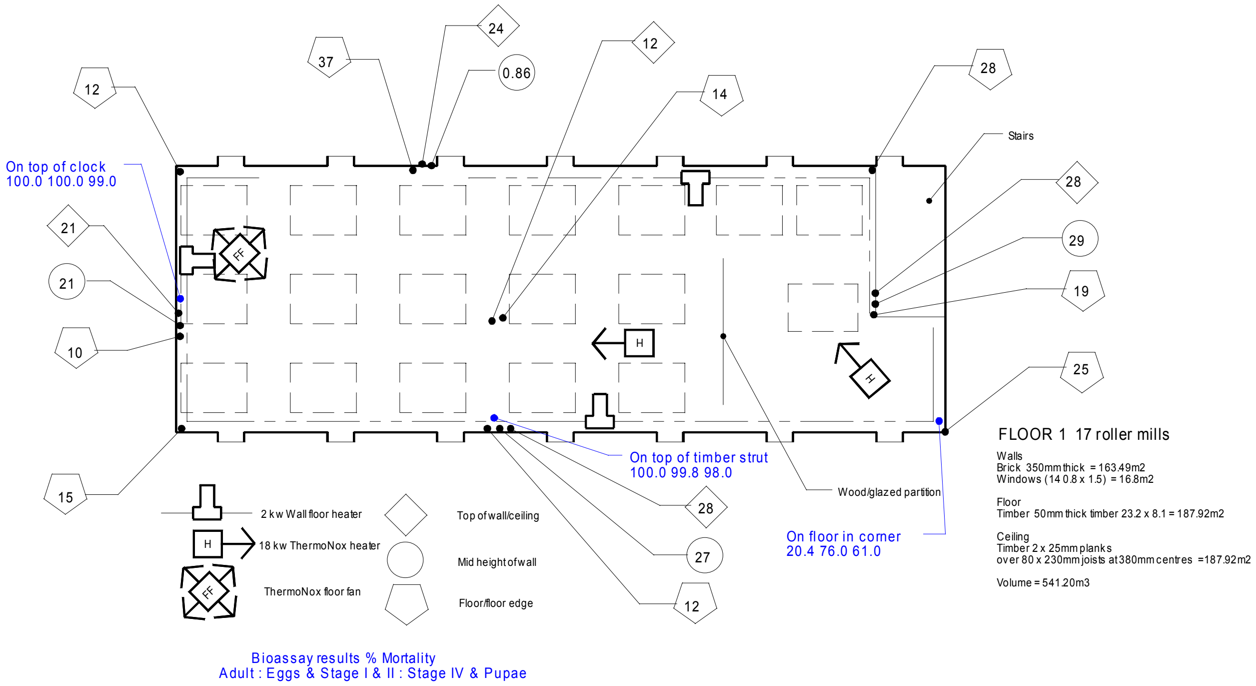


Chart 2. Ramsgate 1st floor



FLOOR 1 17 roller mills

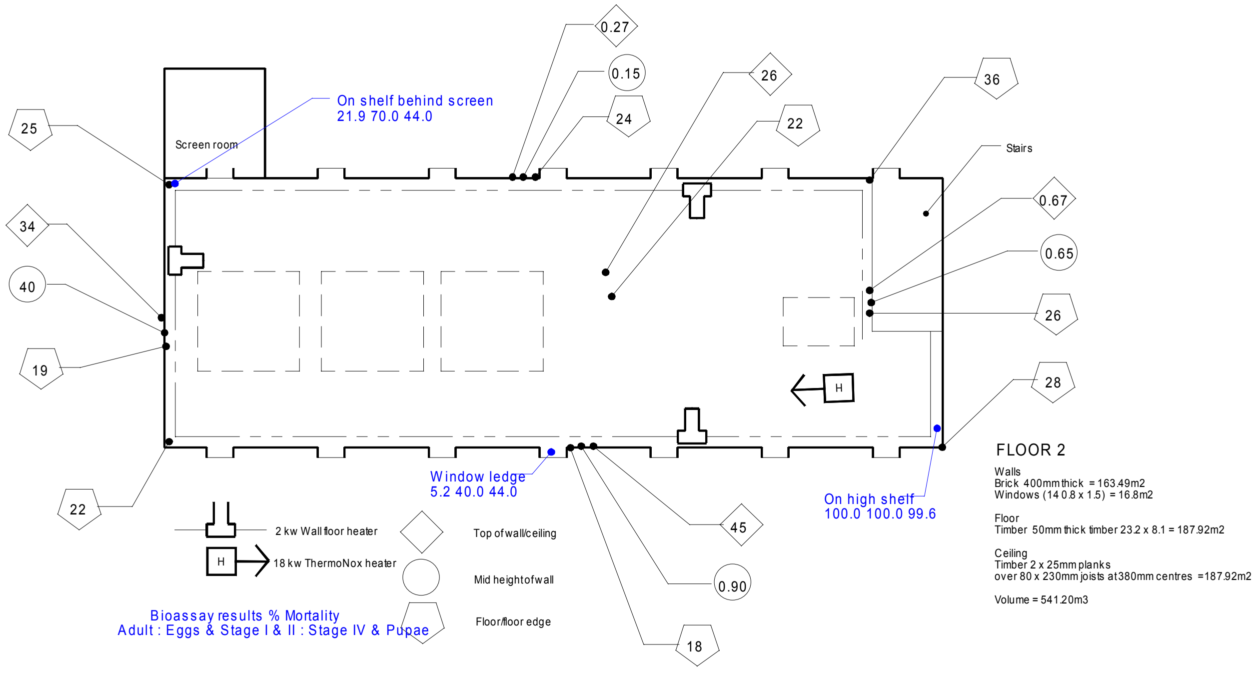
Walls
Brick 350mm thick = 163.49m2
Windows (14 0.8 x 1.5) = 16.8m2

Floor
Timber 50mm thick timber 23.2 x 8.1 = 187.92m2

Ceiling
Timber 2 x 25mm planks
over 80 x 230mm joists at 380mm centres = 187.92m2

Volume = 541.20m3

Chart 3. Ramsgate 2nd floor



FLOOR 2

Walls
Brick 400mm thick = 163.49m2
Windows (14 0.8 x 1.5) = 16.8m2

Floor
Timber 50mm thick timber 23.2 x 8.1 = 187.92m2

Ceiling
Timber 2 x 25mm planks
over 80 x 230mm joists at 380mm centres = 187.92m2

