PROJECT REPORT No. 329

ALTERNATIVES TO METHYL BROMIDE FOR PEST CONTROL IN FLOUR MILLS

FEBRUARY 2004

PRICE: £10.75

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by

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This is the final report of a thirty-nine month project that started in July 2000. The research was funded under the MAFF (now Defra) LINK scheme (Project AFM-93) with the following grants: Defra - £90,000; HGCA - £135,000 (Project No. 2301); National Association of British and Irish Millers (in kind) - £27,000; Igrox Ltd. (in kind) - £18,000.

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ABSTRACT

Potential methods of using heat to disinfest flour mills were investigated. The effect of high temperatures was assessed against ten pest species of flour and flour mills, *Ephestia kuehniella*, *Tribolium castaneum*, *T. confusum*, *Cryptolestes turcicus*, *Ptinus tectus*, *Sitophilus granarius*, *Gnatocerus cornutus*, *Tenebrio molitor*, *Liposcelis bostrychophila* and *Acarus siro*, in the presence and absence of modified atmospheres and inert dusts. Temperatures in excess of 47°C held for 24 h, or 44°C held for 48 h, killed all stages of all the above mill pests. The presence of up to 30% carbon dioxide in the atmosphere did little to reduce target temperatures or treatment times, but the efficacy of inert dust treatments was significantly enhanced above 30°C achieving complete control of flour beetles and grain weevils within 24h at 40°C at dosages down to 1 g/m^2.

Following pilot trials establishing structural component heating rates, maximal non-dust-entraining air movement rates and atmosphere leakage rates, electrical heating of air in flour mills was accomplished using multiple commercial 18 kW 3 phase fan heaters distributed throughout the building. Insect activity is greatly stimulated by increasing temperature and pests tend to emerge from harborages. For effective kill floors need to have become hot enough to kill any insects falling out of refuges in plant and upper structures. However basement floors are the hardest part of a structure to heat.

To enable the heat requirement for practical heating trials in mills to be calculated, a computer model was developed to find an air temperature to simultaneously balance heat flows through up to 10 different types of structure bounding a given volume. The model can predict the surface and internal temperatures of structural elements and can simulate the thermostatic control of the heaters and heat mats. It can also predict energy costs.

To provide the extra heat input required for wall floor joints, silicone rubber electric heating mats were placed in the ground floor area prior to the main air heating period while the mill was still running. This reduced the down-time of the mill for the treatment. Mats were covered with insulation and held in place with sand snakes. When air heating was started, additional floor fans were positioned to blow warm air over ground floor slabs to accelerate their heating and insulation was removed from the mats. The heating of upper floor wall floor joints was accomplished using fans and perforated polythene ducts fed from an available 18 kW heater. The trials demonstrated that with sufficient heaters and local knowledge of trouble areas, mills could be safely disinfested, but costs did exceed those for fumigation.

SUMMARY

BACKGROUND

The principal objective of this programme was to find a viable alternative to the commercially important fumigant methyl bromide, shortly to be restricted under the international Montreal Protocol agreement because of ozone depletion concerns, for dealing with infestation and hygiene problems in structures used for food processing, in particular flour mills. The loss of methyl bromide will remove a major safeguard for the maintenance of food hygiene, increasing the risk of spreading problems arising at various points in the supply chain from the farm to commercial stores, mills, bakeries and retail outlets. It is thus of vital importance to develop viable alternatives to methyl bromide. In the absence of alternatives, the only course of action would be to apply for a critical use exemption, but for this to be accepted by the Technical and Economic Assessment Panel of the UNEP Montreal Protocol, it would have to be shown that alternatives had been tried and had failed. The establishment of a sound technological basis for an alternative control procedure would result in rapid adoption by industry provided that the changes necessary in commercial practice were economically feasible for the market concerned.

Of the various non-chemical alternatives under investigation internationally, the one which appears most widely acceptable to the UK flour milling industry and which is sufficiently developed for refinement and use in the immediate future, is treatment by heating. 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. This has been the reason for adopting methyl bromide as the mainstay for what has become in many cases an annual whole-site treatment strategy. Heat is one of the few options offering rapid 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. To address this problem the current programme was started to investigate the effects of heating and other combinations, including inert dust application and atmosphere modifications, on the efficacy of high temperatures in achieving control within a 24-36h treatment period.

EXPERIMENTAL DEVELOPMENT

Effect of heat on pests

Tests at raised temperatures were conducted on nine insect species, *Tribolium castaneum* (rust-red flour beetle), *T. confusum* (confused flour beetle), *Cryptolestes turcicus* (Turkish grain beetle), *Liposcelis bostrychophila* (book louse), *Ephestia kuehniella* (Mediterranean flour moth), *Gnatocerus cornutus* (broad-horned flour beetle), *Ptinus tectus* (Australian spider beetle), *Sitophilus granarius* (granary weevil) and *Tenebrio molitor* (mealworm), and one mite species, *Acarus siro* (flour mite). The most

tolerant species was *T. castaneum*, adults of which could survive a 24-h exposure at up to 46°C, while the flour mite *A.siro* was completely controlled by a 10-h exposure at 40°C (Table I).

Combination tests

<u>Carbon dioxide</u> **-** The first four species on the above list showed some evidence that the presence of 10-11% CO_2, rather than improving efficacy, actually increased the level of survival and duration of exposure survived at 44°C, 50% r.h. However a small temperature difference was evident between the 44°C controls and the CO_2 treatments, the latter being up to 0.8°C cooler in some cases, and further tests were run with *T. castaneum*, and also with *S. granarius*, a species which showed evidence of increased susceptibility in the presence of CO_2 at 40°C, exposing older and younger stages (> or < 3 weeks from first oviposition), in 10, 20 and 30% CO_2, at 44°C.

Insect cultures were exposed in chambers or desiccators in constant temperature rooms. Carbon dioxide was supplied from a cylinder source via a Signal gas blender regulating the output to the required level in humidified air. For *S. granarius* there seemed to be some improvement in efficacy with the combination of heat and CO_2 but it was small (Table II). A temperature increase of 0.5°C from 44°C had a similar effect to adding 20 or 30% CO_2. Thus at these temperatures near the limits for survival, minor changes in temperature had a much greater effect than major changes in CO_2 concentration. For *T. castaneum* survival of younger stages at 44°C was slightly higher in the presence of 10% CO_2 (Table III). It was apparent that there was no real advantage of adding even 30% CO_2 to exposure at 44°C in achieving control of either species.

To see whether the efficacy of heat was affected by oxygen (O_2) level, a test was run in a 30% O_2 atmosphere at 44°C, 50% r.h. Again, no advantage was evident with older stages actually surviving longer in the enriched O_2 atmosphere (Table IV).

<u>Laboratorv tests with inert dusts</u> **-** The efficacy of a commercially available diatomaceous earth (DE) formulation 'Silico-Sec' was also assessed in controlled environment rooms at exposure conditions of 25°C/70% r.h., 30°C/50% r.h., 35°C/40% r.h. and 40°C/30% r.h. against *S. granarius* and *T. castaneum*. The progressive drop in r.h. simulated the effect of heating in a flour mill. For dosing in the laboratory the DE formulation was sieved through a 250μm wire sieve to give an even coating on 14 cm diameter glass Petri dishes at 1, 5, 7.5 and 10 g/m^2 (n=5). Twenty-five 2-4 week-old adults were added to each separate dish.

In contrast to the results with modified atmospheres, the efficacy of applications of DE and heat was very much improved over heat alone or dust application at 25°C. *T. castaneum*, the more tolerant species to heat alone, was in fact the more susceptible of the two species to dust exposures, all adults being killed after 48 h at 30°C while those of *S. granarius* required 48 h at 35°C for complete control (Table V). Surviving adults held for a further 7 days to recover on food at 25°C after the 48-h exposure to dust continued to be affected, and no *S. granarius* adults surviving exposure to DE at 30^{o}C survived this period. There was some evidence of reduced efficacy of the 1g /m^2 dose level as compared to higher doses, but no evidence of any difference in efficacy at 5g /m^2 or above.

<u>Conclusion</u> **-** Heat treatment efficacy can be improved by the use of residual dusts in cracks and voids, where target temperatures are often hard to achieve, but there seems to be no advantage in modifying the balance of atmospheric gases in order to shorten treatment times or reduce target temperatures.

Field trials with dusts

Concurrent work with the laboratory tests compared the suitability of different dusters for application of DEs in structures. Initially, three different dust applicators were evaluated. An electric powered duster proved too powerful for targeted treatment and was concluded to be more appropriate for treating a large space such as the inside of a building. A simple hand operated model was very flexible and the speed of treatment could be easily adjusted for covering a large area or to aid gentler application to vertical walls. The smaller gas powered applicator was deemed best suited for treating small areas and the narrow nozzle and extendable lance made it useful for treating less accessible "dead-spaces". This latter device, the 'GPS Gaspot' CO_2 powered duster (Killgerm Chemicals Ltd, West Yorkshire, UK) was evaluated in two mill treatments. In the first trial, DE was applied to the dead space under 3 rows of flour rollers that had formerly had infestation from beetles and moths. Holes were pre-drilled into the wooden plinths at ca. 2.5 m intervals. DE was applied at three rates, 5, 10 or 20 g/m^2, a different rate for each plinth. The gas powered duster, proved easy to use and penetrated into the space readily. The effect of varying the DE dosages could not be quantified since no before and after assessments were made of the pest population. However a year later, the mill owner has confirmed that these areas have not been re-infested, suggesting that the DE is giving good residual protection.

In the second trial, a flour mill was heated to a target temperature of 48°C. This time, the dead space was much more difficult to reach, consisting of a 5 mm gap between a 36m ^{2} chimney breast shaped wall cladding and the wooden storage bin behind. Holes were again drilled at 2-3 m intervals and the dust injected as before. Despite the large area, and such a thin gap, the DE gave good penetration and was seen to blow out from injection points up to 3 m away.

In conclusion, the use of targeted DE treatments in UK mills is a practical means of supplementing heat treatments, and could equally well be used to provide residual protection as a component of other control strategies, including fumigation. Future studies need to include a wider range of insect species and investigate effects against different stages. Since there can be variation in efficacy between different DEs, these studies should also include other DE products.

Heating method development studies

Target temperatures - Temperatures above 45°C are lethal to insects but the time taken for death to occur varies with life stage and the exact temperature experienced by the pest in its harborage, which may be quite different from the surrounding air temperature. Temperatures of 48°C or above held for 24 h, or temperatures exceeding 44°C over a 48-h period, will kill all stages of all common mill insect pests. Commercially acceptable treatments must be completed within 48 h. Heat input must therefore be adequate to raise the surface temperature of all structures to 48°C within 24 h. Heating a structure such as a flour mill involves much more than simply raising the temperature of the internal atmosphere. Heat in the air is transferred to the surfaces by convection but up to half of the heat flowing to a brick or concrete surface in practice is transferred by radiation. The source of this radiation is adjacent faster-heating surfaces releasing heat to slower heating materials such as concrete. The rate of convective heat transfer depends on the speed of air movement over the surfaces. In spite of providing fan assistance for convection heaters, air movement over most of the structure will be slow, the result of natural convection. There is thus a need for alternative sources of heating for difficult areas such as concrete wall floor joints.

Selection of heating methods - For reasons of convenience and general availability, electricity was selected as the energy source for heating equipment. Purpose-built 18 kW electric fan-assisted air heaters, already in use under the trade name of 'ThermoNox' for heat-treating flour mills in Germany, were selected for trials work, and a heating strategy using these heaters for raising air temperatures, and thermal mats for raising the temperature of heat sink areas such as wall floor joints, was formulated.

To achieve the required temperature rise, the maximum air delivery temperature from heaters had to be limited to 65 - 70°C to avoid activating fire sprinklers and to limit the thermal expansion and cracking of components and structure. In addition maximum air speeds over dusty surfaces had to be limited to 5m/s to avoid entraining dust. This restriction avoided increased risk of dust explosions, the risk of dust inhalation by personnel and prevented any applied DE being blown away from treatment areas. Floor fans were used to increase air circulation and speed up the heating of concrete floor slabs.

Other considerations - Heating equipment to be used for trials and later in commercial practice must be capable of being moved into place by hand and should be free from any potential contaminants, e.g. glass components. Site power supplies may need to be shut down to allow for connection and disconnection of heaters. The convectional air heaters used in the trials, manufactured by ThermoNox in Germany, came with electrical distribution boards that could supply power to up to 10 units. These needed to be attached directly into the mill supply grid but avoided the need for many cables to be run from the central supply.

The chosen solution methods – The final arrangements for trials was as follows:

1. Electric air heating using multiple 18 kW 3 phase fan heaters distributed throughout the mill.

2. Silicone rubber electric heating mats to heat ground floor wall floor joints prior to the main air heating period while the mill is still running. Mats should be insulated and held in place with sand snakes.
3. The heating of upper floor wall floor joints using fans and perforated polythene ducts after temperatures rise.
4. Floor fans to blow warm air over ground floor slabs to accelerate their heating.

Practical heating trials at Boxworth

Calculations and modelling – The thermal properties of structural components are summarised in Table VI. These were reflected in the results obtained from temperature monitoring of surfaces using an infrared thermometer to find the time taken to halve the difference between surface and heating air temperatures in practical trials (Table VII). A model capable of predicting the surface and internal temperatures of all of the structural elements that bound a given space together with the heat load due to air exchange, and which can predict the temperature for a given energy input, was developed. The model also takes into account the thermostatic control of the heaters and heat mats used in the trials and predicts energy usage which enables the operating costs to be estimated.

Principal results of practical trials – A single 18 kW fan heater directed onto a concrete floor in a large closed building raised the surface temperature from 14°C to 32°C in 2 hours with output air at 45°C. Experiments to establish the maximum rate of air movement while still avoiding dust entrainment showed that air speeds below 5 m/s caused only slight movement of the flour. At between 6 and 7 m/s the flour started to move and above 7 m/s the surface was rapidly cleared. The 18 kW fan heaters caused no flour dispersal. Practical floor heating trials with 38 W/m heating cables and 250 W/m^2 mats confirmed computer modelling predictions. With multi-layer reflective insulation a 250 W/m^2 mat will heat a wall floor join to between 17 and 23°C above room air temperature. Un-insulated 500 W/m^2 mats heated a wall floor join to 22°C above room air temperature. For corners, 700 W/m^2 are needed to achieve the same effect as 400-500 W/m^2 for a non-corner join.

FIELD TRIAL SUMMARIES

Mill trial at Hull

The objective of this trial was to measure the thermal response of a range of mill structures to air heating. The trial zone was a top floor room (18m x 19m) of a working mill. Model predictions suggested that, using the available two 18 kW heaters it would be possible to raise the temperature of the structure by 10-15°C. An average heater discharge temperature of 43°C was recorded. Wooden structures heated quickly, concrete and brick ones more slowly. Hot air distributed to wall floor joints by perforated polythene ducts was effective in heating this part of the structure above room average air temperature. These ducts restricted the air flow through the heaters and resulted in higher delivery air temperatures than when the heaters were unrestricted.

Stuttgart

The set-up and first 24 h of a 48 h commercial heat treatment of half of a flour mill in Stuttgart was observed. The structure was 8 floors of reinforced concrete. Temperatures in only part of the treated building were recorded. The observed floor was heated by 6 x 18kW heaters, a volume of 853m^3 (142 m^3/heater). The heating rate was limited by heater capacity to 1°C/hour on average but some parts of the structure had reached lethal temperatures after 24 hours heating. The temperature of packing material and bags of finished product rose much more slowly.

Langley mill

A test fumigation with sulphuryl fluoride required the mill structure to be heated beforehand to 28-30°C to ensure effective treatment. The majority of the heat was provided by two 65kw indirect fired oil burning heaters located outside the building. The hot air from these was distributed by polythene ducting on the ground floor. Two 18kW electric heaters were used to heat the upper floors, again using perforated polythene ducting to distribute the heat.

The concrete floor slab was predicted to take the longest to heat up so heating started before mill shut down by directing hot air towards the ground floor wall floor joints. Temperature records show that the average surface temperatures fell from 31°C to 23°C during the fumigation. By the end of the treatment the average floor temperature had fallen to 21°C.

Rainham

The modern steel framed structure clad with 50 mm thick steel faced insulating panels and housing six bins and a pellet press was heated using 5 x 18 kW electric heaters. The plant and structure reached 40°C in 10 hours but the concrete floor slab took 19 h to reach this temperature and reached a maximum of 44°C after 24 h. All bioassay insects survived on the ground floor and some did so on the first floor.

A test to investigate the prospect for adding carbon dioxide to the atmosphere established that the air leakage rate during the heat treatment was 2.2 changes per hour, which would greatly limit the practicality of any modified atmosphere treatment.

Cambridge

The basement area of the old mill building (no longer in use for milling) was selected for testing the effectiveness of heating mats both with and without supporting air heating. The effectiveness of insulating covers for the heating mats was also tested. Two 18kW air heaters raised the air temperature to 47°C compared to a model prediction of 49.6°C after 48 hours.

Un-insulated 500w/m2 heating mats raised the surface temperature from 17°C to 41°C after 45 hours. An un-insulated 500w/m2 mat combined with air heating raised the floor surface temperature to 50°C after 20 hours and 64°C after 48 hours. A poly-duct delivering room air heated the floor surface to 40°C after 48 hours.

Holbeach

A full-scale commercial heat treatment was conducted to demonstrate the application of processes and techniques developed during the project. Twelve 18kW fan heaters and 5.4kW of floor heating mats were used to treat the brick structure. The average air temperature achieved in the mill was 48 – 51°C for 30 hours. All the upper floors were raised to 50°C and held there for 12 hours or more. Much of the ground floor was raised to 50°C but some sheltered areas only reached 38°C.

Insulated wall floor joint heating mats warmed the edge of the floor to 71°C (700w/m^2), 61°C (400w/m^2), and 47C (250w/m^2) after 14 hours. A poly-duct heated wall floor joint was maintained at 5°C below the duct air temperature (52.5 °C). The control section of the basement wall floor joint was maintained at approximately 11°C below air temperature. Some survival of insects occurred in the basement but all bioassay insects were killed elsewhere in the mill.

General conclusions

1) Heating mats should be used on basement wall/floor joints for 24–36 h prior to starting air heating. Special attention to corners of rooms is needed because insects can migrate to these cool areas.

2) Heating mats need to be rated at 500w/m^2 or more and be shaped so that they fit into the angle of the wall floor joint. They should extend 50mm up the wall and 150mm onto the floor. Room corners need shaped mats rated at 700 W/m^2 to ensure effective treatment.

3) Multilayer reflective insulation ensures that most of the heat from the mat goes into the structure and not into the air. Insulation should be removed when the air temperature is above 50°C. Mats and insulation should be held in place with sand snakes.

4) Enough heating should be present to raise heater air discharge temperatures to 65°C within 6–8 h. An 18 kW heater for every 300-700 m3 of space depending on mill size and temperature will be needed.

5) Perforated polythene ducts blowing heated room air into is an effective means of warming wall floor joints on upper floors. Poly-duct heating is best started when air temperatures reach 50°C and wall floor joints can be heated to within 3°C of the ducted air temperature within a few hours.

6) Effective cleaning and spraying of the ground floor will minimise survival where lethal temperatures cannot be maintained for long enough.

7) The building should be closed sufficiently to prevent excessive air exchange during treatment.

8) An infra-red hand held thermometer is ideal to check on distribution of heat during the treatment.

Table I. Effect of exposures at 40°C on the survival of mill pests

Species	**Stage**	**Time some survive (h) and survival level**	**Time for 100% kill (h)**
Flour mite *Acarus siro*	All	-	10
Turkish grain beetle *Cryptolestes turcicus*	Younger Older	72 (10%) 72 (25%)	- -
Mediterranean flour moth *Ephestia kuehniella*	Eggs Larvae	- 24 (7%)	24 48
Broad horned flour beetle *Gnatocerus cornutus*	Younger Older	- 24 (4%)	24 48
Booklouse Liposcelis bostrychophila	Eggs Nymphs, adults	72 (>50%) 48 (4%)	- 72
Australian spider beetle *Ptinus tectus*	Older	48 (1%)	72
Granary weevil - *Sitophilus granarius*	All	72 (<1%)	
Mealworm *Tenebrio molitor*	Younger Older	48 (2%) 24 (2%)	- 48
Rust-Red flour beetle *Tribolium castaneum*	All	72 (>50%)	-
Confused flour beetle *Tribolium confusum*	All	72 (>50%)	-

Table II. Effect of added carbon dioxide (CO_2) on the efficacy of heat treatments at 50% r.h. against older and younger stages of *Sitophilus granarius*

Temperature (°C)	% CO_2 in air	Stage: Y = <3 weeks O = >3 weeks	Longest exposure survived (h)	Exposure (h) needed to give 100% kill
43.5	0	Y	16	20
43.5	10	Y	10	16
44	0	Y	8	16
44	20	Y	8	16
44	30	Y	8	16
44	0	O	24	32
44	11	O	20	>20
44	20	O	16	24
44	30	O	8	16
44.5	0	O	8	16

Table III. Effect of added carbon dioxide (CO_2) on the efficacy of heat treatments at 50% r.h. against older and younger stages of *Tribolium castaneum*

Temperature (°C)	% CO_2 in air	Stage: Y = <3 weeks O = >3 weeks	Longest exposure survived (h)	Exposure (h) needed to give 100% kill
43	0	Y	48	>48
43	10	Y	48	>48
43	20	Y	48	>48
44	0	Y	40	48
44	10	Y	48	>48
44	20	Y	40	48
44	30	Y	40	48
44.5	0	Y	24	40
44	0	O	48	72
44	11	O	48	>48
44	20	O	48	>48
44	30	O	40	48
44.5	0	O	40	48

Table IV. Effect of adding 9% oxygen to air on the efficacy of treatment at 44 $\pm$ 0.4°C, 50% r.h. against older and younger stages of *Tribolium castaneum*

% oxygen in air	Stage: Y = <3 weeks O = >3 weeks	Max exposure survived (h)	Exposure needed for 100% kill (h)
21	Y	40	48
30	Y	40	48
21	O	40	48
30	O	48	>48

Table V. Mean % mortality for *Sitophilus granarius* after exposure to to diatomaceous earth (DE) at different dose levels at 5 temperature/humidity combinations, simulating mill conditions during heating

Dose	24-h exposure				48-h exposure			
Temp. (^{o}C):	*25°C*	*30°C*	*35°C*	*40°C*	*25°C*	*30°C*	*35°C*	*40°C*
% r.h.:	*70%*	*50%*	*40%*	*30%*	*70%*	*50%*	*40%*	*30%*
No DE	0 *a*	0 *a*	0 *a*	80 *a*	0 *a*	0 *a*	21 *a*	100 *a*
1 g/m^2	0 *a*	6 *b*	50 *b*	100 *b*	16 *b*	94 *b*	100 *b*	100 *a*
5 g/m^2	0 *a*	14 *b*	91 *c*	100 *b*	40 *c*	99 *b*	100 *b*	100 *a*
7.5 g/m^2	0 *a*	13 *b*	94 *c*	100 *b*	39 *c*	99 *b*	100 *b*	100 *a*
10 g/m^2	0 *a*	11 *b*	94 *c*	100 *b*	33 *c*	98 *b*	100 *b*	100 *a*

Based on 5 replicates per treatment. Proportions in the same column followed by the same letter are not significantly different at p = 0.05.

Table VI. Thermal properties of materials found in mills

Material	**Thermal conductivity w/m°C**	**Specific heat J/kg °C**	**Density kg/m^3**
Brick	0.65	830	1700
Concrete	2.4	920	2300
Timber	0.13	2300	600
Steel	45.0	480	7900
Glass (window)	1.05	750	2600
Slate	1.9	920	2700
Polyurethane panel	0.026	1000	30

Table VII. Times to halve the difference between heating air and structural surface temperatures

Structural surface	**Half heating time (hours)**
Internal brick wall	3.3
Ground floor concrete slab with floor fan	4.1
Ground floor slab (no fan)	10.4
Upper floor (timber)	2.1
Roof (timber board and slate)	0.5
Steel clad polyurethane wall panel	2.1
Structural steelwork	0.5
Steel machinery (pellet press)	2.1

TECHNICAL DETAIL

GENERAL INTRODUCTION

The fumigant methyl bromide (MB) is scheduled for phase out in 2005 as an ozone depleting compound under the Montreal Protocol (UNEP, 1998). A move away from 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. Another consequence of milder winters is that the heating systems present in many northern USA and Canadian mills are absent from UK mills. The UK climate does not offer the benefit of a 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. Nevertheless heat treatments of flour mills have been practiced sporadically since the turn of the century and 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 48^{o}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 obtaining a uniform heat profile throughout the structure without encountering high localised temperatures.

SELECTING AN ENERGY SOURCE

All previous work has used heated air as the means of warming the machinery and structure. Where oil or gas has been the fuel source an indirect burner was used and hot air had to be ducted into the building making recirculation back to the heater difficult. The current project investigated atmosphere modification to enhance the heating process so any system providing heat from outside the building would need a recirculation system to minimise air exchange and loss of atmosphere. For this reason both gas and oil were rejected as energy sources.

Where adequate steam boiler capacity is available steam coils can be located inside the building and electric fans used to circulate the hot air. The maximum surface temperature of a steam coil is limited by the steam pressure so there is no risk of dangerous high temperatures. However, steam is not widely available in UK mills and steam hoses from an external supply unit would constitute a safety hazard.

Electricity provides a flexible, easily distributed energy source that can be used to power radiant air heaters, convectional air heaters or thermal mats for contact heating of floors and wall bases, all located within the building. A survey of the installed electrical capacity in mills showed that, when the mill is stopped, there is enough power to heat the building. Delivery ducting for electric heaters is not needed so installation is relatively quick and easy. For these reasons, electricity was selected as the energy source.

SELECTION OF HEATER

The initial concept for heating flour mills was to develop a hot air gun that could be mounted at convenient locations on each level in the mill. The intention was that each air gun would produce a jet of hot air (60°C) that would sweep the whole of the surrounding space (5 – 6 m dia). It was also proposed that an infra red-temperature detector would be mounted on the air gun to measure the temperature of the surfaces being heated by the air jet. The speed of movement of the jet would be adjusted to produce uniform surface temperatures throughout the heated zone. The same concept but using an infra red heat source was also considered.

After surveying three flour mills it was concluded that the initial air gun concept would not prove to be a practical solution. Radiant heating was ruled out because too much of the structure would be shaded by plant and machinery. Also the source temperature would be above the safety threshold for dust explosion risk and some structures and machinery near to a heater in some circumstances could become seriously overheated. An air gun device would also produce too much air movement and could cause dust clouds.

About this time a purpose-built electric air heater for use in flour mills was found to be available in Germany. Using this device, a strategy was developed to investigate the potential of a combination for heating of convection heaters for raising air temperatures and thermal mats for raising the temperature of wall floor joints.

HEAT IN COMBINATION

Heat can provide an alternative treatment method to using chemicals but also provides opportunities for other measures to work better. For fumigants and modified atmospheres it does this in three ways; by increasing the diffusion and distribution of gases and hence their powers of penetration, by reducing physical sorption and by increasing the toxicity to target pests. Heat is particularly effective in increasing the efficacy of control using high concentrations of CO_2. Carbon dioxide is a waste product of metabolism which in high concentrations is toxic to most organisms. At lower concentrations (down to 3-4%) it can stimulate an increased rate of oxygen uptake and in larger insects can cause spiracles to be kept open, increasing the rate of desiccation (Mellanby, 1934; Hoyle, 1960). For structures such as mills its action would be confined to the desiccation mechanism because it would not be possible to seal buildings to a level permitting the near total atmosphere replacement needed for modified atmosphere treatments. Experience in the USA in applying the heat, phosphine, CO_2 combination technique has indicated that, depending on the mill, CO_2 concentrations of 3-12% (mean 7%) of the total atmosphere can be applied and maintained in large structures (Mueller, 1994; 1996; Bell, 1997).

USE OF DUSTS

There has recently been a rekindling of interest in inert dust formulations. Dusts have long been used as carriers for insecticides, but the latest approach has been to formulate them for use in their own right, minimising their abrasive properties to surfaces and enhancing their insecticidal action as desiccants by promoting their capacity to selectively absorb insect cuticular waxes. The dust formulations are comprised of finely milled natural amorphous silicon dioxide which is non-toxic to mammals, and is registered as a food additive in the UK, Canada, USA and many other countries. Like modified atmospheres their effectiveness against pests is enhanced by heat. They are applied as dusts or, more frequently, as water-based sprays, which reduce the level of dust in the atmosphere. There are a variety of applicators on the market for applying dusts to structures, including power sprayers, hand-held electric dusters, and hand-held sprayers (Fields *et al*., 1997). In the current programme dusts were applied to voids and other areas inaccessible to cleaning and spraying operations where endemic pests may be harboured, using standard safe and effective application techniques before the heat exposure.

SECTION A: LABORATORY AND DEVELOPMENTAL STUDIES

MODELLING OF THERMAL PERFORMANCE

Transient heating of structures

Commercial treatments require that the mill is shut down for the minimum period but heating of the structure of a flour mill takes time. Heat has to be stored in the structure and the heat being lost from the outside of the structure must be replaced. Most traditional mill structures are of brick or concrete and wood. Thick masonry structures take up to 48 hours for a steady state temperature gradient to develop through them. In the early stages of heating the heat input to a surface must supply the steady state loss and the heat needed to raise the temperature of the structure towards the internal air temperature. Heat transfer to a surface from air is proportional to the temperature difference between the surface and the air. To minimise the heating time the internal air temperature must be raised to the maximum safe level (55^oC) as soon as possible and held constant.

A simple computer model was used to gain an understanding of the speed of heating of various structures in the mill. This in turn allowed the testing of different heater capacities and control strategies without the expense of full scale experiments. The model predictions were compared with the results from practical heating trials and these results were used to improve the model performance.

Thermal properties

Standard reference values for conductivity, specific heat and density (Ede, 1967; IHVE, 1970; ETSU, 1987) have been used for structural elements. To improve accuracy it would be necessary to use on-site measurements to classify the thermal properties of a particular structure, which may not always be practical. A transient heating test in which the dynamic temperature response of the test surface is observed when subjected to heat could be developed for practical use in classifying building components and machinery.

Heat transfer coefficients

Most surfaces are heated by convection and radiation. Heat in the air is transferred to the surfaces by convection but half of the heat flowing to a surface may be transferred by radiation. This heat comes from quick warming surfaces that are hotter than the slower responding bulky parts of the structure. Convection heating depends on air movement over the surfaces and on mixing between the bulk room air and that in contact with the surfaces. This natural air movement and mixing is not uniform over all surfaces and is restricted in corners and where heat flow is downwards. The effect is equivalent to all surfaces being covered by a layer of insulation. Heat contained in the bulk air must flow through this layer to get to the surface. Depending on the rate at which heat flows through this boundary layer there will be a temperature gradient from the bulk air to the surface. Surfaces that can conduct heat away quickly will remain cooler because the high heat flux through the boundary layer results in a large temperature gradient between the bulk air and the surface.

A study of heat transfer at internal building surfaces (ETSU, 1987) summarises the typical heat transfer coefficients that may be expected.

Horizontal surfaces with heat flowing downwards (floors) are most difficult to heat because the convective air movement tends to stagnate resulting in a heat transfer coefficient of less than 1W/m^{2}C. Where the heat flow is upwards the transfer coefficient is 4.0 W/m^{2}C. The transfer coefficient for vertical surfaces depends on their height but a typical value is 3.0 W/m^{2}C. The tendency for natural convective air movement to bypass the corners of a room explains the difficulty of heating wall floor joints.

Standard surface heat transfer coefficients (IHVE, 1970) have been used in initial modelling tests but subsequent tests have used values that better reflect the local conditions.

Model description

The computer model calculates an air temperature in the space that will simultaneously balance the heat flows through up to 10 different types of structure. The temperature gradient through each structure type is calculated based on its thickness and thermal properties. The heat flow balance is established for a time step and the result of this is used as the starting value for the next time step. The model time step is chosen to ensure stability and convergence of the solution.

The model can predict the surface and internal temperatures of all of the structural elements that bound a space and can simulate the operation of the heaters and heating mats under thermostatic control. The effect of some internal boundaries receiving a heat input from both sides can also be taken into account. Heater energy input is reported so that the costs of alternative treatments can be found. The model also allows for two different levels of air exchange during the treatment so that heating during mill operation can be investigated. The Fortran programme developed is given in Appendix 1.

Estimation of heater capacity

In practice the heater capacity used will be a compromise between speed of treatment and cost. Extra heater capacity will ensure a more uniform and rapid warm up of the structure. Fewer heaters will mean longer warm up times and will require more active management of the heater positions to ensure uniform treatment.

Practical experience has shown that simple methods can be used to estimate the heating capacity required. The number of heaters used will be governed by the need to achieve effective distribution of heat throughout a complex building structure as well as by the calculated heat losses. An approximate indication of the heating capacity can be based on the total building volume. On average a volume of 250 m^3 requires an 18 kW power input. Lighter or heavier than average structures may need less or more heat.

The computer model mentioned above can be used to check the treatment times based on the initial layout of heaters. The model will also help to identify those parts of the building that can be expected to need special attention. A more reliable estimate of the heating requirement of a particular facility can be calculated only by a detailed survey of the plant to be treated. Overall dimensions of the structure are required and a record of the construction (materials and thickness) is needed. From the survey data the thermal capacity and heat transmission characteristics (U value) of each part of the structure can be calculated. From a practical point of view it is convenient to treat each floor as a separate heating zone.

For each heating zone the steady state heat loss and the quantity of heat that will be stored in the structure when it is hot is calculated. The structural heat capacity between ambient and 50°C is divided by twice the expected heating time to give a heat input rate and this is added to the steady state heat loss at 50°C to give the required heating capacity for the zone. The same process is repeated for each zone and the total for all zones is the overall heating requirement.

PRACTICAL ASPECTS OF HEATING STRUCTURES AND TEMPERATURE MEASUREMENT

Structural heating

The maximum air temperature for heating is limited to 55 – 60°C by the need to avoid damage to the structure or the triggering of fire control systems. The control of insect pests requires the surface of the structure to be heated to and maintained at an insect lethal temperature which is not far below this level. Old structures may have cracks into which insects may move. These structures need to be heated so that the lethal temperatures extend to the depth of the crack. The important heat transfer processes at the scale of cracks 1 – 2mm wide is conduction within the structure. These spaces are too small for the development of convective heat transfer between the air and the structure.

Air heaters

Flour mills represent a dust explosion hazard so any heating source must operate under strict safety constraints. The temperature of the heating element surface must not exceed 250°C so that it does not constitute an ignition source. Many mills are fitted with automatic fire sprinklers which are activated by air temperatures of over 68°C. Air heaters need automatic control to modulate the heat input so that during warm-up the maximum is available but when target temperatures have been reached heat input will reduce. Safety cut-outs are required to stop the heater if any component fails. Heaters need to be small enough to be moved between fixed items of machinery and light enough to be moved by one person. In some locations fan noise can be a problem.

Contact heating mats

The most difficult parts to heat in most mills are the ground floor wall floor joints. This is also a common refuge for insects. Heating mats laid along the perimeter of the ground floor can quickly raise the temperature of this area to lethal temperatures. This technique is particularly useful for corners where two walls meet the floor. Heating mats can be deployed before mill shut down to reduce overall down time but for best effect they should be covered with reflective insulation until the air temperature has been raised to 50°C by the air heaters.

It is difficult to raise the temperature of the ground floor slab to 50°C but the cordon of heat mats prevent insects that fall on to the floor from escaping, particularly if the floor has been treated with an insecticidal spray. Any insects falling directly on to the mats should be quickly killed.

Experience has shown (see following section on the individual trials) that 500 W/m^2 will produce surface temperatures of 50°C over a solid concrete floor. Higher heating rates are needed (700 W/m^2) to heat into corners.

Polythene ducts

Polythene ducts and small fans have proved effective in distributing heated air to parts of the building and plant where it is not practical or desirable to locate a heater. Where a number of small rooms have to be heated with a single heater, polythene ducts can be used to take heat from the room with the heater in it and deliver it to each room. In addition the practical trials described in Section B have demonstrated the value of perforated polythene ducts in heating wall floor joints. An air flow of $0.2m^3/s$ per 10m of duct is effective and heating is best started when air temperatures approach the target level.

Floor fans

The provision of constant active air movement over ground floor slabs dramatically improves the heating rate. Additional fans to those forming part of the heater units can be used for this purpose. 1.8 kW 600 mm diameter fans blowing directly down onto the floor can have an effect up to 3.0 m from the fan.