Volume = 541.20m3

Chart 4. Ramsgate 3rd floor

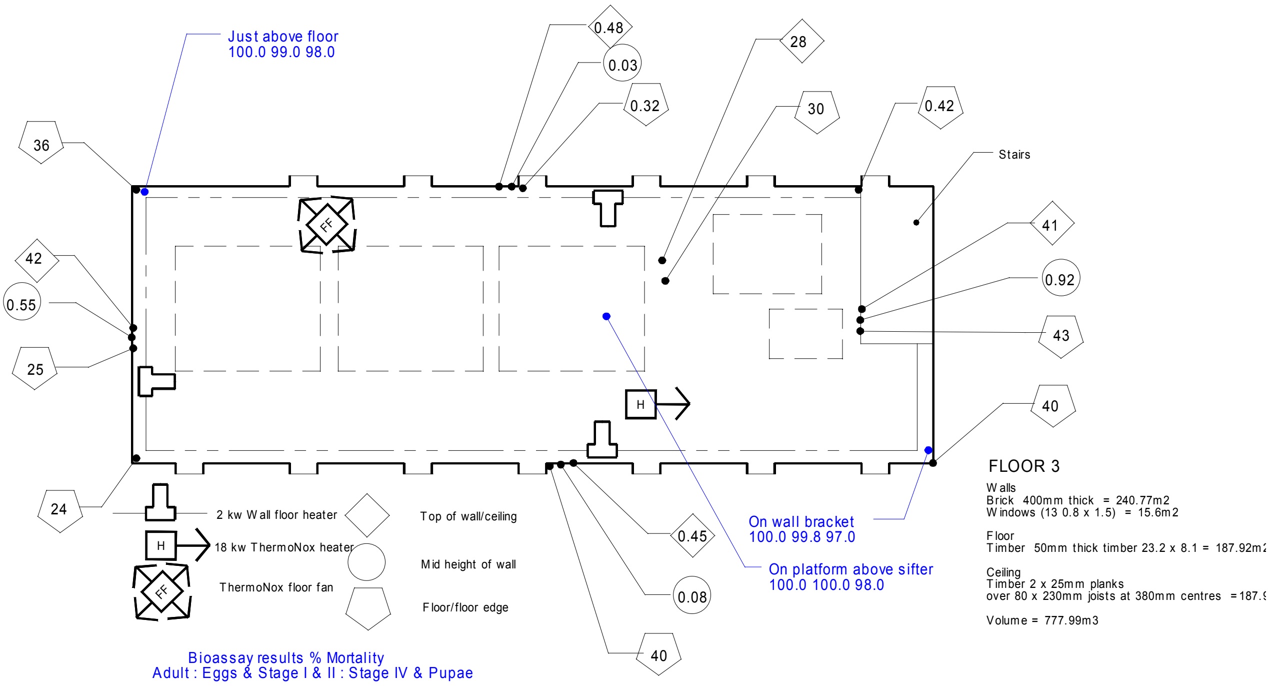


Chart 5. Ramsgate 4th floor (Top)