Air exchange

Initial tests showed that it is impractical to start heating the structure by air heating while the mill is running. The process air exchange would require a heat input several times the steady state building heat loss. The fan action during treatment causes a smaller but still significant air exchange and the building needs to be closed up as far as possible, though not sealed to the standard required for fumigation. The level of air exchange makes it quite impractical to combine a heat treatment with a modified atmosphere application.

Temperature response of mill components

During the trials the air temperature in the building rose to a level controlled by the heater thermostats at a rate governed by the heater capacity and the heat absorbing capability of the heated zone. After this the temperature difference between the structure and plant surfaces and the heating air decreased exponentially until a steady surface temperature was reached.

The time to halve the temperature difference between the air and a surface (Z) is a good measure of the response of that structure to the heating process. It is safe to assume that the surface will reach a steady state in 3 such half heating times. The rate of change of surface temperatures was measured during the practical trials and these results have been used to estimate the half-heating times for structure and plant (Table A.1). Heating air temperature is variable during trials so heating rate has been calculated based on short intervals when conditions were steady.

Table A.1 Times to halve the difference between air and surface temperatures for various structural components

Structure type	Half heating time Z (hours)
External brick wall	8.2
Internal brick wall	3.3
Basement concrete floor with floor fan	4.1
Ground floor slab with floor fan	1.2
Ground floor slab (no fan)	10.4
Upper floor (timber)	2.1
Roof (timber board and slate)	0.5
Steel clad polyurethane wall panel	2.1
Structural steelwork	0.5
Steel machinery (pellet press)	2.1

Placement of heaters

18 kW heaters are the maximum capacity that can safely be operated from a 32A three phase socket. The number of heaters needed to heat a zone is given by dividing the zone heating requirement by 18 and rounding up to the next whole number. Where there are a number of separate rooms on a floor it will be necessary to use one heater for each. If the rooms are small then heaters can be used at a lower heat output. Alternatively heating air may be distributed by polythene ducting run from an available heater.

Heaters should be positioned so that they create a circulating air flow in the room, often achieved by blowing along a wall. If two heaters are used they should blow along parallel walls in opposite directions. Heaters should not be directed at sensitive control equipment or at potential outlets from the zone, and each should have enough free cable to allow it to be re-positioned freely within the zone during heating.

Temperature measurement

In the current trials surface temperatures were measured by attaching sensors in representative locations. Mill buildings are complex and have many surfaces so the measurement of all surfaces is impractical.

The use of thermal imaging, while potentially useful for management of the heating process, would result in unmanageable quantities of data and is expensive.

Temperature recording during heating trials relied on a combination of multipoint thermocouple loggers and hand-held infra red thermometer observations. The hand-held thermometer provided the capability to check heating progress at many points while the data logger was used to gather trend information at representative locations. Thermocouples were also used to monitor the air temperatures at the flow and return of the heaters.

Remote temperature sensing

The chief disadvantage of using multi-point temperature logging is the work of setting up and removing the sensors and cabling. Commercially available radio remote temperature sensors are available that could provide real-time display of temperatures outside the heated area. Cost per channel will limit the number of points that could be monitored but these devices could be used to log the air delivery and return temperatures from heaters to identify any malfunction. Remote sensing is unlikely to replace hand held infra red monitoring for process management.

Process monitoring

The success of a treatment depends on achieving lethal temperatures at all points where insects may be present for long enough to kill all life stages. It is not sufficient to know that a location has reached 48°C; it must have been kept at 48°C or above for 24 hours. The most convenient and practical method of recording surface temperatures during a treatment is by using a portable infra red thermometer and bar-code reader to log the temperatures at code marked sites through the mill at regular intervals, say every two hours. This information indicates how the treatment is progressing can be used to reposition the heaters to ensure uniform treatment.

Additional precautions

Pneumatic systems should be fully vented during heating.

Pressurised containers such as fire extinguishers and pressurised spray cans should be removed from the treatment zone.

It is not necessary to seal the building to the same level as for MB fumigation but all practical steps should be taken to minimise air exchange with the outside as this will reduce the energy cost of the treatment and reduce the risk of cool spots where outside air enters.

Operating costs

Treatment costs are classified under four headings:

1. Process energy consumption

2. Ownership or hire charges for heating equipment.

3. Labour for setup, take down, supervision and process quality monitoring

4. Losses associated with lost production during shut down.

Items 2 and 3 may be combined in a service contract. Equipment costs are difficult to define. No suitable heaters are on the market in the UK. The project trials have used hired heaters that have been transported from Germany. Labour costs may be expected to be lower than for fumigation treatments because it is not necessary to seal the treated area to the same level of gas tightness. However extra effort may be required for temperature monitoring and re-positioning of heaters.

Once the numbers of heaters have been decided the energy consumption can be estimated by the computer model. The type of structure, ambient temperature and wind conditions will affect the energy used. Test results suggest that, as a guide, the energy consumption may range from 4 to 10 MJ/m^3 of gross building volume.

An approximate estimate can be made by assuming that for the first 12 hours all the heaters will be working at full capacity. For the next 12 hours it can be assumed that the load will be the sum of the steady state heat loss from the building plus half of the difference between this and the maximum heater capacity. The remainder of the time (24 h) the energy use will be the steady state heat loss from the building. For example: A mill requiring 12 x 18kW heaters and having a steady state heat loss rate of 155 kW at 50C would consume 8532 kWh during a 48-hour treatment.

The current average hire cost of Thermonox heaters in the UK (including transport) is approximately £175 per unit (heater or distribution box) per week. The capital cost is £2200 per heater which if written off over 3 years is £733 per year and if 4 treatments are carried out each year this also gives a cost of approximately £175 per unit per treatment. Clearly if there is a large demand the cost per unit may reduce significantly but this is unlikely to occur until the system has been thoroughly tried and tested in practice. A summary of projected costs for heat disinfestation of two mills of different size is presented in Table A.2. Costs for a small mill will significantly exceed those for fumigation, but this difference reduces for larger mills. Costs for heater mats/fans/ducting to enable efficient heating of wall floor junctions have been estimated on the basis of trial costs but will be variable.

Table A.2 An approximate estimate of some of the costs associated with mill heat treatments

Larger Mill e.g. 30,000 cubic metres		
No of heaters 50	At £175.00	8750.00
No of distribution boards 5	At £175.00	875.00
Cost of electricity supplied by Mill		1500.00
Cost of fittings to allow electric power to be provided by the mill		500.00
Charge for heater mats / ducts / fans		1000.00
TOTAL COST(excluding labour)		**£12625.00**
Number of technicians required to prepare the treatment	4 x 10 hours each	
Number of technicians required to oversee the heat treatment	2 x 40 hours each	
Number of technicians required to clear the site	3 x 8 hours each	
Total labour requirement	**144 hours**	
Smaller Mill e.g. 8,000 cubic metres		
No of heaters 16	At £175.00	2800.00
No of distribution boards 2	At £175.00	350.00
Cost of electricity supplied by Mill		500.00
Cost of fittings to allow electric power to be provided by the mill		500.00
Charge for heater mats / ducts / fans		500.00
TOTAL COST(excluding labour)		**£4650.00**
Number of technicians required to prepare the treatment	2 x 10 hours each	
Number of technicians required to oversee the heat treatment	2 x 40 hours each	
Number of technicians required to clear the site	2 x 8 hours each	
Total labour requirement	**116 hours**	

The hours technicians would be required to work have been assessed but no costs are assumed at this stage because it is not known whether technicians would be staff from the mill, or provided by a contractor. Also it is not known what training, supervision and any other compliance requirements would be applicable.

The costings have been prepared on the basis of one days preparation followed by 40 hours under heat and 8 hours preparation for re-start during cooling (a total of 48 hours while production is stopped, normally Saturday early a.m. to Monday early a.m.).

THE RESPONSE OF INSECTS TO HEAT EXPOSURES

Rationale

The high temperatures required for control of insect pests in the disinfestation of structures are difficult to achieve evenly throughout the building and much effort is required to ensure that marginal areas reach target temperatures while other areas do not overheat. In theory, one way of reducing the burden on heat energy is to add carbon dioxide. At concentrations above 4-5%, carbon dioxide (CO_2) affects spiracular control and water balance in insects (Mellanby, 1934), and this seemed likely to present a serious challenge for survival at raised temperatures. Existing technology permits the dosing of flour mills with CO_2 up to about 10-12% in air. Beyond this level, it is hard to maintain concentration levels without the continuous running of multiple point gas application equipment, rendering the process uneconomic. For this reason tests were run on the effect of CO_2 at this level to see if target temperatures could be lowered.

From a similar standpoint tests were also run on the efficacy of a commercially available diatomaceous earth (DE) formulation 'Silico Sec' at raised temperatures. It was hoped that by using a combination of supporting measures, target temperatures might be lowered towards 40^{o}C. The DEs marketed for invertebrate pest control in the UK are composed of the safer amorphous, rather than crystalline silica which can cause respiratory problems. The mode of action against insects is through gentle abrasion and sorption of cuticular waxes, stripping away the insects' water-proofing and resulting in desiccation when insects crawl among dust-coated kernels (Ebeling, 1971; Le Patourel and Singh, 1984). DEs can be admixed to stored grain or applied to storage structures to control a wide range of invertebrate pests (Golob, 1997), and despite being less effective at high humidities, research has shown efficacy under damp UK conditions (Cook and Armitage, 2002).

DE has already been used to augment the effect of high temperature (>48°C) in flour mill trials in Canada (Fields *et al.*, 1997; Dowdy and Fields, 2002). In the current tests DE treatments were targeted at inaccessible areas such as crevices and voids, where the high temperature may not penetrate easily.

Methods

Preparation of test insects and mites

The mill pests used in the tests were laboratory stocks reared on an optimal food at 25^{o}C, 60% relative humidity (r.h.), or in the case of the flour mite in desiccators at 75-80% r.h. (Table A.3). Prior to exposure to high temperature insect stages were set up in 100 ml glass jars on 20-30 g of rearing medium, three replicates being provided for each exposure. Flour mite replicates were set up one week prior to exposure by adding a small spatula of culture (estimated 100-200 of mixed stages) to about four times the amount of culture medium in a glass tube sealed with a cotton wool plug.

For exposure of eggs of Mediterranean flour moth, adults reared at 25°C were collected from a freshly emerging culture by momentarily anaesthetising them with CO_2 before confining them in a plastic sieve by attaching a glass dish. Drinking water was provided by taping a moist cotton wool pad inside the dish. The sieve was placed over a collecting dish in a holding room at 25°C, 60-65% r.h. in a 16 h light, 8 h dark (LD 16:8) lighting regime. Under these conditions, eggs are laid mostly in the first hours of darkness (Bell, 1981). After "lights on" the following day eggs laid in the dish were collected and were counted out in batches of 50 on to watch glasses, using a fine paint brush and a binocular microscope, prior to adding to the exposure jar and transfer to the test temperature. Eggs with obvious defects were avoided.

For collecting eggs of beetles and psocids, flour (or yeast) was sieved through a 100 mesh (150 µm aperture) sieve and a thin layer placed on the bottom of a large crystallising dish coated with fluon on the inside. At least 200 adults were placed on the flour and each dish covered with a muslin square secured by an elastic band. The dishes were incubated for three days, at 25°C, 60% r.h., LD 16:8. After 3 days, the adults were removed using a 30 mesh sieve and the eggs isolated from the food using a 72 mesh (212 µm aperture) sieve for high temperature exposure as described for moths.
Other stages were obtained by allowing development to occur from egg laying for the appropriate period for each species. In these, numbers were not restricted to 50 individuals per replicate as adults were introduced to the jars and allowed to lay freely to seed the culture. For all tests, some of the cultures were held continuously at 25°C to act as controls, and the subsequent emergence was used to estimate the test culture sample size. Results from all the tests was assessed on the basis of adult emergence after incubation at 25°C following high temperature exposure.

Provision of CO_2 at high temperature

Insect cultures were exposed in chambers or desiccators in constant temperature rooms. Carbon dioxide was supplied from a cylinder source via a Signal gas blender regulating the output to about 10% in air in the first series of tests and to higher levels in later tests. Humidity was maintained at 50% r.h. by passing the gas mixture over sulphuric acid at a flow rate of 1 l/min for chamber tests or through glycerol solution at a flow rate of 100 ml per minute for desiccators. High temperature controls were held in the same constant temperature room in which there was a hourly air change. The temperatures inside desiccators were monitored by "Tinytag" temperature recorders from which data from each exposure was downloaded on to a computer.

Table A.3 Rearing food of test species

Species	Rearing food
Flour mite *Acarus siro*	Yeast/Wheat germ (3:1)
Turkish grain beetle *Cryptolestes turcicus*	Rolled oats/Yeast (10:1)
Mediterranean flour moth *Ephestia kuehniella*	Wheatfeed/Glycerol/Yeast (10:2:1)
Broad horned flour beetle *Gnatocerus cornutus*	Wheatfeed/Fishmeal/Yeast (8:4:1)
Booklouse *Liposcelis bostrychophila*	Dried yeast
Australian spider beetle *Ptinus tectus*	Fishmeal/yeast (16:1)
Granary weevil *Sitophilus granarius*	Whole wheat
Mealworm *Tenebrio molitor*	Wheatfeed/Rolled oats/yeast (5:5:1)
Rust-Red flour beetle *Tribolium castaneum*	Wholemeal flour/yeast (20:1)
Confused flour beetle *Tribolium confusum*	Wholemeal flour/yeast (20:1)

Tests on the diatomaceous earth formulation Silico-Sec

Bioassays on dust were run in controlled environment rooms at exposure conditions of 25°C, 70% r.h.; 30°C, 50% r.h.; 35°C, 40% r.h. and 40°C, 30% r.h. The decrease of r.h. with increasing temperature was chosen to reflect humidities that could be encountered in flour mills when heated air was applied. A higher r.h. (50%) was tested at 40°C to simulate a local availability of free water.

The dry dust treatments were achieved by sieving sufficient quantity of DE through a 250 μm wire sieve to give an even coating on 14 cm diameter glass Petri dishes. The DE was applied at doses of 1, 5, 7.5 and 10 g/m^2. Untreated dishes were used as controls showing the effect of heating alone. For each temperature humidity combination, an additional set of untreated dishes was set up at 25°C, 70% r.h. as a batch control. The dishes were held overnight in controlled environment rooms at each condition before exposure of test insects. Insects were reared at 25°C, 70% r.h. After conditioning overnight at 30°C, 70% r.h., batches of 25 two to four week old adults of *Sitophilus granarius* (L.) and *Tribolium castaneum* (Herbst) were added to each separate dish to provide 5 replicate dishes for each treatment. Batch controls were set up with insects held continuously at 25°C, 70% r.h. Mortality was assessed 24 and 48 hours after treatment. After the 48-hour assessment, the insects were transferred to jars containing wheat at 15.5% moisture content and recovery was assessed after a further 7 days.

The percentage mortality data was subjected to the angular transformation ($\sin^{-1} \surd p$). The data were then statistically compared using ANOVA at the 5% probability level, with individual comparisons made using Tukey's pair test.

Results

Effect of heat alone on insects

The results of heat exposures at 40°C, 50% r.h. against *Cryptolestes turcicus*, *Liposcelis bostrychophila*, *Sitophilus granarius*, *Tribolium castaneum*, *T. confusum*, *Ephestia kuehniella, Gnatocerus cornutus, Ptinus tectus*, *Tenebrio molitor* and *Acarus siro* are set out in Table A.4. The first five species showed various levels of survival after being held for 72 h at 40°C, the longest exposure tested. The most heat tolerant species, *T. castaneum*, required a temperature of 46°C for control with heat alone within 48 h and 48 °C to achieve complete kill of all stages within 24 h (Table A.5).. It is noteworthy that this species is the most common pest of flour mills world-wide.

For *S. granarius*, which had shown some survival at 40-44°C, the effect of adding 10% CO_2 was highly beneficial (Table A.6). The target temperature for control within 24 - 48 h was reduced to 40°C and survival levels were reduced at each exposure. For *Tribolium confusum*, one of the species showing very high levels of survival after 72 h at 40°C, the addition of CO_2 had very little effect on older stages in reducing survival, although survival of younger stages after a 72 h exposure was prevented (Table A.6). At 44°C, 50% r.h., however, the presence of CO_2 at 10% seemed to adversely affect the effectiveness of the exposure in several species, in some cases lengthening the time required for complete control over that for heat alone (Table A.7), eggs of *L. bostrychophila* and older stages of *T. castaneum* surviving 48 h exposures.

Further tests conducted at 44°C, 50% r.h., on *T. castaneum* and *S. granarius* with raised levels of CO_2 to show the point at which CO_2 started to increase mortality (Tables A.8 – A.11) showed that there was still no benefit by adding even 30% of CO_2 in air. To some extent the effect could be explained by a small temperature difference between the heat alone and the heat plus CO_2 exposures, the latter being up to 0.8°C cooler. Fig. A.1 shows a typical temperature trace as monitored by thermocouples for a test exposure. Small temperature differences between heat alone treatments revealed that an 0.5°C difference at these high temperatures had a greater effect on survival than the presence of absence of CO_2.

An additional test to check whether raised oxygen would have an opposite effect on insect metabolism to the passive or inhibitory effect of raised CO_2 showed no advantage over heating in air by holding test insects in a 30% oxygen atmosphere at 44°C (Table A.12). Fig. A.2 shows the temperature trace for this test.

Dust treatments

The DE treatments significantly enhanced the effects of heating alone ($p > 0.05$). At 25°C r.h., mortality of *S. granarius* was <50% for all DE doses after 48 hrs, but rose to over 90% for all doses when heating took place (Table A.13). Although there were significant differences between the levels that DE were dosed at 25°C, there was no significant difference at the higher temperatures ($p < 0.05$). In spite of *T. castaneum* adults being far more tolerant to heat alone than *S. granarius*, the DE treatments were very effective against this species and reversed the order of tolerance. At 25°C, mean mortality of *T. castaneum* was >87%, with no significant difference between any of the doses ($p < 0.05$). Complete mortality occurred at every dose at 30°C and above after 48 hrs (Table A.14).

After the seven-day recovery period on food, mortality rose to 100% for all DE doses against both species, for all temperatures other than 25°C (Table A.15). Even at 25°C, mortality rose to >95%, with the exception of the lowest DE dose against *S. granarius*.