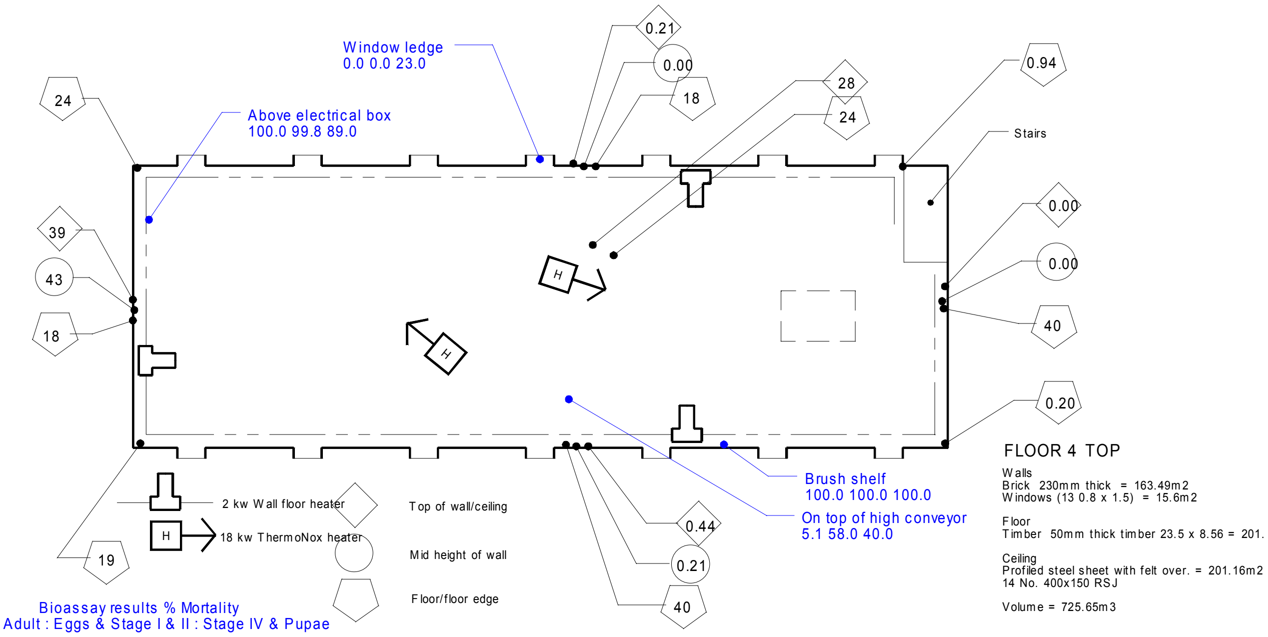


Chart 6. Tilbury ground floor