Discussion

All insect species other than *T. castaneum* were controlled by a 48-h exposure at 44°C while the flour mite succumbed to a few hours exposure at 40°C. For kill of *T. castaneum* within 24 h, the exposure temperature needed to be increased to 48°C. The results obtained are compatible with those collated for many species by Fields (1992) in his review of extreme temperature effects. Jay (1986) reported that exposure to CO_2 at 43°C achieved control of all stages of *T. castaneum* within 48 h with 63% CO_2, decreasing to only 6 h with 99% CO_2. The current tests showed that with 10-30% CO_2 there was no advantage over heat alone and that these lower levels of CO_2 may even detract from the efficacy of the heat exposure.

The use of heat offers a solution to the problem of finding a replacement of methyl bromide to disinfest flour mills but there are a number of factors that must be taken into account for practical applications of heat to be effective. Although air temperatures can readily be brought up to target temperatures, most pests are hidden away from view in harbourages ranging from packaging materials to crevices in walls or floors, and in such locations more time must be allowed for temperatures to build up. The overriding need is to achieve an adequate distribution of heat to those regions acting as a heat sink during the initial build up of temperature without over-heating any other area. Whereas the conventional heat application methodology of circulating heated air and relying largely on convectional heating to achieve target temperatures can still be employed, care is needed to selectively direct the heated air supply towards the difficult zones identified as potential infestation sources. This will require the use of polythene ducting to allow direct contact of the heated air stream with the surface of wall floor joints and concrete surfaces prior to its release to heat the surrounding air space.

Heat requires energy and measures which can help reduce the level of heat are worth investigating. Carbon dioxide is known to act as a respiratory stimulant at concentrations as low as 2-3% in air (Wigglesworth, 1965; Mellanby, 1934) and causes insect spiracles to remain open even in the presence of oxygen (Hoyle, 1960), increasing water loss. Thus under conditions of low humidity at temperatures stimulating active development the presence of low levels of CO_2 results in rapid water loss and death by desiccation. Hence it was anticipated at the outset of this study that at temperatures above the normal developmental range, the effect of adding CO_2 at up to 10% would be to greatly enhance the prospects for rapid disinfestation.

The effect of carbon dioxide (CO_2) on insect physiology is, however, complex and there are differences between different insect groups. Low levels of CO_2 (<15%) have little effect on survival of stored product species at normal temperatures for development if humidities are high, indicating some acclimation within this group to fermenting or partly anaerobic conditions. The effect of spiracular opening on water loss is reduced in many typical small beetle pests of grain, because most spiracles open into the subelytral space which acts as a barrier to water loss. Levels of CO_2 above 20-40% in air appear to act via the oxidative metabolic cycle and the remaining oxygen in the atmosphere enhances the effect of the gas mixture up to about the 90% CO_2 level. Because of the solution of CO_2 in water to form carbonic acid and the resultant tendency for an alteration of pH, it has long been suspected that CO_2 toxicity may be explained by the inhibition of various enzyme systems or by interference with cell membranes. Navarro and Friedlander (1975) investigated the pyruvate and lactate levels in the haemolymph of *E. cautella* pupae exposed to CO_2 and noticed that while pyruvate levels remained constant, there was a steady increase in lactate as CO_2 was increased from 0 to 89%. Further studies revealed drastic reductions in ATP levels in treated pupae, indicating a lesion in the electron transport chain (Friedlander and Navarro, 1979). Neural transmitters such as acetyl choline require high levels of ATP for regeneration. The tripeptide glutathione, also involved in neural transmission as well as in many biosynthetic and metabolic pathways, is also greatly suppressed in CO_2-treated pupae of *E. cautella* (Friedlander and Navarro, 1984). Furthermore, CO_2 exposure has been shown to inhibit the enzyme systems which "top up" deficiencies of the coenzyme NADPH which is involved in biosynthesis and microsomal metabolism and, with NADH, in the production of ATP. Hence decarboxylation of malate to pyruvate and of 6-phosphogluconic acid to 5-ribulose phosphate in the pentose phosphate cycle are inhibited by raised CO_2 levels (Friedlander et al., 1984).

High levels of CO_2 (>75%) have an anaesthetising effect on insects from which they usually make a complete recovery if restored to air quickly (Dawson, 1995), but if exposure to 95% CO_2 in air is prolonged, death by asphyxiation occurs in much the same way as would exposure to a nitrogen atmosphere. For some insects, exposure at such high levels of CO2 are less effective than exposures at around 60% in air (Bell, 1984; Leong and Ho, 1995).

Whereas initial results indicated that the presence of 10% CO_2 did shorten the exposure time to achieve 100% kill (see Table A.6) for some species at 40°C, subsequent tests on several other species showed either no effect or an increase in survival and time required for control at 44°C in the presence of CO_2. However small temperature differences occurred in some exposures so that CO_2-treated batches ended up with slightly lower mean temperatures for the exposures, probably as a result of the gas being fed continuously from a clinder supply. Further tests at 10 – 30% levels of CO_2 in air confirmed the non-contributory role of this range of gas levels, a temperature increase from 43°C of less than 1°C having a far greater effect on survival than the presence of CO_2. There are thus serious impediments for success in the pursuit of a combination method based on CO_2 and heat.

High temperatures are lethal because they cause denaturation of proteins and liquidisation of phospholipids in cell membranes. In the short term cooling by evaporative loss of water can confer protection but this mechanism cannot explain the current results. It is possible that the raised temperature has lowered the concentration range over which CO_2 has a direct effect on enzyme inhibition, slowing down metabolism and the destructive processes induced by heat. It is interesting to note that raising oxygen levels to 30%, which may have had a stimulatory rather than inhibitory effect on enzyme systems, also did nothing to help the efficacy of the heat treatment.

In contrast to modified atmosphere applications, the use of DEs has the potential to be an excellent subsidiary treatment to the heating of mills, and could equally well be used to provide residual protection as a component of other control strategies, including fumigation. The combination of heat and DE treatments had a complementary effect, which has also been found by other workers. Dowdy (1999) exposed *T. castaneum* adults on glass Petri dishes to temperatures of 34 or 50°C, with and without DE. In these tests, adults were exposed to four different DE products at 0 or 5 g/m^2 for 15 or 30 minutes and mortality assessed after 24 and 7 day recovery periods. He found that whereas the exposures at 34°C had minimal effect on insect survival, those at 50°C caused up to 100% mortality.

The intention in the current programme was to use DEs for treating voids and crevices in the mill structure to supplement heat disinfestation and provide subsequent residual protection. The increased mortalities among insects placed on food to recover suggests, even if adults move away from DE-treated harbourages after the heat treatment has finished, they may still die. The higher mortalities after 7 days gives a truer picture of the success of the treatment, and suggests complete control of these two species can be achieved at a dose as low as 1 g/m^2, providing the temperature can be raised to 30°C. In a trial in Canada, a mill was heated to ca. 50°C and DE treatments were evaluated on the floor surfaces (Dowdy and Fields, 2002). A DE dose of 0.31 g/m^2 was considered to give no advantage over heating alone, in contrast to a dose of 1 – 2 g/m^2. Future studies need to include a wider range of insect species and investigate effects against different stages. Since there can be variation in efficacy between different DEs, (Dowdy, 1999) these studies should also include other DE products.

For heat treatments without any enhancement of efficacy from added CO_2, higher target temperatures must be achieved to achieve satisfactory efficacy than those originally envisaged and there is no scope for a temperature reduction. The use of inert dusts provides an additional protection for insects in voids and inaccessible regions, but from the outset it was recognised that such regions would always require an alternative as temperatures would always trail the heat control temperatures obtained throughout the main area of plant and air space. Two principal findings emerge from this study to improve the efficacy of heat-based treatments in commercial practice. Firstly, the better methods of heat transfer that have been demonstrated here need to be implemented. Secondly, longer times need to be allowed for heating structures than currently practised in order to achieve the target temperatures of 48^{o}C for 24 hours or longer which are needed to achieve complete control of pests.

Table A.4. Effect of exposures at 40°C on the survival of mill pests

Species	Stage	Time some survive (h) and survival level	Time for 100%kill (h)
Flour mite *Acarus siro*	All	-	10
Turkish grain beetle *Cryptolestes turcicus*	Younger Older	72 (10%) 72 (25%)	- -
Mediterranean flour moth *Ephestia kuehniella*	Eggs Larvae	- 24 (7%)	24 48
Broad horned flour beetle *Gnatocerus cornutus*	Younger Older	- 24 (4%)	24 48
Booklouse *Liposcelis bostrychophila*	Eggs Nymphs, adults	72 (>50%) 48 (4%)	- 72
Australian spider beetle *Ptinus tectus*	Older	48 (1%)	72
Granary weevil *Sitophilus granarius*	All	72 (<1%)	-
Mealworm *Tenebrio molitor*	Younger Older	48 (2%) 24 (2%)	- 48
Rust-Red flour beetle *Tribolium castaneum*	All	72 (>50%)	-
Confused flour beetle *Tribolium confusum*	All	72 (>50%)	-

Table A.5 Exposures at different high temperatures required for control of storage pests

Temperature (°C)	Species	Stage	Time needed for 100% kill (h)
38	Flour mite *Acarus siro*	All	10
44	Confused flour beetle *Tribolium confusum*	All	48
	Granary weevil *Sitophilus granarius*	All	32
	Turkish grain beetle *Cryptolestes turcicus*	All	48
	Mediterranean flour moth *Ephestia kuehniella*	Larvae	8
46	Rust-Red flour beetle *Tribolium castaneum*	Younger Older	48 24
	Confused flour beetle *Tribolium confusum*	All	24
	Turkish grain beetle *Cryptolestes turcicus*	All	24
	Booklouse *Liposcelis bostrychophila*	All	16
47	Rust-Red flour beetle *Tribolium castaneum*	Younger	16
48	Rust-Red flour beetle *Tribolium castaneum*	Younger	10

Table A.6. Effect of 10% carbon dioxide at 40°C, 50% r.h., on survival of two beetles

Species	Stage	Without CO_2 Time some survive (h) (% survival)	Without CO_2 Time for 100%kill (h)	With 10-11% CO_2 Time some survive (h) (% survival)	With 10-11% CO_2 Time for 100%kill (h)
Granary weevil	Younger	48 (<1%)	72	16 (43%)	24
Sitophilus granarius	Older	72 (<1%*)	-	24 (42%)	48
Confused flour beetle	Younger	72 (>50%)	-	48 (33%)	72
Tribolium confusum	Older	72 (>50%)	-	72 (>50%)	-

* 23% survival of 48-h exposure

Table A.7. Effect of 10% carbon dioxide at 43.8 ± 0.3°C, 50% r.h., on survival of mill pests

Species	Stage	Without CO_2 Time some survive (h) (% survival)	Without CO_2 Time for 100%kill (h)	With 10-11% CO_2 Time some survive (h) (% survival)	With 10-11% CO_2 Time for 100%kill (h)
Turkish grain beetle *Cryptolestes turcicus*	Older	28 (1%)	32	32 (8%)	40
Booklouse	Eggs	32 (1%)	48	48 (5%)	-
Liposcelis Bostrychophila	Nymphs, adults	16 (2%)	24	16 (4%)	24
Granary weevil	Younger	16 (19%)	20	10 (5%)	16
Sitophilus granarius	Older	24 (1%)	32	20 (5%)	24
Rust-Red flour beetle	Younger	24 (<1%)	40	48 (9%)*	-
Tribolium castaneum	Older	48 (1%)	72	48 (10%)	-
Confused flour beetle	Younger	32 (0.4%)	48	32 (1%)	48
Tribolium confusum	Older	24 (8%)	32	32 (30%)	48

* Temperature was only 43.0°C

Table A.8. Survival of *T. castaneum* in a 20% carbon dioxide atmosphere at 44°C and 50% r.h. - subsequent adult emergence after juvenile treatment (mean of 3 reps)

Time (Hours)	Heat Younger stages (<3 weeks)	Heat Older stages (>3 weeks)	Heat + CO_2 Younger stages (<3 weeks)	Heat + CO_2 Older stages (>3 weeks)
Control (25°C)	2004.0	1045.0	2004.0	1045.0
16	1107.0	572.3	1108.7*	616.3
24	529.0	423.0	600.0*	404.0
40	37.7	184.0	164.0*	114.0
48	11.7	91.3	76.3*	88.7
Control (25°C)	1686.7	-	1686.7	-
16	456.7	-	662.3	-
24	184.0	-	355.7	-
40	0.0	-	0.3	-
48	0.0	-	0.0	-

*Temperature with CO_2 atmosphere was 43°C, test repeated below at 44°C

Table A.9. Survival of *T. castaneum* in a 30% carbon dioxide atmosphere at 44°C and 50% r.h. - subsequent adult emergence after juvenile treatment (mean of 3 reps)

Time (Hours)	Heat Younger stages (<3 weeks)	Heat Older stages (>3 weeks)	Heat + CO2 Younger stages (<3 weeks)	Heat + CO2 Older stages (>3 weeks)
Control (25°C)	1398.0	1473.3	1398.0	1473.3
16	142.7	1072.3*	238.3	741.3
24	10.7	422.7*	64.0	276.0
40	0.0	4.0*	0.0	10.0
48	0.0	0.0*	0.0	0.0

*Mean temperature was 44.5°C

Table A.10. Survival of *S. granarius* in a 20% carbon dioxide atmosphere at 44°C and 50% r.h. - subsequent adult emergence after juvenile treatment (mean of 3 reps)

Time (Hours)	Heat Younger stages (<3 weeks)	Heat Older stages (>3 weeks)	Heat + CO2 Younger stages (<3 weeks)	Heat + CO2 Older stages (>3 weeks)
Control (25°C)	904.0	987.0	904.0	987.0
16	1.0*	32.0	0.0	81.0
24	0.0*	15.0	0.0	0.0
32	0.0*	0.0	0.0	0.0
48	0.0*	0.0	0.0	0.0
Control (25°C)	1138.0	-	1138.0	-
8	0.3	-	156.3	-
16	0.0	-	0.0	-
24	0.0	-	0.0	-

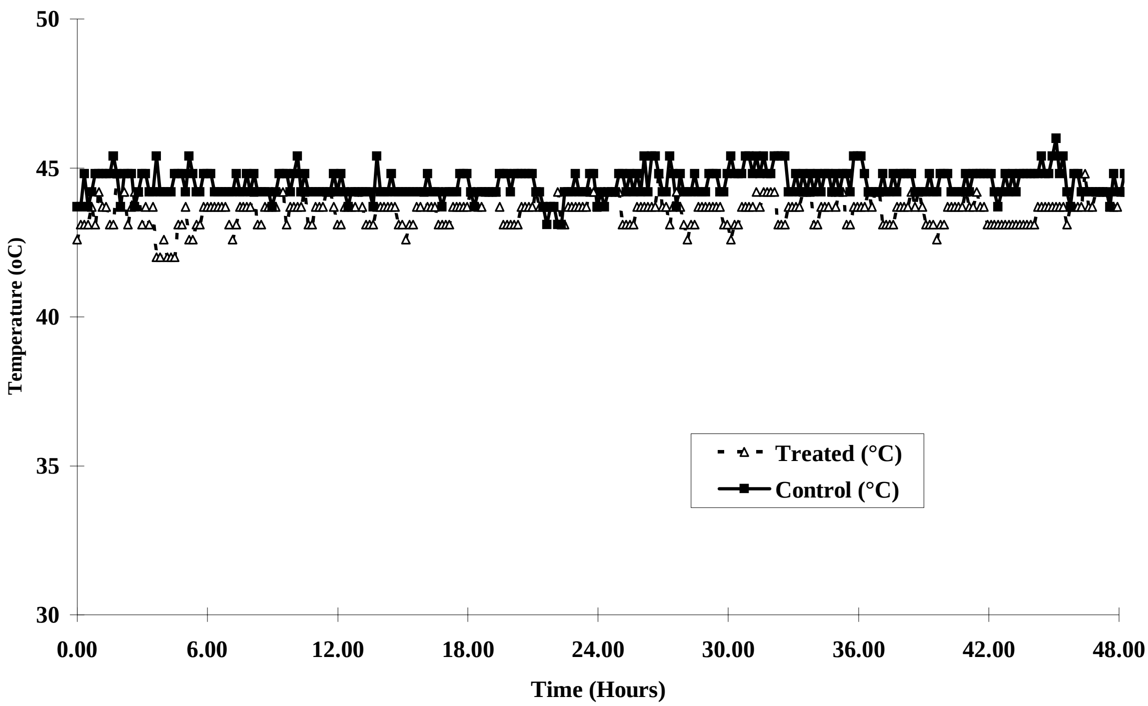
* Mean temperature 43.7°C

Table A.11. Survival of *S. granarius* in a 30% carbon dioxide atmosphere at 44°C and 50% r.h. - subsequent adult emergence after juvenile treatment (mean of 3 reps)

Time (Hours)	Heat		Heat + CO2	
	Younger stages (<3 weeks)	Older stages (>3 weeks)	Younger stages (<3 weeks)	Older stages (>3 weeks)
Control (25°C)	1340.0	1168.7	1340.0	1168.7
8	12.3	365.0*	0.7	479.0
16	0.0	0.0*	0.0	0.0
24	0.0	0.0*	0.0	0.0

*Mean temperature was 44.5°C

Fig. A.1. **Temperature profiles within the treatment chamber and in controlled environment room containing the chamber over the 48-hour exposure period of younger stages of *T. castaneum* and *S. granarius* with 30% carbon dioxide**

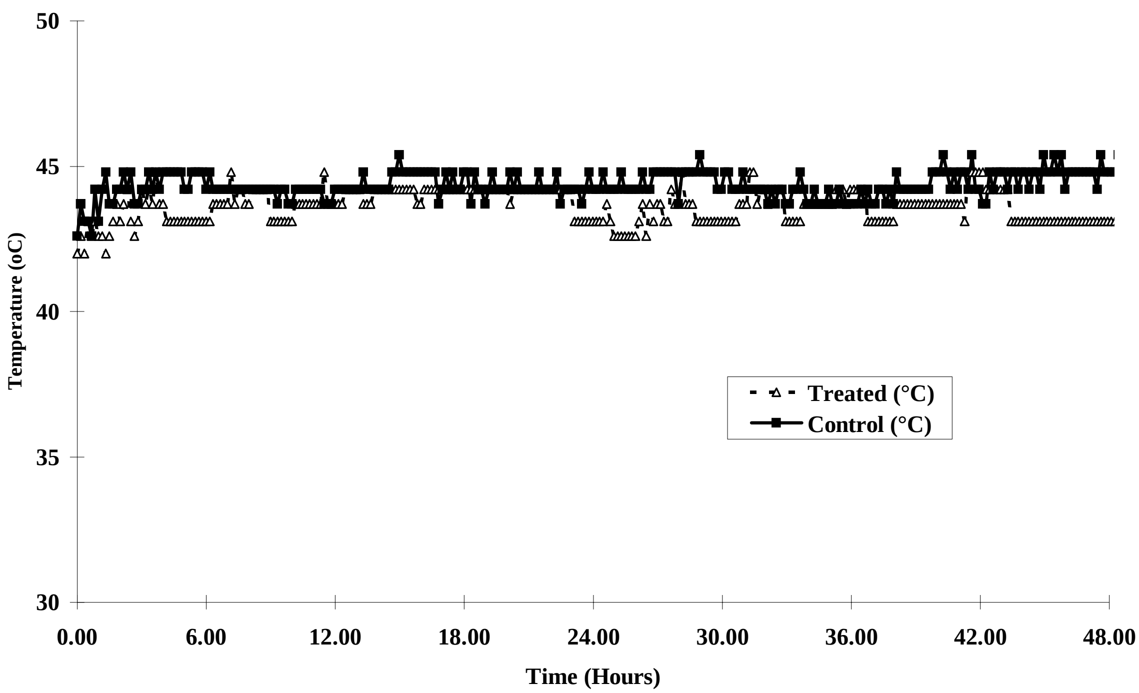


Temperature (°C)	Treated	Control
Average	43.6	44.4
Minimum	42.0	43.1
Maximum	44.8	46.0

Table A.12. Survival of *T. castaneum* in a 30% oxygen atmosphere at 44 $\pm$ 0.4°C and 50% r.h. (mean of 3 reps)

Time (Hours)	Heat		Heat + CO2	
	Younger stages (<3 weeks)	Older stages (>3 weeks)	Younger stages (<3 weeks)	Older stages (>3 weeks)
Control (25°C)	1811.0	1546.7	1811.0	1546.7
16	334.0	878.7	691.0	1144.7
24	20.7	289.7	236.0	577.7
40	0.3	1.3	2.0	30.0
48	0.0	0.0	0.0	0.7

Fig. A.2. Temperature profiles within the treatment chamber and in controlled environment room containing the chamber over the 48-hour exposure period of younger stages of *T. castaneum* with 30% oxygen



Temperature (°C)	Treated	Control
Average	43.6	44.3
Minimum	42.0	42.6
Maximum	44.8	45.4

Table A.13. Mean % mortality for *S. granarius* after exposure to DE at 5 temperature /humidity combinations, simulating mill conditions during heating (range in parenthesis; n=5; * n=25).

Dose	24 hrs exposure					48 hrs exposure				
	25°C 70%	30°C 50%	35°C 40%	40°C 30%	40°C 50%	25°C 70%	30°C 50%	35°C 40%	40°C 30%	40°C 50%
No DE	0 * *a* (0)	0 *a* (0)	0 *a* (0)	80 *a* (60-92)	74 *a* (64-84)	0 * *a* (0)	0 *a* (0)	21 *a* (16-28)	100 *a* (100)	100 *a* (100)
1 g/m^2	0 *a* (0)	6 *b* (0-8)	50 *b* (28-84)	100 *b* (100)	100 *b* (100)	16 *b* (4-24)	94 *b* (88-100)	100 *b* (100)	100 *a* (100)	100 *a* (100)
5 g/m^2	0 *a* (0)	14 *b* (8-16)	91 *c* (84-100)	100 *b* (100)	100 *b* (100)	40 *c* (36-44)	99 *b* (96-100)	100 *b* (100)	100 *a* (100)	100 *a* (100)
7.5 g/m^2	0 *a* (0)	13 *b* (4-20)	94 *c* (84-100)	100 *b* (100)	100 *b* (100)	39 *c* (20-48)	99 *b* (96-100)	100 *b* (100)	100 *a* (100)	100 *a* (100)
10 g/m^2	0 *a* (0)	11 *b* (0-16)	94 *c* (84-100)	100 *b* (100)	100 *b* (100)	33 *c* (20-44)	98 *b* (92-100)	100 *b* (100)	100 *a* (100)	100 *a* (100)

Proportions in the same column followed by the same letter are not significantly different at p = 0.05

Table A.14 Mean % mortality for *T. castaneum* after exposure to DE at 5 temperature/humidity combinations, simulating mill conditions during heating (range in parenthesis; n=5; * n=25).

Dose	24 hrs exposure					48 hrs exposure				
	25°C 70%	30°C 50%	35°C 40%	40°C 30%	40°C 50%	25°C 70%	30°C 50%	35°C 40%	40°C 30%	40°C 50%
No DE	0 * *a* (0)	0 *a* (0)	0 *a* (0)	0 *a* (0)	0 *a* (0)	0 * *a* (0)	0 *a* (0)	0 *a* (0)	0 *a* (0-4)	0 *a* (0)
1 g/m^2	34 *b* (20-52)	88 *b* (80-92)	100 *b* (100)	100 *b* (100)	99 *b* (96-100)	89 *b* (76-96)	100 *b* (100)	100 *b* (100)	100 *b* (100)	100 *b* (100)
5 g/m^2	20 *bc* (4-29)	90 *b* (84-96)	99 *b* (96-100)	100 *b* (100)	100 *b* (100)	87 *b* (78-96)	100 *b* (100)	100 *b* (100)	100 *b* (100)	100 *b* (100)
7.5 g/m^2	19 *bc* (12-24)	85 *b* (80-88)	100 *b* (100)	100 *b* (100)	100 *b* (100)	90 *b* (80-96)	100 *b* (100)	100 *b* (100)	100 *b* (100)	100 *b* (100)
10 g/m^2	16 *c* (8-20)	82 *b* (76-96)	100 *b* (100)	100 *b* (100)	100 *b* (100)	87 *b* (77-96)	100 *b* (100)	100 *b* (100)	100 *b* (100)	100 *b* (100)

Proportions in the same column followed by the same letter are not significantly different at p = 0.05

Table A.15. Mean % mortality for both species after 7 days recovery on wheat at 25°C and 70% r.h. (range in parenthesis; n=5; * n=25).

Dose	*S. granarius*					*T.castaneum*				
	25°C 70%	30°C 50%	35°C 40%	40°C 30%	40°C 50%	25°C 70%	30°C 50%	35°C 40%	40°C 30%	40°C 50%
No DE	1 * *a*	2 *a*	42 *a*	100 *a*	100 *a*	0 * *a*	0 *a*	4 *a*	19 *a*	9 *a*
	(0-4)	(0-4)	(28-64)	(100)	(100)	(0-4)	(0)	(0-8)	(8-40)	(0-16)
1 g/m^2	82 *b*	100 *b*	100 *b*	100 *a*	100 *a*	99 *b*	100 *b*	100 *b*	100 *b*	100 *b*
	(72-96)	(100)	(100)	(100)	(100)	(96-100)	(100)	(100)	(100)	(100)
5 g/m^2	96 *bc*	100 *b*	100 *b*	100 *a*	100 *a*	98 *b*	100 *b*	100 *b*	100 *b*	100 *b*
	(92-100)	(100)	(100)	(100)	(100)	(96-100)	(100)	(100)	(100)	(100)
7.5 g/m^2	97 *c*	100 *b*	100 *b*	100 *a*	100 *a*	100 *b*	100 *b*	100 *b*	100 *b*	100 *b*
	(92-100)	(100)	(100)	(100)	(100)	(100)	(100)	(100)	(100)	(100)
10 g/m^2	94 *c*	100 *b*	100 *b*	100 *a*	100 *a*	98 *b*	100 *b*	100 *b*	100 *b*	100 *b*
	(88-100)	(100)	(100)	(100)	(100)	(96-100)	(100)	(100)	(100)	(100)

Proportions in the same column followed by the same letter are not significantly different at $p = 0.05$

SECTION B. DESCRIPTION OF TRIALS

1. MILL STRUCTURAL HEATING TRIAL AT HULL

Introduction

The trial was carried out on one floor of a working flour mill at Hull. The objectives were as follows:

1. To measure the thermal response of structures and machinery to quick heating.
2. To test a perforated polythene duct heat distribution system.
3. To observe the temperature distribution from heaters without ducting.

Methods

Three heating tests were made during a one-week period, allowing the structure to cool between each test. Two 18 kW heaters designed to control room temperature at 50°C by thermostatic control were employed in the trials. Initial heating calculations for the test zone showed that the heaters would be capable of raising the temperature 14°C above ambient and were thus not expected to switch off during the tests unless there was a fault.

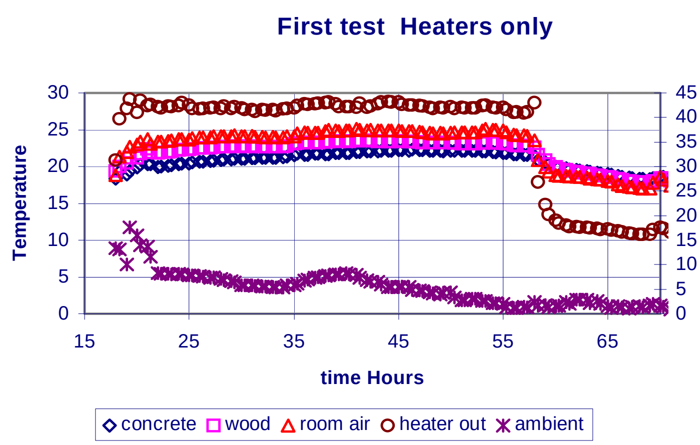
The most important part of each test was the warm up period. Temperature measurements of the room air and the structure surfaces were made at intervals during the test. Surface temperatures were measured with an infra-red thermometer. Air and some surface temperatures were measured by thermocouples stuck to the surface and recorded by an automatic data logging system.

Results

Heating test 1: Two heaters without ducting in diagonal corners.

The average temperatures of wood, concrete and room air are plotted in Fig. 1.1.

Fig. 1.1 Surface and air temperature plots in the first test at Hull

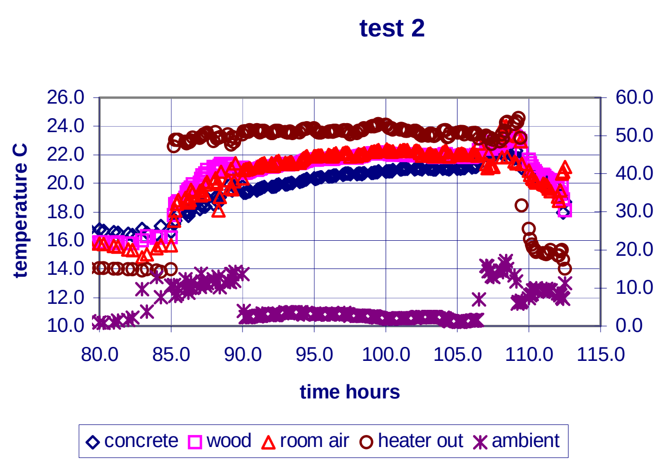


The right hand temperature scale in Fig. 1.1 relates to the heater discharge temperature only. The trial took place in cold weather with temperatures falling throughout the trial towards . The maximum temperature achieved was 25°C.

Heating test 2: Two heaters with two polythene ducts each laid near the walls

The time scale for the result chart of test 2 is only 24 hours compared with 50 hours for test 1. Results are shown in Fig. 1.2. Although ambient temperatures recovered during this trial period the structure started at a much lower temperature than Test 1 and the maximum temperature achieved was about 24°C.

Fig. 1.2 Surface and air temperature plots in the second test at Hull



Heating test 3: Temperature rises with directed air flows

In this trial one heater was directed at a roller mill while the other heater was connected to a polythene duct directed to a section of wall. Results are shown in Figs 1.3 and 1.4. Temperatures at the mostly metal surfaces of the roller mill were raised about 8°C from ambient within 15 hours but then levelled off. The concrete floor heated slowly but steadily throughout the trial period.

On the vertical axes in Fig 1.4, zero represents the wall floor junction. Below this is the floor and above it is the wall. The commercially perforated duct delivered more heat to the closed end than to the fan end. The section of chart at 17 m shows a short section of unheated wall.

Fig. 1.3 Results from directional heating of roller mills

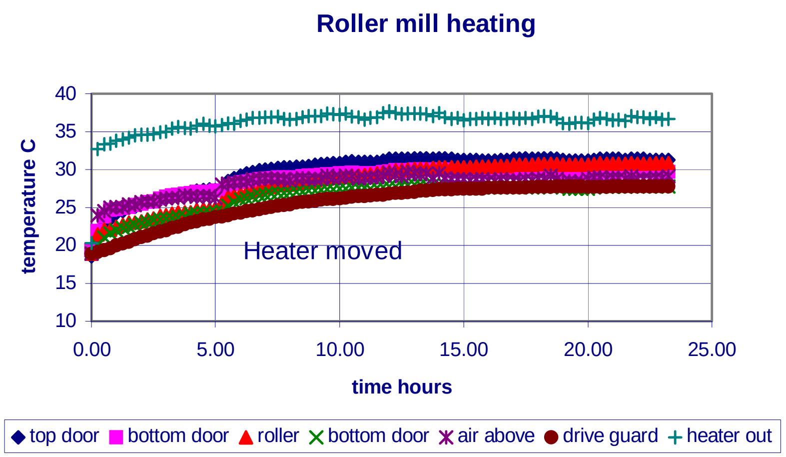
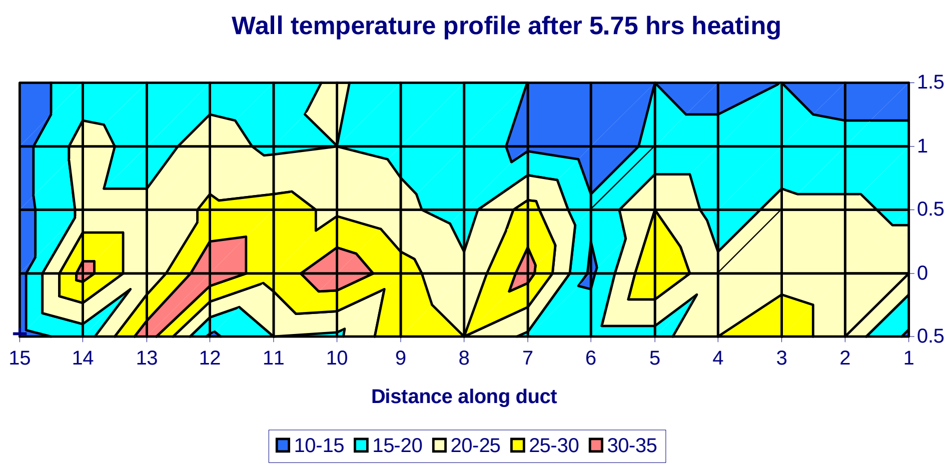
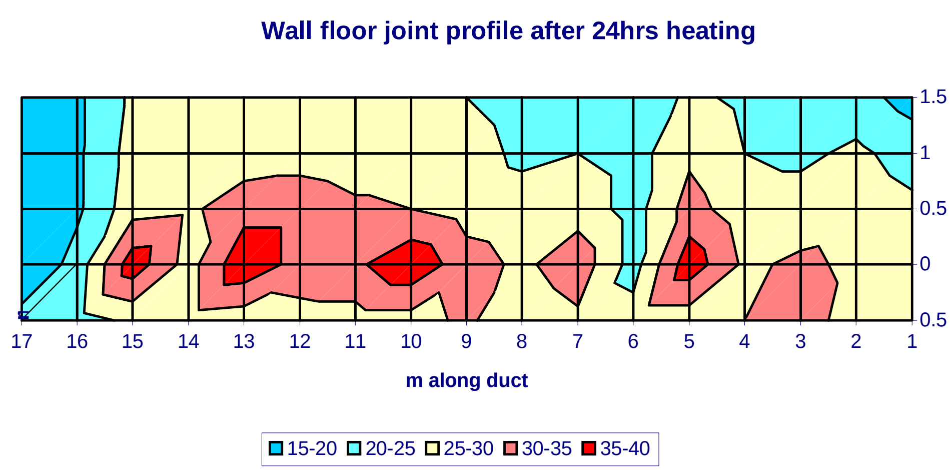


Fig. 1.4 Wall temperature profiles at two heating times





Observations and conclusions

- The temperatures achieved in the room were lower than calculations suggested. This was attributed to an un-quantified air exchange as a result of the continued operation of the plant.
- All the results show that the surface of wooden structures increase quickly and thereafter track room air temperature closely.
- Concrete structures warm up much more slowly and cool more slowly.
- Heater output temperature was effectively controlled at 43^{o}C during the first test and at about 50^{o}C during the second and third tests.
- The polythene ducts restricted the heater output and slowed the overall heating rate that was observed.
- There were some disturbances to the logged record as a result of interference caused by the computer that was used to display the current temperatures.
- The roller mill heated to a steady temperature in 14 hours. The initial stages of heating were restricted by the changes in heating air temperature over the first 6 hours.
- Test 3 showed that the wall floor joint can be heated above the average room air temperature by directing hot air onto part of the structure. This is also shown to be a local effect. The maximum temperature that can be achieved by local heating is limited by the maximum air temperature that the heaters can deliver.
- The heat flux measurements were unreliable and are not reported.

2. MILL HEATING TRIAL, STUTTGART 23/24 NOV. 2001

Introduction

The flour packing plant of the Fesenmeyer BackerMuhlen in Stuttgart was scheduled for thermal disinfestation over the weekend 23-25th November. The project team were given the opportunity to observe the set-up and first 24 hours of the commercial treatment using the 18 kW convectional heaters powered with an 0.75 kW fan manufactured and operated by the German company ThermoNox.. The other half of the mill containing the flour production plant had been treated the previous weekend.

The plant is housed in a substantial reinforced concrete structure on 8 floors. The outside walls are about 25 cm thick and are penetrated by only a small number of windows. The internal support structure comprises 1m x 1m reinforced concrete columns. The dividing floors are formed from concrete. Part of the floor on level 5, where our measurements were concentrated, is of 25 mm thick block board. Four cylindrical flour storage bins together with the associated large common vertical spaces occupy about half of the internal volume from floors 4 to 8. At the time of the trial packing machinery was installed on the lower floors. A number of floors were used for temporary storage of pallet loads of bagged flour or supplies of paper sacks.

Methods

Heater placement and adjustment

The heaters were concentrated on the lower floors of the mill. It was expected that heated air escaping from the lower levels would find its way up through the spaces around flour bin bases. Power for the heaters was distributed by a portable distribution panel. Heavy power cables were threaded through openings in the floors and connected directly to the site main supply. Heaters were plugged into the distribution panel on the nearest floor.