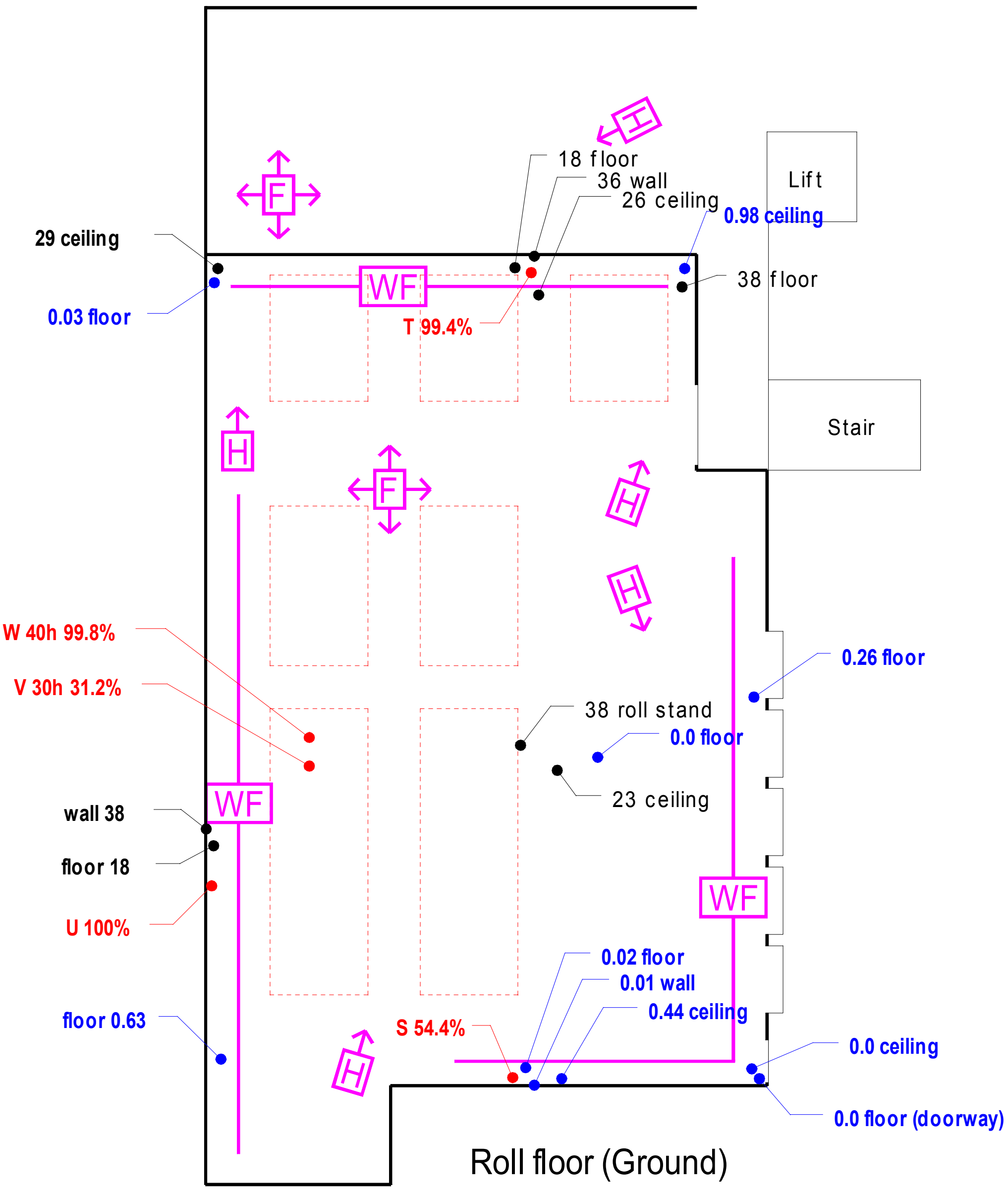


Chart 7. Tilbury 1st floor

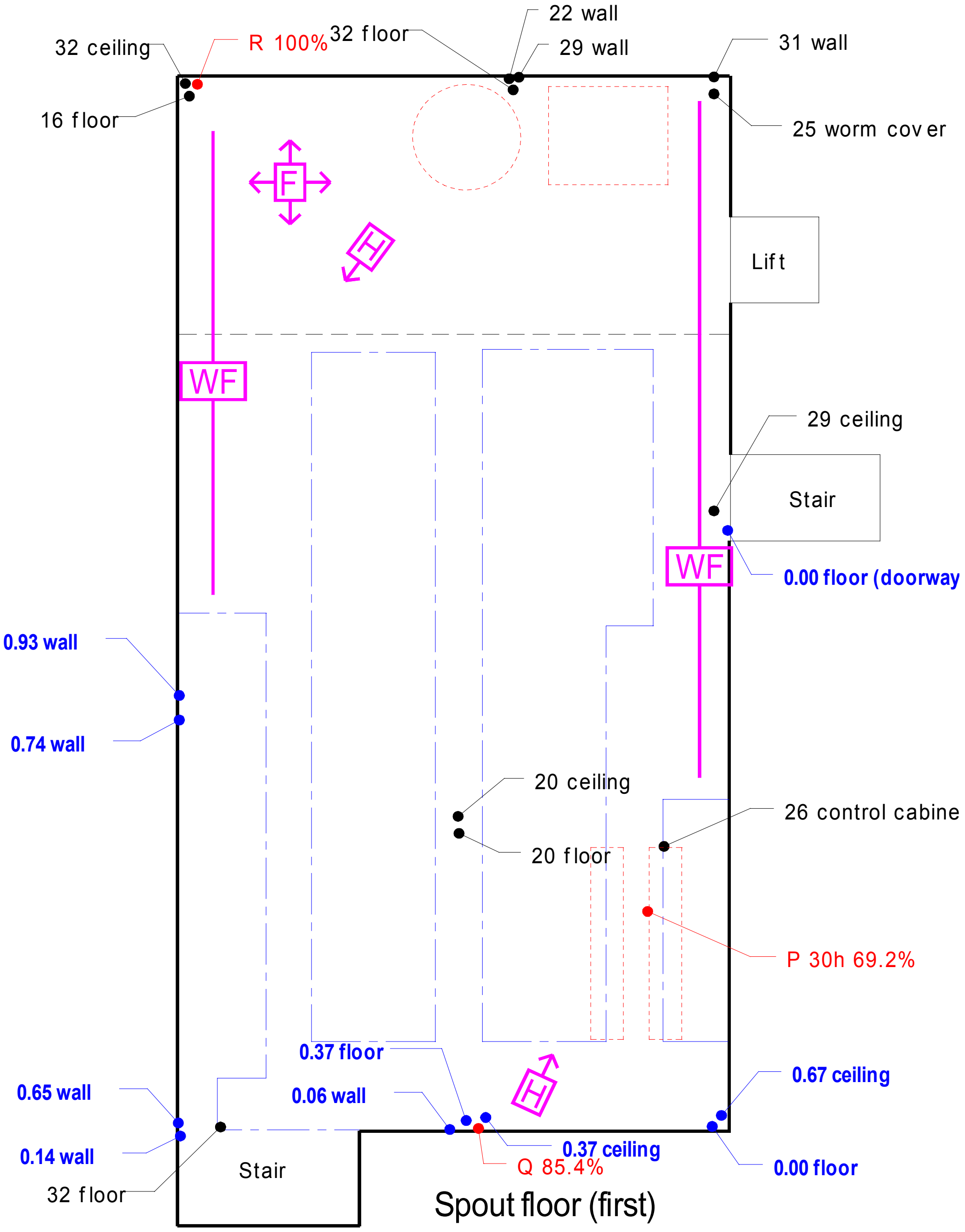