Six heaters per floor were located on the lower floors and four on the upper ones. Heaters were placed so that they produced horizontal rotating air movements. Care was taken to avoid placing heaters so that hot air was directed onto electrical/electronic control boxes. Some extra fans blowing directly down onto the floor were operated in an attempt to improve the air movement and heat transfer at floor level. The objective was to concentrate on directing heat to the floor of each level so that when other parts of the structure warmed up, any insects falling on to floors were unable to escape to cooler areas.

After 24 hours the structure and plant temperature was checked with an infra-red thermometer. Heater positions were readjusted to direct heat to cool areas.

Temperature Monitoring

Six thermistors, attached to a squirrel data logger, were installed in selected locations on level 5 before heating started. Surface temperatures of 5 different structural elements were also measured on level 5 using the infra-red thermometer at intervals throughout the monitoring period. These temperatures were measured on a 1m square grid and profiles were plotted by computer.

Results

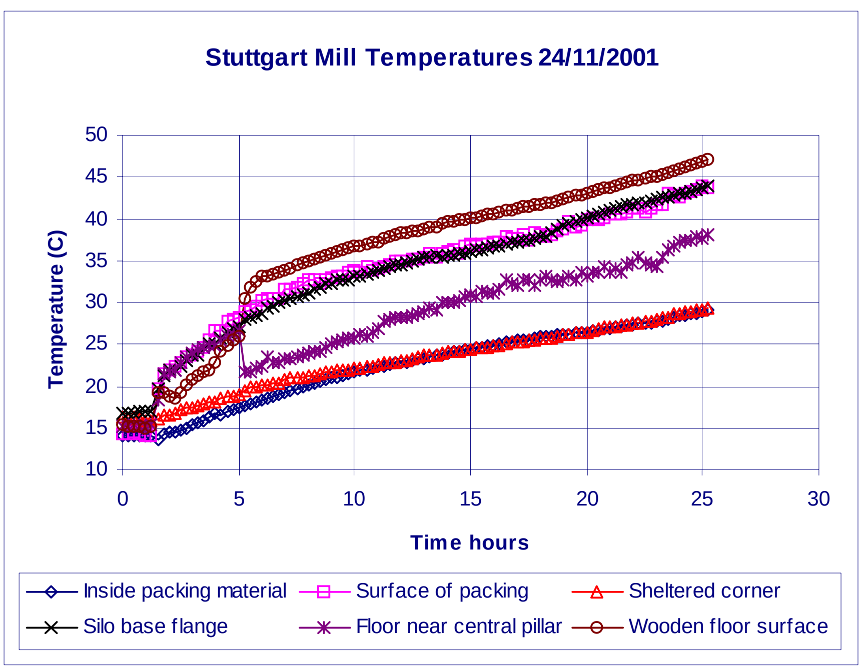
The air leaving the heaters reached 65°C but quickly fell as the jet entrained cooler room air. The air jet was buoyant and was observed to begin to curve upwards 4m from the heater. Inspection after 24 h showed evidence of dead adult insects and larvae. Some parts of the plant had reached 50°C. The majority was above 40°C. Insects had fallen from ledges and cable conduits and had emerged from flanges etc in the machinery.

The upper parts of the mill were still cool after 24 h, at between 20 and 30 °C. The external walls behind the flour bins were also cool (18-20°C)

Temperatures monitored by thermister probes

The temperature records made by the thermistor probes and squirrel logger are shown in Fig. 2.1. After an initial settling period of about 4 h when heater position was being adjusted the air temperatures rose linearly for the first 20 h. The heaters operated continuously during this time because the air temperature did not reach the control thermostat setting. Air temperature rose at the rate of 1°C/h

Fig 2.1 Heating profiles on floor 5 at the Stuttgart mill



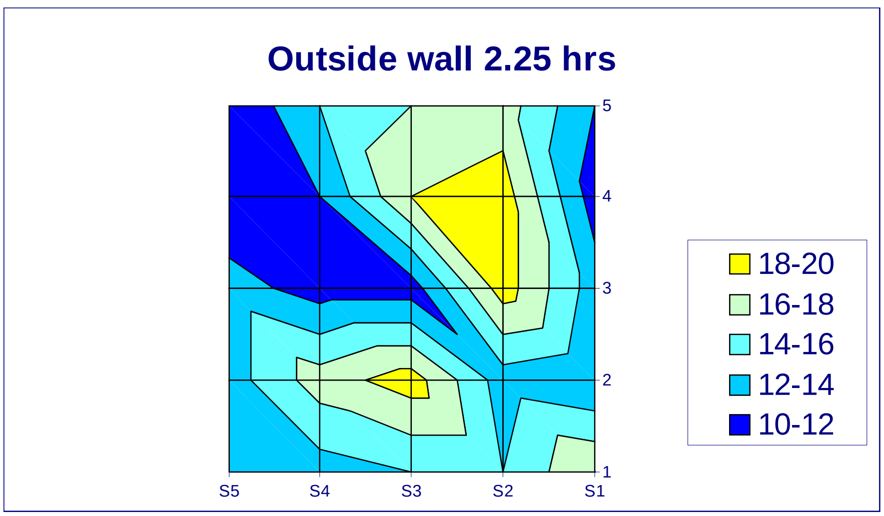
Packing material in the room, monitored by thermistors, warmed more slowly than air at 0.63 °C/h. The wooden floor heated more quickly at 1.33 °C/h (This probe was near to the hot air jet from one of the heaters). A thermister probe placed in a 'dead' corner at floor level showed a much slower heating rate (0.5 °C/h) than the average room air.

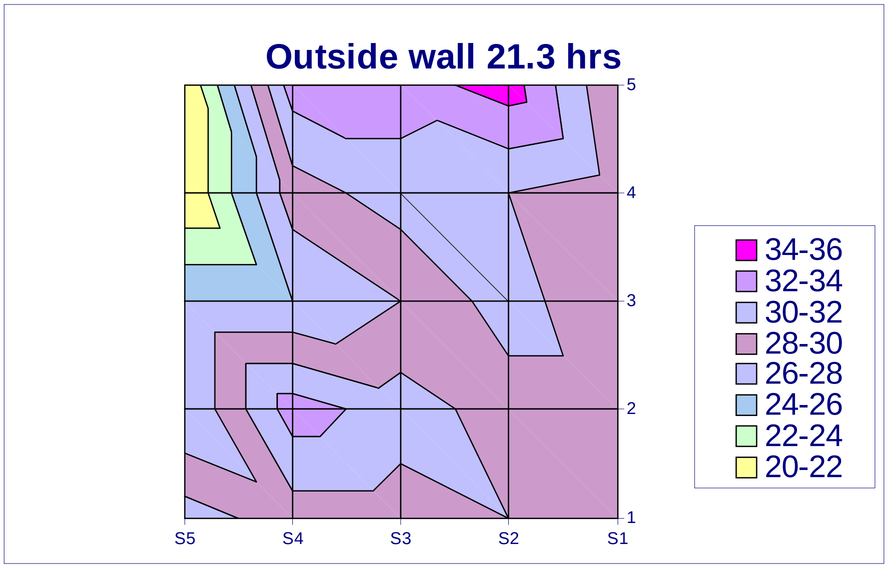
The outside ambient temperature during the observed period was 3°C. Some snow flurries were seen but the wind was generally light and the sky overcast.

Surface temperatures measured by infrared thermometer

A sequence of three distribution examples for the outside wall are shown in Fig. 2.2. The temperature distribution on a section of concrete floor in front of one heater is shown in Fig. 2.3.

Fig. 2.2 Outside wall heating sequence




Outside wall 21.3 hrs
5
4
3
2
1
S5
S4
S3
S2
S1
34-36
32-34
30-32
28-30
26-28
24-26
22-24
20-22

(Fig. 2.2 contd)

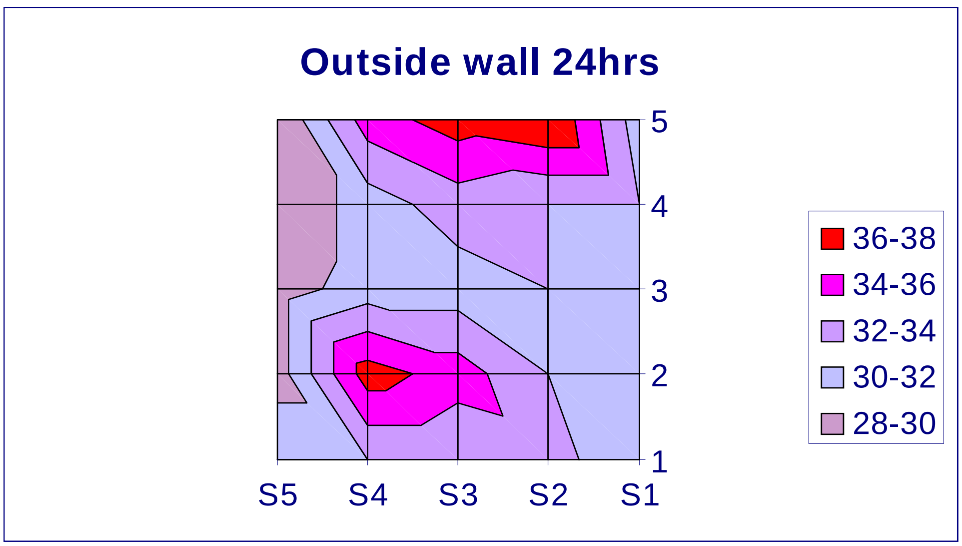
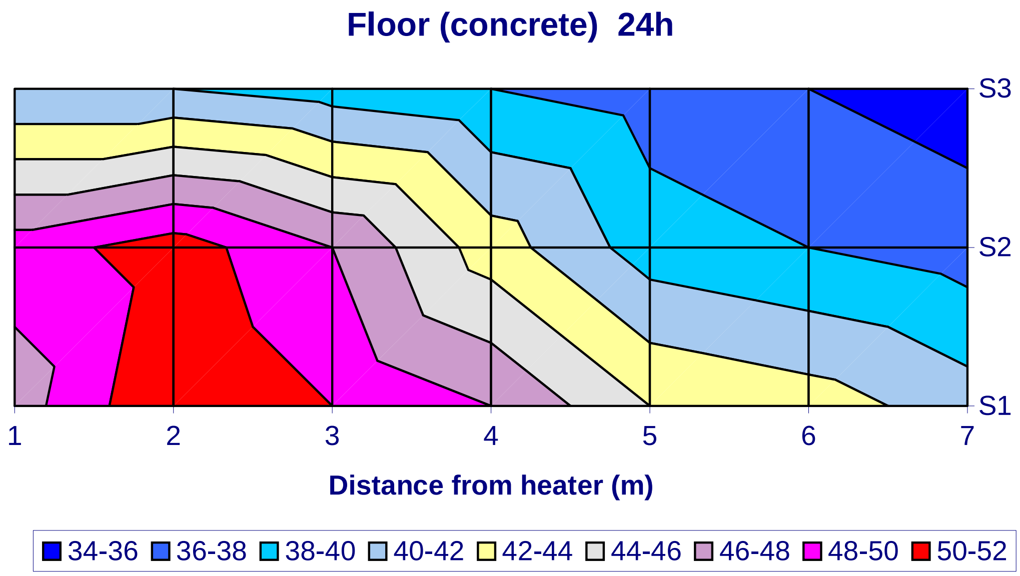

Outside wall 24hrs
5
4
3
2
1
S5
S4
S3
S2
S1
36-38
34-36
32-34
30-32
28-30

Fig. 2.3 Heat profile of concrete floor after 24 h of heating



In order to understand the heating process the average surface temperatures for each of the structures have been calculated and, based on the average room air temperature, the heat flux to the surface has been estimated as shown below in Table 2.1.

As expected the outside wall absorbed heat at a faster rate than internal parts of the structure. Some parts of the internal wall reached higher temperatures than the average room air. This was because warm air from one of the heaters reached the wall before mixing with the room air.

The heat flux for all surfaces fell from 5 h to the end of observation at 24 h. This is the result of the structure temperature rising. Most of the metallic parts of the plant were close to average room air temperature after 24 h and so were only absorbing heat slowly.

Summary

- The monitored zone (5^{th} floor) had a volume of 853 m^3 and a wall/ceiling/floor area of 490 m^2.
- Six 18 kw heaters were used in the monitored zone.
- The temperature records show that after 24 hours some parts of the plant and structure had reached lethal temperatures. Dead insects and larvae were found.
- Some parts of the structure were well below lethal temperature after 24 hours. This illustrates the need for effective heat distribution if the whole structure is to be treated. In the case of this treatment, a further 24 h of heat application ensued before release of the mill for resumption of production.

- The heating rate was limited by the capacity of the heaters. A substantially linear change in air temperature of 1 °C/h was observed throughout the 24 h observation period.
- The heaters did not stir up the dust during operation.
- It is desirable to remove in particular packing material before starting a treatment as packs of these cannot be heated quickly.

Table 2.1 Average surface and room air temperatures

Heating time (h)	0.0	1.1	2.25	5.5	21.3	24.0
Average room Air C	14.0	22.0	25.0	30.0	38.0	42
Outside wall (1) C	3.43	13.3	14.39	12.91	29.65	32.43
sd	1.27	2.34	2.81	2.15	2.37	2.43
boundary Δt C		8.70	10.61	17.09	8.35	9.57
Heat flux w/m^2		69.6	84.9	136.7	66.8	72.5
Outside wall (2) C	2.1	16.3	19.3	20.5	35.5	40.4
sd	1.45	2.83	3.20	3.31	2.80	2.72
boundary Δt C		5.7	5.7	9.5	2.5	1.6
Heat flux w/m^2		45.6	45.6	76.0	20.0	12.8
Inside wall	9.4	20.2	23.4	28.2	44.8	47.2
sd	0.89	0.45	1.52	3.96	5.22	5.36
boundary Δt C		1.8	1.6	1.8	-6.8	-5.2
Heat flux w/m^2		14.4	12.8	14.4	-54.4	-41.6
Concrete floor C	16.29	18.71	19.86	26.0	40.0	43.57
sd	0.76	0.76	1.21	2.52	5.39	5.77
boundary Δt C		3.29	5.14	4.0	-2.0	-1.57
Heat flux w/m^2		26.3	41.1	32.0	-16.0	-12.6
Internal column	11.4	20.6	21.6	23.8	38.0	42.8
sd	0.55	0.55	0.55	0.45	0.71	0.84
boundary Δt C		1.4	3.4	6.2	0.0	-0.8
Heat flux w/m^2		11.2	27.2	49.6	0.0	-6.4

3. TRIAL AT LANGLEY MILL, NOTTS

Introduction

This trial was conducted as an adjunct to a fumigation trial at Langley Mill with the candidate chemical methyl bromide replacement sulphuryl fluoride, for which some heat input was required. Previous modelling showed that when the mill was working, the air change rate of 16 m^3/s would prevent the air temperature in the building being raised to treatment temperatures unless an excessive heat input was employed. (The air heating load is 20 kW/ °C so to heat to 28°C with ambient at 14°C would take 280 kW)

The walls and floor are thick concrete structures which would take a number of hours to heat up so heating was planned to start well in advance of the fumigation. The aim was to heat a substantial part of the structure to above 30°C before the start of fumigation so that fabric temperatures would remain above 25°C for most of the fumigation period.

Directing a heating air supply at 55°C up the walls would result in heat being absorbed at a rate of 350W/m2. The floor slab takes up heat at the rate of 400 W/m2. If 10% of the floor and 50% of the walls in the ground floor are heated at this rate 70 kW will be needed. As the wall warms up the rate of heat input will fall. It is estimated that after 6 hours heating some of the wall surfaces will have warmed to about 40°C and parts of the floor slab may have reached 35°C. These temperatures only apply to those parts of the structure that the hot air contacts.

It is difficult to estimate how much of the heat is absorbed in the structure and how much is lost in the ventilation air. The most optimistic estimate is that 45% of the heat will go into the structure and 55% will go into the air. Some of the heating air will find its way to the upper floors where it will contribute to warming these parts of the plant and structure. It is unlikely that the air temperature in the mill will exceed 30°C when the plant is running.

The quantity of heat needed to raise the temperature of the fabric and plant through 15°C was estimated as 8674 MJ, representing a constant heat input of 100 kW for 24 h. The steady state heat loss from the building when maintained at 30°C was estimated as 62.4 kw. Both of these figures assume no air exchanges.

Methods

Heater capacity and ducting positions

The heaters employed for this trial were supplied by Aggreko Ltd. Two 65 kw indirect oil fired heater units, each delivering heated air at 1.43m^3/sec at 56°C above ambient, were used to input heat to the roller floor at ground level. The temperature of the heating air was set not to exceed 70°C at the heater. It was estimated that 20m of duct will loose 10 kw so the delivery temperature at the end of the duct was estimated to be 60°C. This air was expected to quickly be diluted by cool room air and give up heat to cool surfaces so that no threat would be posed to sprinkler systems.

The heaters were designed to work with 509 mm dia ducting. Most of the air used in the plant was drawn in through the rollers. In order to minimise the mixing of the heating air with the process air drawn through the mills, the heating air was directed along the sides of the ground floor rooms. Layflat polythene ducting, perforated to create air jets into the wall floor joint and up the wall, was used for this purpose. These and the floor slabs were some of the most difficult parts of the structure to heat. The edge of the floor slab and the walls of the roller floor commenced heating using these ducts while the plant was running, heat being directed towards these surfaces during the last 6 h before fumigation started.

The two upper floors were heated by the two ThermoNox heaters, one per floor. These heaters were assisted by fumigant recirculation fans that drew air from the roller floor and delivered it to the sifter floor. These fans operated throughout the heating period. The ThermoNox heaters were fitted with ducts to distribute heat throughout the length of the spout floor and the sifter floor and were moved as necessary during the heating process to ensure that all components were effectively heated.

Temperature monitoring

The temperature of the principle structural components were monitored by attaching thermocouples to the surface. The datalogger and multiplexer for the thermocouples were located on the spout floor. The temperature of the walls of the roller floor were monitored by routine manual measurement with the infra-red thermometer to check progress of heating. The same approach was used on the upper floors to check the heat distribution produced by the ThermoNox heaters.

Bioassay associated temperature monitoring

Ten bioassay monitoring positions were established throughout the mill to assess fumigation efficacy but temperature was monitored at each position which provided extra data for the bolt-on investigation of heat distribution, the trial reported here. Insect bioassay cultures, gas sampling lines and copper-constantan thermocouples were placed at each position. The thermocouples were run to a Yokogawa HR2300 hybrid chart recorder where temperature data was collected. The total volume of the fumigated part of the mill was approximately 3000 m^3. All heaters were switched off before the fumigant was introduced.

Inert dust application

Initially, three different dust applicators were evaluated when used to treat a steel structure (Cook *et al.*, 2003). An electric powered duster proved too powerful for targeted treatment and was concluded to be more appropriate for treating a large space such as the inside of a building. A hand operated model was very flexible and the speed of treatment could be easily adjusted for covering a large area or to aid gentler application to vertical sides. The third model was a small gas-powered applicator suitable for treating small areas, and featured a narrow nozzle and extendable lance useful for treating less accessible "dead-spaces". This latter device, the 'GPS Gaspot' CO_2 powered duster (Killgerm Chemicals ltd, West Yorkshire, UK) was chosen for this trial. DE was applied to the dead space under 3 rows of flour rollers that had formerly had infestation from beetles and moths. Holes were pre-drilled into the wooden plinths at ca. 2.5 m intervals. DE was applied at 5, 10 or 20 g/m^2.

Results

Temperatures achieved

The results obtained are summarised in Figs 3.1. Air temperatures rose from ambient levels of about 17-18^oC to about 30^oC in the monitoring zone for the start of the fumigation period (250 h in Fig.3.1), but then fell sharply. Ducting hot air to areas of higher heating requirement showed the need for a substantial lead time for there to be a chance of such areas reaching target temperatures within the time frame available for a disinfestation treatment based on heat alone. The average temperature in the mill just before dosing of the fumigant was 24.6^oC (Table 3.1).

Inert dust application

The gas powered duster proved easy to use and dust penetrated into the space readily at the required dosage levels. The effect of the DE could not be quantified since no before and after assessments were made of the pest population. However a year later, the mill owner has confirmed that these areas have not been re-infested, suggesting that the DE is giving good residual protection.

Discussion

Heating results again illustrated the rapid temperature rise of materials such as wood and the much slower rise of concrete surfaces. Temperatures recorded at the bioassay positions tended to be rather lower than surface temperature measurements recorded by infrared thermometer, indicating that the flour medium used for bioassays was losing heat quicker than most structural materials. The low ambient temperature (mean 5.4^oC during this period) resulted in a rapid temperature fall once heating was discontinued.

Fig. 3.1 Average air and surface temperatures 4/04/03 - 8/04/03 at Langley Mill

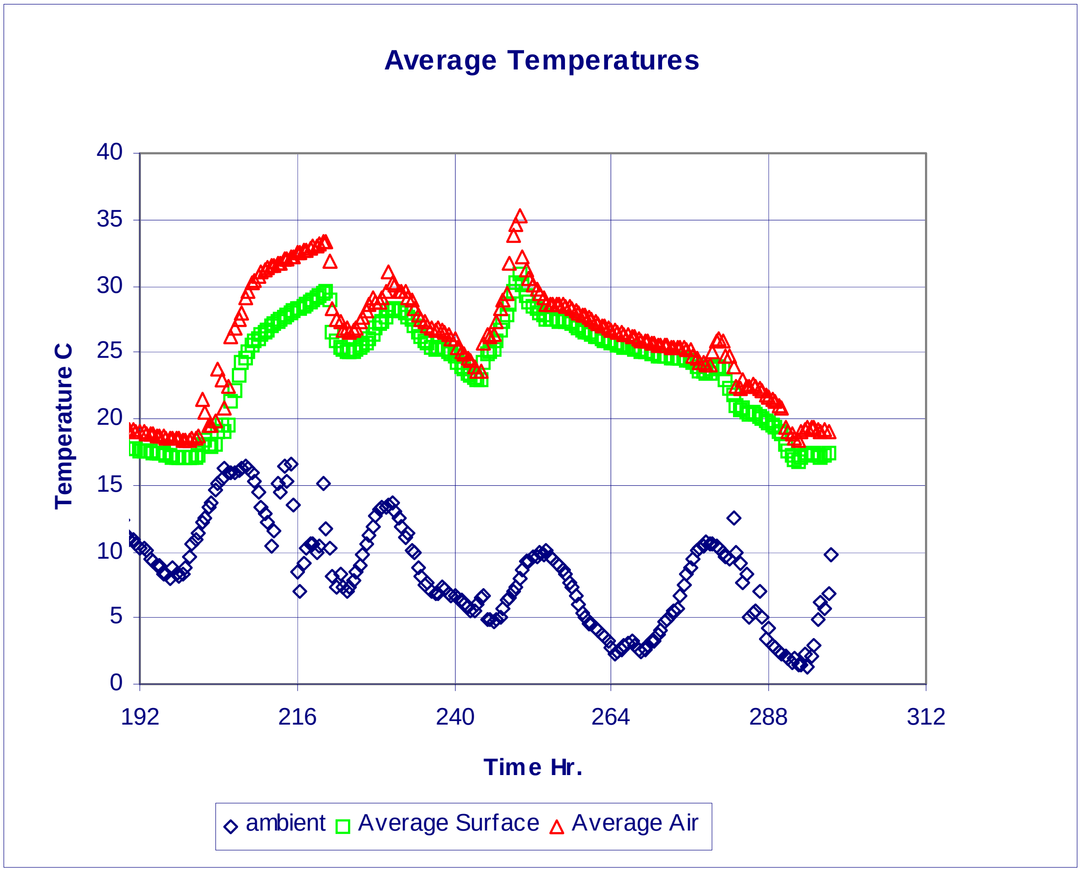


Table 3.1 Location of sampling positions and average temperatures in the mill during the fumigation (hours 250 to 273 on Fig. 3.1)

Position	Floor	Location	Average Temperature (°C)
1	2	High point. 1 m under roof apex on a cross girder.	23.2
2	2	On the floor of the raised annex room farthest from stairwell	20.5
3	2	1 m from the floor on a circular unit on the left near the stairwell.	24.2
4	2	By motor near end wall farthest from stairwell 1 m from the floor.	24.3
5	1	On the floor of the anteroom.	21.1
6	1	First floor, main room halfway along main room 0.5 m from floor.	23.5
7	1	First floor, halfway along main room 1 m from floor on right.	24.4
8	Ground	Ground floor, anteroom near stairwell on raised platform.	21.0
9	Ground	Ground floor, main room, on the left plinth between machines 1 & 2.	21.1
10	Ground	Ground floor, main room, on the right plinth between machines 4 & 5.	22.6

4. RAINHAM BRAN HOUSE TRIAL

Introduction

An opportunity for heat treatment of a complete building together with a leakage evaluation study for possible use of controlled atmospheres became available at the Tilda site in Rainham, Essex, utilising the bran house. The building is of steel framed construction measuring 12.5 x 9 x17m high and clad with profiled steel insulating sandwich panels containing 50mm thick polyurethane foam. The roof is formed from the same insulating panels but with plastic roof-lights. The plant housed within the structure is integral with the building frame and is accessed on three steel decked floors. Half of the building space is taken by six hopper bottomed bins. Each bin has an access hatch from the roof space.

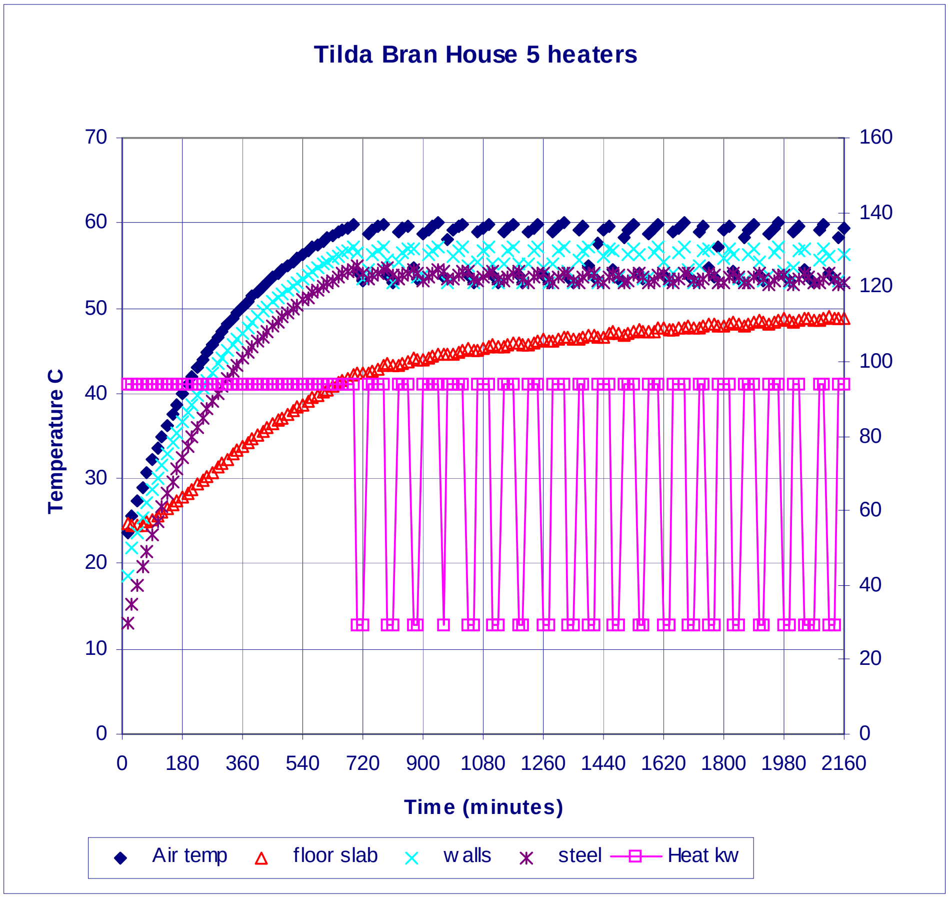
The ground floor comprises a solid concrete slab and internal concrete curb. This floor is largely clear of plant but provides access to the elevator boots and a number of cross conveyors. There was a sprinkler system in the bran house set to operate at temperatures above 70^{o}C.

The bran house plant is controlled by a plc unit located on the second floor. Most of the actuators for product flow control are pneumatically operated. During the heating trial all compressed air systems were depressurised and open to atmosphere.

Projected heating rates

The heating response of the bran house was calculated on the basis of a mass of 70 tonnes of steel. An air change rate of 0.8 changes per hour was assumed. It was calculated that five heaters would bring the air temperatures up to 60°C in about 12 hours, a much longer time being required for the floor slab to heat. The CSL recommendation for using heat alone to kill insects is 24 hours at 48°C. To comply with this it would be necessary to continue heating for 24 hours after the 18-hour warm-up period making a total of 42 hours for the treatment. It was therefore decided to start heating the concrete floor area before the main treatment because even with a starting temperature of 25°C, it was calculated that 45°C would only be reached after 18 hours (Fig. 4.1).

Fig. 4.1 Calculated heating times for bran house with 5 x 18 kW heaters (right hand axis is kW input)



Methods

Installation of heating equipment

Five 18/9 kw ThermoNox heaters were used to provide the heat input and these were powered through a 6 way distribution panel from a 180 kVA diesel generator that was located outside at ground level. Two heaters were placed on the ground floor and were fitted with deflector plates to direct the heated air onto the floor. One heater was placed on each of floors 1 and 2. These four heaters were positioned so that hot air circulated within each of the heated spaces.

The 5th heater was installed in the roof space and was connected to 6, 20 cm dia polythene ducts. These ducts were positioned to blow through the inspection hatches of the six bins and deliver hot air to the bottom of these bins. The air was able to escape from the bins through the inspection hatches.

After 9 hours of heating, two 600 mm dia short case axial fans were installed on the ground floor blowing down onto the floor slab to improve the heating rate of this part of the structure. These fans continued to operate until the end of the treatment.

Temperature monitoring

Temperatures of the air and the structure as measured by thermocouples were logged at 5 minute intervals throughout the treatment. The air temperature entering and leaving each heater was measured. The inside surface temperatures of walls, floor and ceiling were measured. The remaining thermocouples were attached to elements of plant and internal building frames.

A hand held infra-red thermometer was used to check on the progress of heating at regular intervals. Comparisons between the infra-red and thermocouple measuring systems showed that the infra-red instrument reads 8 - 10°C too high when used in an ambient of 50°C. The results from the infra-red instrument are useful indicators of temperature distribution within the space.

Air Exchange Measurements for use of carbon dioxide

In order to estimate the quantities of carbon dioxide (CO_2) that will be needed in a practical treatment it is necessary to know the air exchange rate that takes place in such structures. The air exchange rate in the bran house was monitored as follows. The level of CO_2 in the building was raised during the heating treatment by introducing a small quantity of CO_2 from a cylinder at a known constant rate during the heating trial through the heater unit on floor 2. The rate of input was controlled by a constant pressure regulator and measured by regularly weighing the CO_2 bottle, to give a maximum concentration in air of 1000ppm. The concentration of CO_2 in the bran house and in the surrounding outside air was monitored continuously throughout the trial with an infra red analyser. From these measurements the air exchange rate was calculated.

As a precaution oxygen depletion monitors were worn by staff entering the building at any time during the test.

The Bioassay

The bioassay comprised 100 ml cultures set up with 20g food medium and 100 adults of the heat tolerant flour beetle *Tribolium castaneum* two days prior to the start on the heating trial. On the 8th May, cultures were placed in pairs through the bran house as follows: Top floor, on top of elevator (near roof space) and on a ledge near stair hole, intermediate level, near a pheromone trap and opened hatch, first floor, on conduit shelf against the outside wall and also in centre on conveyer and finally on a low ledge against the outside wall on the ground floor. A site control was placed in the adjoining mill. The samples were returned to the laboratory on 10th May and incubated at 25^{o}C. After 1 week of incubation, a count of adult survival was performed.

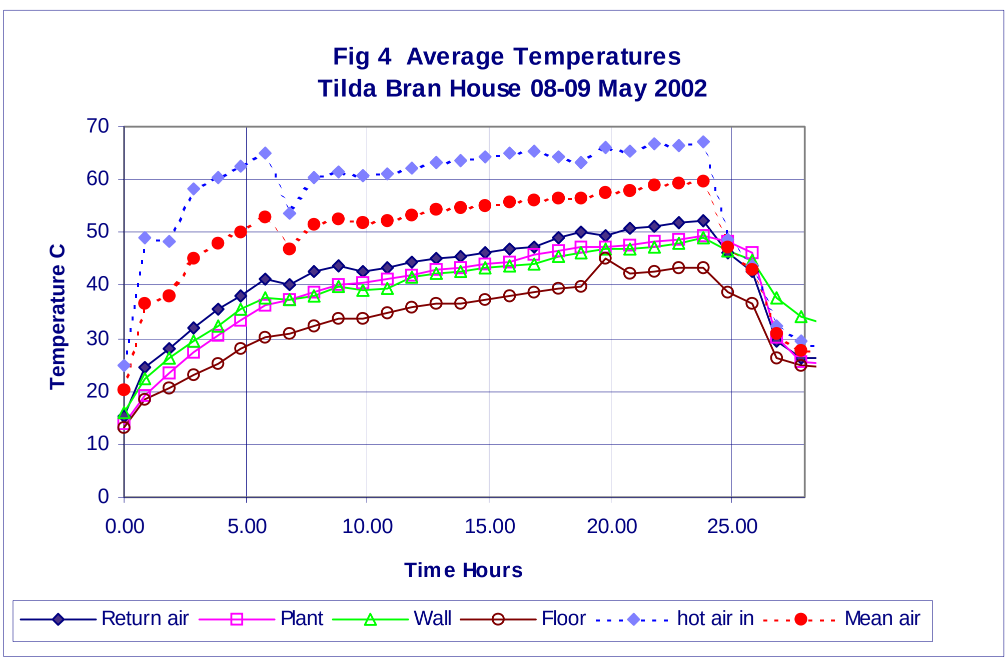
Results

Heating results

Fig. 4.1 shows the average temperatures at hourly intervals during the trial. The floor slab heated slowly and the walls and steel structure more quickly. The dip in the heating rate at about 7 hours was due to the trips in the distribution panel switching out. The system could not operate with all heaters switched to 18 kW. Stable operation was achieved only by switching two heaters to half power. The peak in the floor heating trace at 20 hours was the result of the thermocouples becoming unstuck from the floor as temperatures rose.

After 15 hours the internal thermostat settings in all the heaters except the one serving the bins were raised from the standard 80-90°C to 105°C in an attempt to increase the heat input rate. There was, however, no evidence that this increased the heating rate although the average maximum air temperature delivered by the heaters rose to 68°C for the last 4 hours of the treatment. All parts of the structure with the exception of the concrete floor slab were heated to 50°C by the end of the 24-h treatment period. Floor temperatures only exceeded 40°C after 19 hours and the maximum temperature reached by the floor slab was 44°C (Fig. 4.1). However the temperature of all parts of the structure and the floor slab was still increasing at the rate of 0.9°C/h at the end of the treatment.

Fig. 4.1 Air and surface temperatures achieved in the bran house



Leakage results with carbon dioxide

The rate of carbon dioxide input was calculated from the change in weight of the cylinders over time. These results are shown in Fig. 4.2.

Fig 4.2 Carbon dioxide input rate

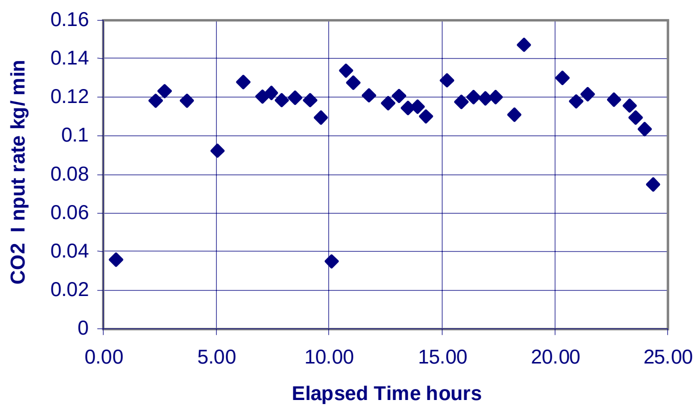


Fig. 4.3 shows the concentration measured in the building during the heating. The first drop to 1200 ppm resulted from the increased air exchange when the floor fans were installed. The second drop to below 1200 ppm was the result of a cylinder running out. The background CO_2 outside the building was about 400 ppm.