Chart 8. Tilbury 2nd floor

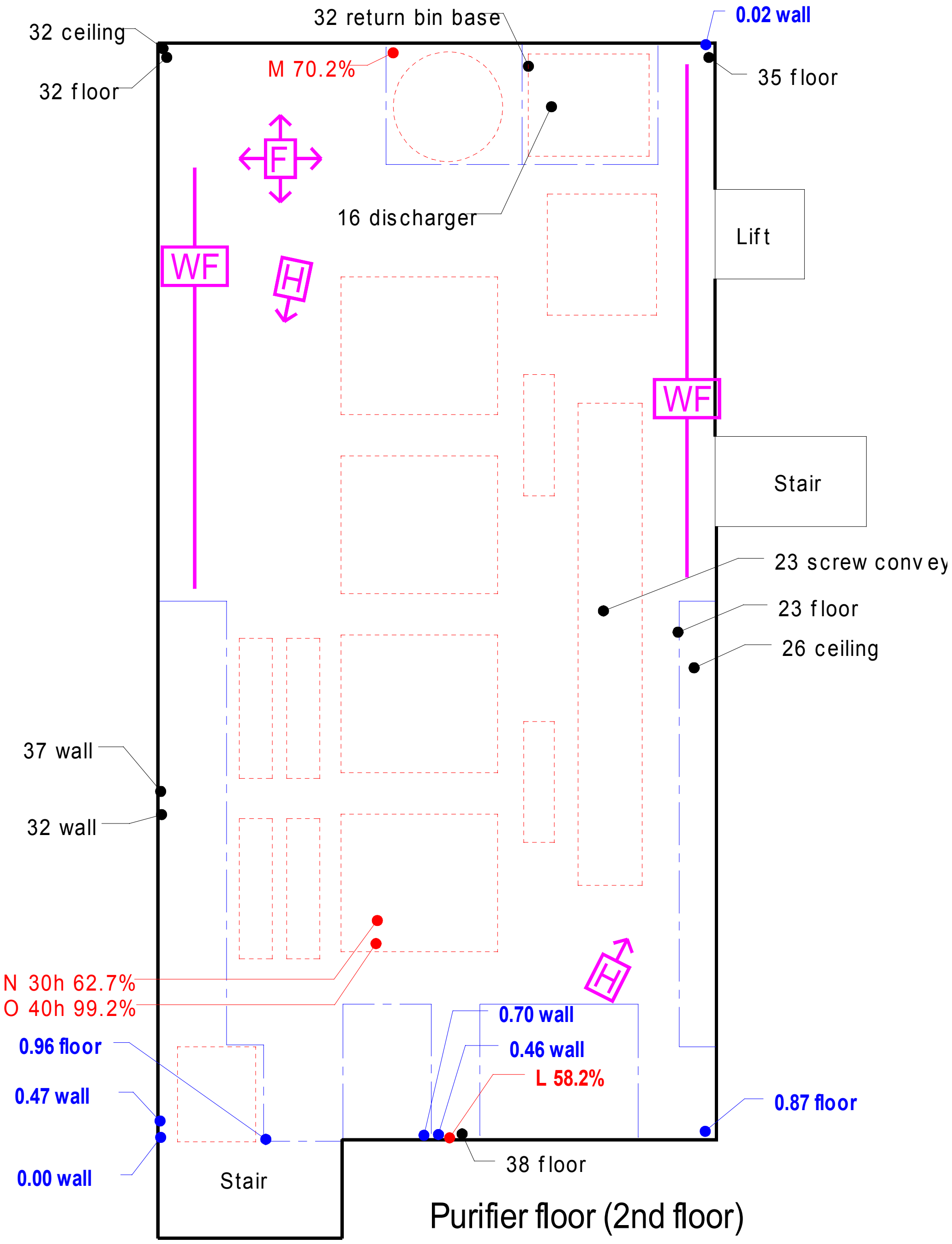


Chart 9. Tilbury 3rd floor

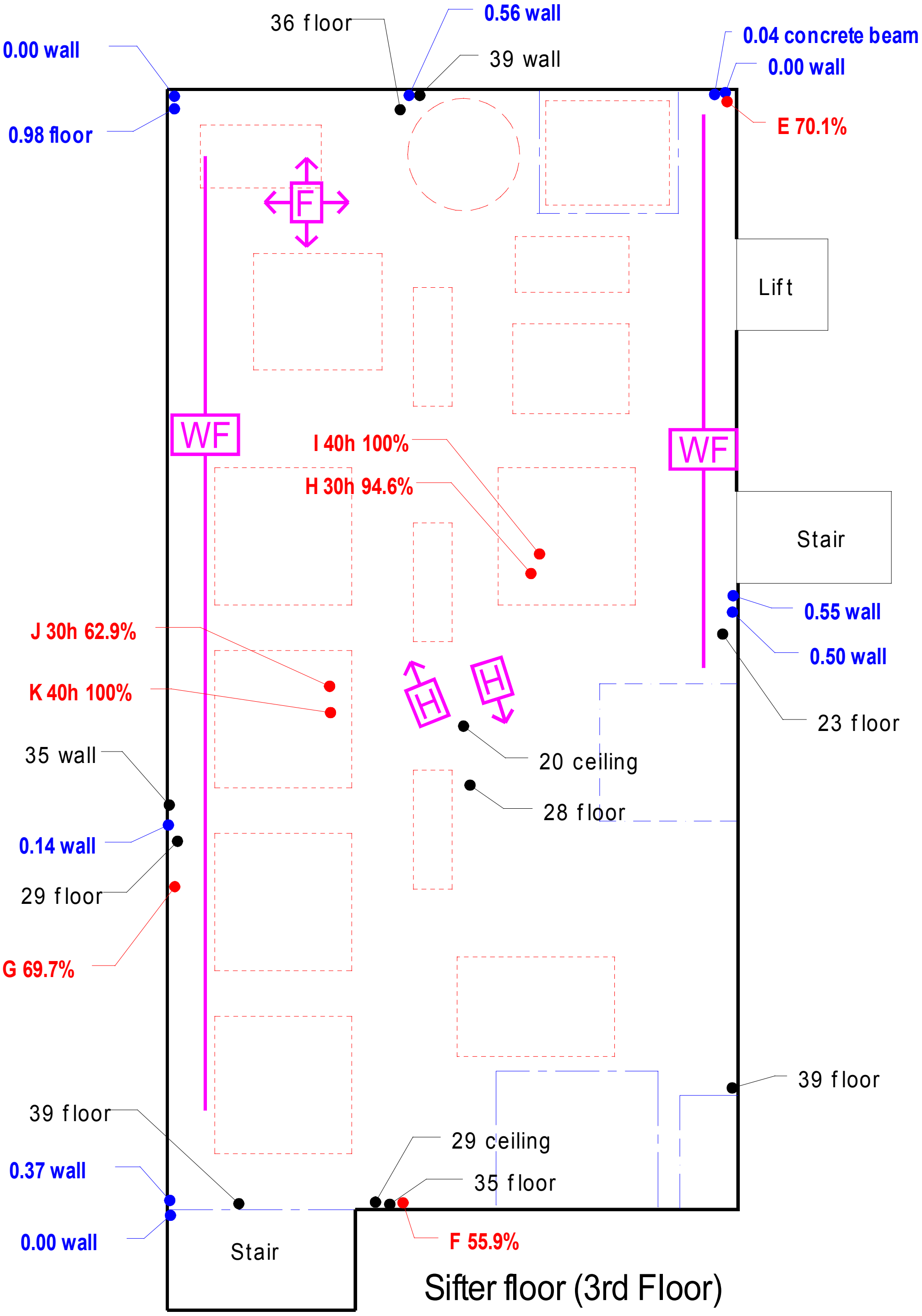


Chart 10. Tilbury 4th floor (Top)

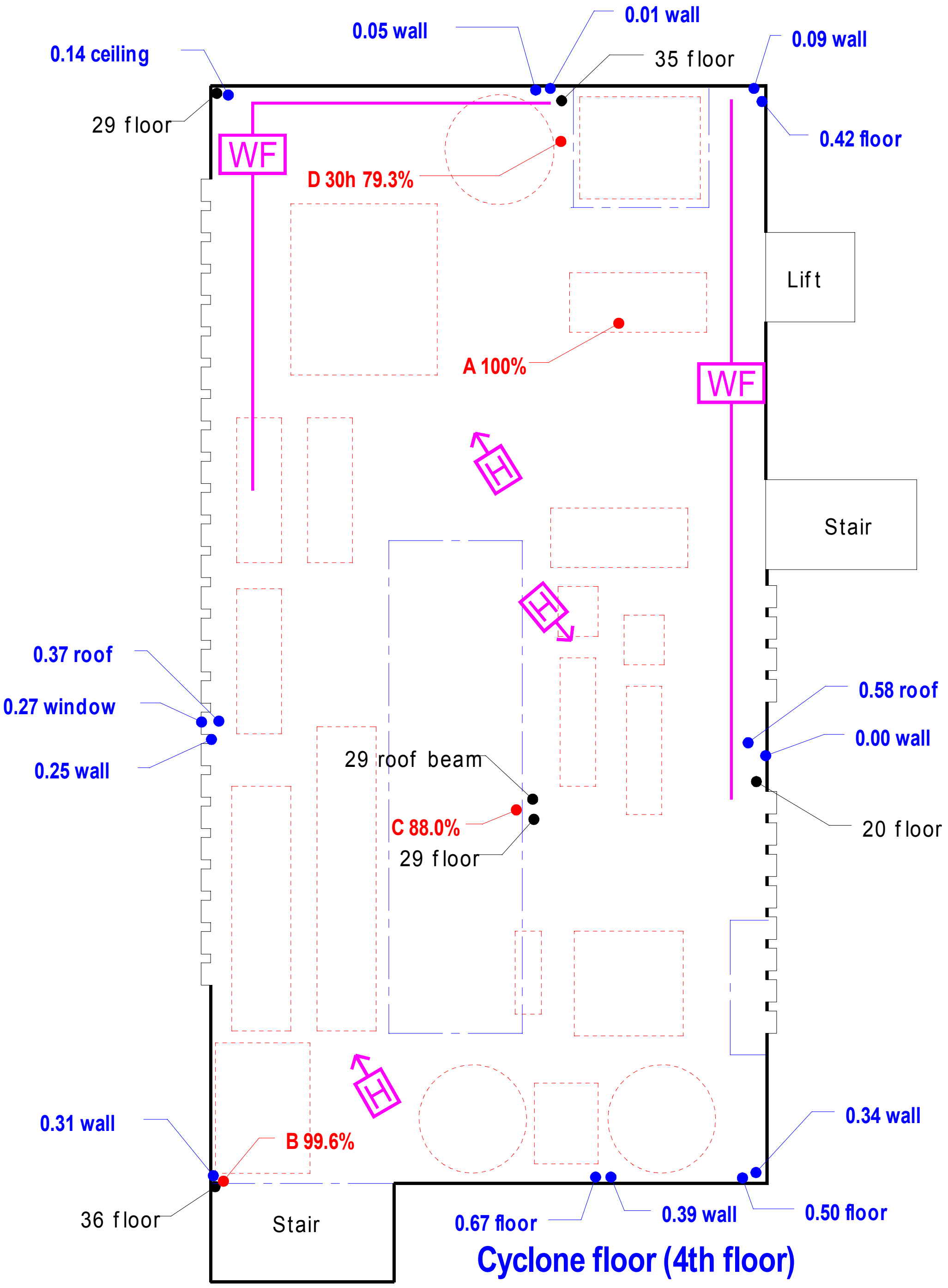


Chart 11. Tilbury, Bin Bases