Fig. 4.4 shows the air exchange rate versus concentration with a CO_2 input rate of 3.885 m^3/h. At 1400 ppm, the ventilation rate is 1.2 m^3/s. The building gross volume is 1890 m^3 so this represents 2.2 changes/hour. Outside wind conditions were light or still throughout the test.

Fig 4.3 Carbon dioxide concentration

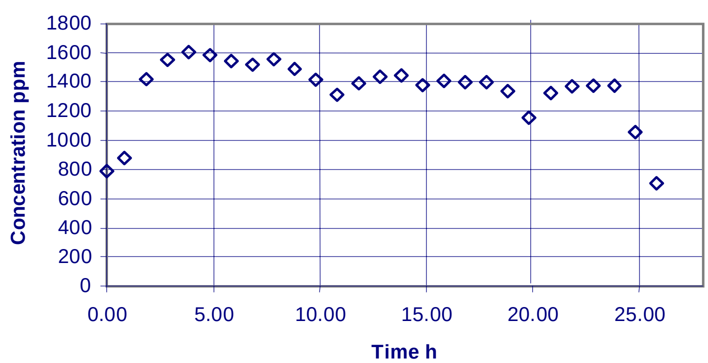
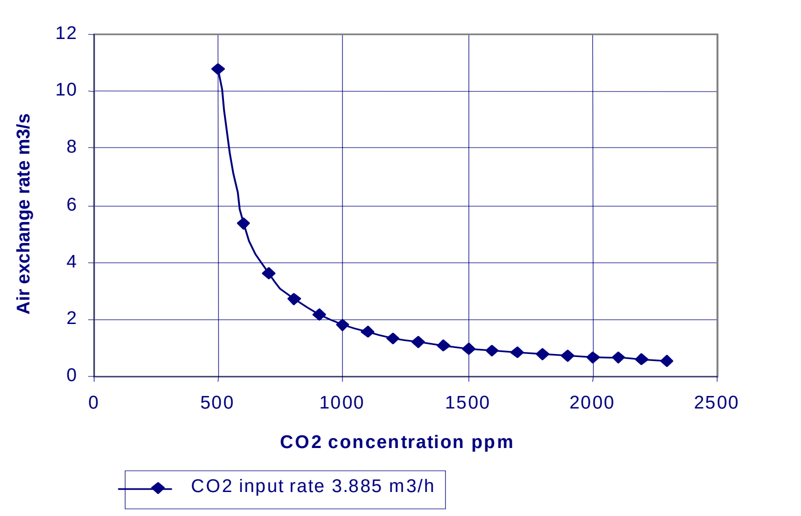


Fig 4.4 Air leakage rate v CO2



The bioassay results

Survival occurred of both endemic pests and the bioassay insects on the ground and first floors, and possibly higher up the building near the outside walls. Adult survival of the bioassay is shown in Table 4.1 together with an indication of progeny production from eggs laid up to 2 days before the treatment. Progeny was produced in all samples positioned at first or ground floor level.

Table 1.– Survivals of adult *Tribolium castaneum* in the bioassay and progeny production

Position	Percentage survival in replicates:	
	A	B
Laboratory control at 25°C, 60% r.h.	100*	100*
Site control (in mill at 10-20°C)	100*	100*
Top floor near roof space	0	0
Top floor near stair hole	0	0
Intermediate level near pheromone trap	0	0
First floor near outside wall	35*	24*
First floor, central position	0*	1*
Ground floor, ledge near outside wall	100*	100*

* Progeny produced from eggs laid before or during the treatment.

Discussion

There was generally good agreement between the predicted and measured temperatures. However, for a fully effective treatment either a longer heating period or more heater units would need to be employed so that energy can be put into the building at a higher rate or over a longer period. An effective action would be to pre-heat the floor slab before plant shutdown, using at least one additional heater. The edges of the floor slab could also be heated by perforated polythene ducts delivering heated air directly at the wall/floor joint.

Floor fans were effective in reducing the variation in floor slab temperature but the additional air movement inevitably increased the building air leakage rate. This would have implications for any proposed use of modified atmospheres as part of the control strategy.

Some problems were encountered in the heating of the silo bins. The polythene ducts were not adequately inflated to deliver air uniformly into the bins. A restriction on the outlet end of the duct or more fan capacity would overcome this problem. Another alternative could be to use polypropylene land drainage tube to distribute the air to the bins. The polythene duct restricted the air flow from the heater so that it could only be used at the 9 kW setting. It was however necessary to run two of the five heaters at this setting to prevent interruptions of the electrical power supply in this particular trial.

The adhesive tape used to attach the thermocouples to the structure and plant did not always stick effectively, especially as temperatures increased. Surfaces need to be thoroughly cleaned free of dust before sticking the tape on. Magnetic plastic might be more effective for metal surfaces.

The carbon dioxide leakage test revealed that an atmosphere change of over 2 changes an hour in a building of nearly 2,000 m^3cubic metres would make it necessary to introduce 400 m^3 of gas per hour to hold a 10% carbon dioxide atmosphere. Such an operation would prove far too expensive to be practical.

The lower than required target temperatures achieved in the lower part of the building because of problems in heating the concrete base gave rise to pest survival which necessitated treating the concrete floor by insecticidal spray after the heating treatment.. That progeny was produced in all bioassay samples positioned at first or ground floor level indicates that eggs laid by the adults up to two days before the start of heating, or during the heating process, were as tolerant as adult *T. castaneum* in withstanding heat.

The only subsequent observation following the treatment was that some of the fluorescent lights had failed. However their operation was not checked systematically before the trial and this event may have been a result of long use or old age rather than the heat.

Summary

- The bran house was heated to 50°C in 24 hours using 5 x 18/9 kW electric fan heaters.
- The plant and structure reached 40°C in 10 hours but the concrete floor slab took 19 hours to reach this temperature and only reached a maximum of 44°C.after 24 hours.
- All bioassay insects survived on the ground floor and there was some survival also on the first floor, a very small survival in the centre and a greater (c. 30%) survival adjacent to an outside wall.
- The insect activity on the concrete floor was controlled by insecticide spray at the end of the heating treatment.
- The air leakage rate during the treatment was 2.2 changes per hour.
- The plant was re-started with no serious problems after the treatment.

5. TRIALS AT BOXWORTH

5.1 Floor heating test

Summary

A single fan heater directed onto a concrete floor in a closed building to establish the heating rate of this structure The surface temperature was raised from 14°C to 32°C in 2 hours with air at 45 °C. An average heat flux of 156 W/m°C was measured after 3 hours heating.

Objective

This test was made to measure the thermal response of a solid concrete structure heated by convection from a warm air jet.

Method

A small scale trial was set up using a 1kW fan heater directed over a clear section of concrete floor. Air speeds over the floor were measured using a pitot tube and micromanometer. Floor temperatures were measured with an infra-red thermometer. Air temperatures were measured with thermocouples. The heat flow rate into the floor was measured at one point using a conductivity plate which was taped to the surface. Temperature measurements were made at intervals for a period of three hours.

Results

Air temperatures were fairly stable after the first few minutes at between 43 and 45^{o}C (Fig. 5.1). The heat flux measurements were made towards the end of the test when temperatures had stabilised. The observed values were 163 W/m°C with a 12 °C difference between the hot air and the surface and 150 W/m°C with an 11 °C difference (see Table 5.1).

The air temperature 3 mm above the floor surface at each test point was measured near the end of the test.

Discussion

The observed heating rate for the concrete floor was 13.6 W/m^{2}°C. In order to reach and maintain a surface temperature of 45°C will require an air temperature of 55°C. The air jet cools quickly as the heat flows to the structure so the hot air supply needs to be delivered close to the heated structure.

Fig. 5.1 Temperature profiles in the Boxworth concrete slab test

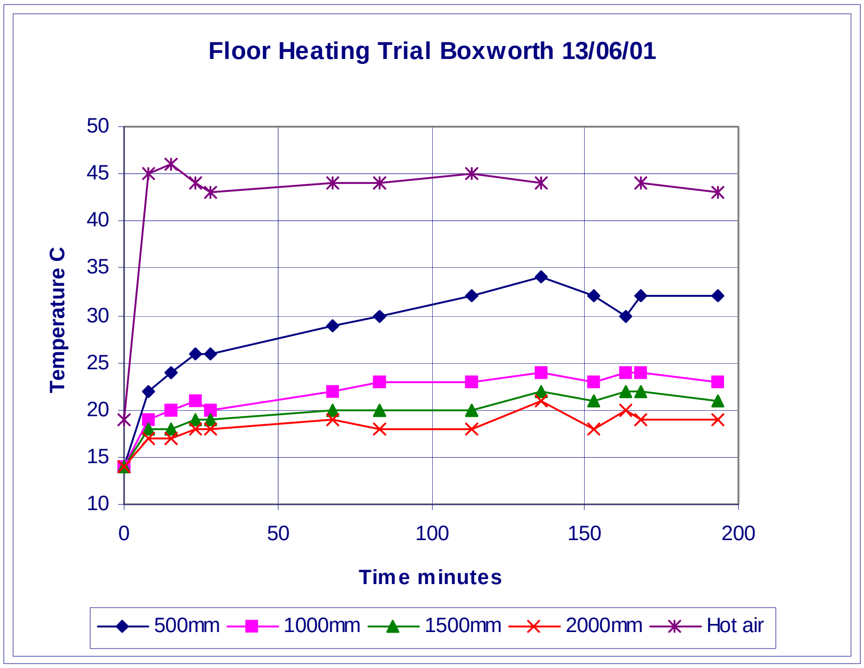


Table 5.1 Results of the floor heating test at Boxworth

Distance from heater mm	500	1000	1500	2000	
Air speed m/s	1.1	0.4	0.1	0.0	
Time min	Floor temperatures C				hot air
0	14	14	14	14	19
8.00	22	19	18	17	45
15.00	24	20	18	17	46
23.00	26	21	19	18	44
28.00	26	20	19	18	43
68.00	29	22	20	19	44
83.00	30	23	20	18	44
113.00	32	23	20	18	45
136.00	34	24	22	21	44
153.00	32	23	21	18	-
163.00	30	24	22	20	-
168.00	32	24	22	19	44
193.00	32	23	21	19	43

5.2 Flour dust blowing trial

Summary

Air speeds below 5m/s caused only slight movement of the flour. At between 6 and 7 m/s the flour started to move and above 7m/s the surface was rapidly cleared.

Method

A smooth dark surface was coated with wheat flour and an air stream of increasing velocity was directed across it. The air speed was measured 3mm above the surface by a pitot tube and micromanometer. The procedure was repeated several times to confirm the result.

Result

Air speeds above 6 m/s were observed to start dust movement (Table 5.2). Any vibration of the surface was observed to increase the chance of movement.

Table 5.2 Effect of air speed on dust entrainment

Observation	**Air speed (m/s)**
No movement	2.4
No movement	3.7
No movement	5.1
Slight movement	6.1
Movement	6.9
Severe movement	8.0

Conclusion

Heating systems should be designed to deliver air in contact with dusty surfaces at less than 5m/s to minimise the generation of dust clouds.

5.3 Conduction heating of concrete floor slabs.

Summary

- Model predictions and measured results are in good agreement with overall heating time.
- Heating cable must be in good contact with the surface to be heated.
- The heated surface must be covered with insulation to prevent heat loss to the air
- Contact heating of wall floor joints without surface insulation is ineffective.
- A heat input rate of 253w/m^2 produced an average surface temperature in a concrete floor slab of 47°C ±10°C after 48 hours (15cm cable centres)
- A heat input rate of 380w/m^2 produced an average floor surface temperature of 65°C ±9°C after 36 hours. (10cm cable centres)

Model development

The transient heating model developed for use with whole structures has been modified to predict the heating times for slab structures where heat is introduced by conduction at one surface.

It became clear, using the model, that the heat transfer from the surface to the air represents 57% of the total heat input required to maintain a concrete surface temperature of 50°C. Effective insulation, laid on top of the heat source is essential for practical heating of the structure to insect lethal temperatures.

Initial predictions suggested that 260 w/m^2 would raise the surface temperature to 50°C in 42 hours. Practical tests with 253 w/m^2 produced an average temperature of 55°C in this time. The model can only predict average surface temperature and does not give information about the variations under and between heating cables.

Heating of steel structures by conductive heating was investigated. As expected the response of steel was more rapid than concrete. The heating time to 50°C was about 5 hours with 260 w/m^2. The temperature variation between cables on steel could be expected to be much less than for concrete. Potentially higher heat input rates could be used without overheating the cables. This would significantly reduce the heating time for steel.

Experimental work

Practical floor heating trials were undertaken to confirm the model predictions and to investigate the inter cable temperature distribution. Three tests were run:

1. An uninsulated 38w/m cable was placed at a wall floor joint (solid concrete ground floor and concrete block wall). Temperatures were measured on the adjacent floor and wall surfaces.

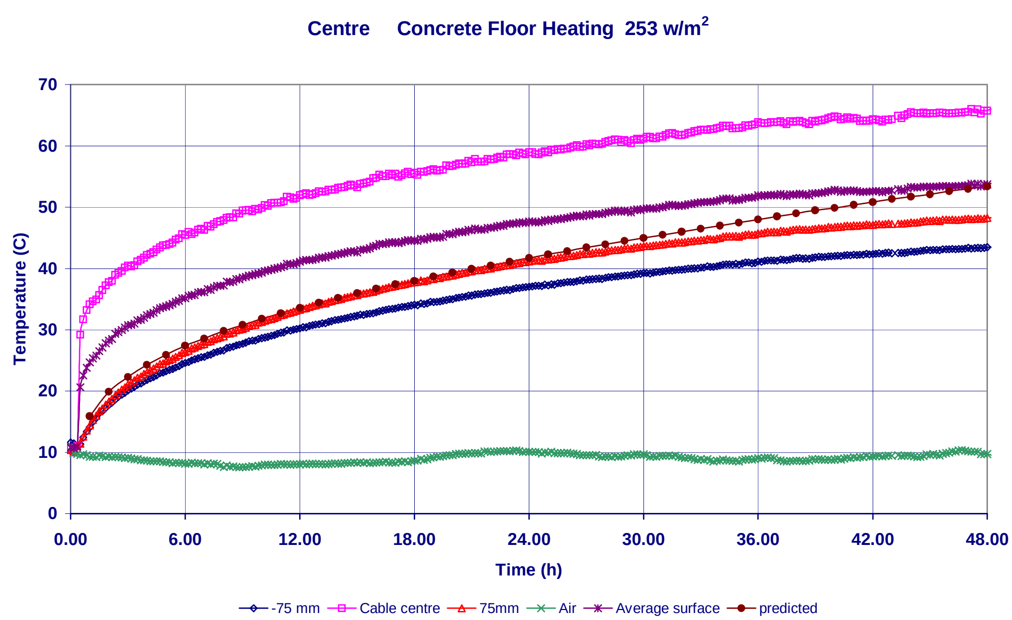
2. 38w/m cables were laid on a solid concrete floor at 15cm centres to give a heat input rate of 253 w/m^2. Floor surface temperatures were measured at the cable and at the mid point between cables. The whole area was covered by a sheet of multi-layer reflective insulation.

3. The same cable was re-laid on a new section of concrete floor at 10cm centres to give a heat input rate of 380 w/m^2. Temperature measurements were made at the cables and at mid points between cables. The whole area was covered by the same reflective insulation.

Results

The temperature of the cable in the wall/floor joint test reached 40°C with an average ambient air temperature of 12°C. The wall and floor temperature 50mm from the cable reached 25°C after 48 hours heating. There is evidence that the wall and floor surface temperatures change in response to changes in air temperature. The temperature history of the floor surface with 253 w/m^2 is shown in Fig. 5.3.1.

Fig. 5.3.1 Concrete floor surface temperature during heating

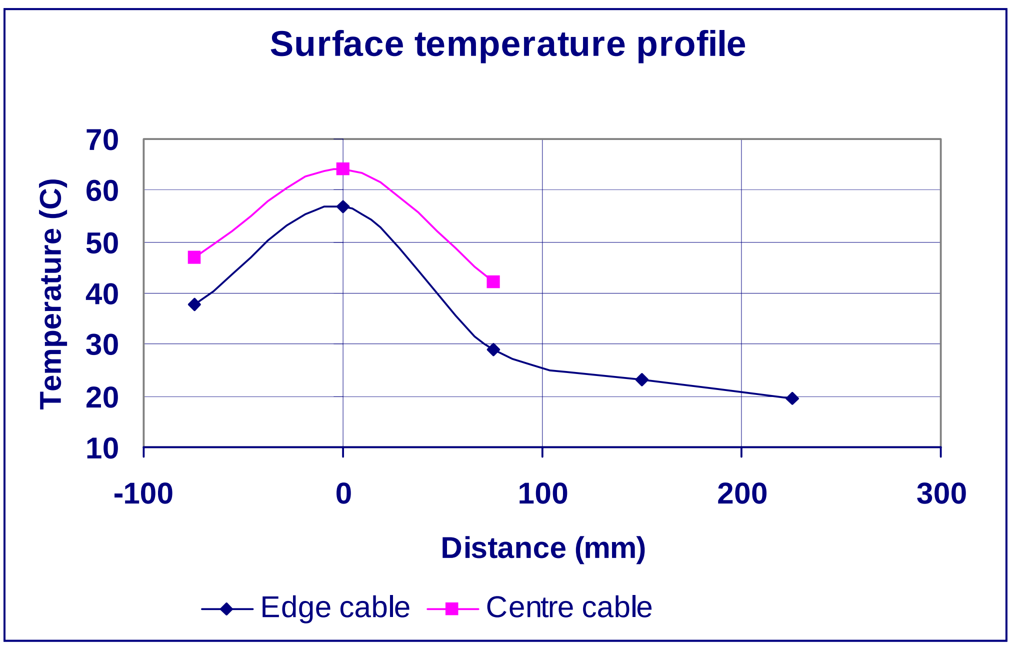


The average measured surface temperature is compared with the model predictions. Fig. 5.3.2 shows how the surface temperature varies with distance from the heating cable after 42 hours. The diamonds show the edge effect and squares represent the centre of the heated area. The difference between the mid point temperatures in the centre area are due to one of the adjacent cables not making firm contact with the concrete surface.

The average floor temperature took 30 hours to reach 50°C and with 15cm cable spacing the mid point temperature reached 47°C after 42 hours. The rate of rise of temperature at 42 hours is 0.04°C/h, close to steady state for this structure.

Increasing the heat input rate to 380 w/m^2 reduced the time to raise the average surface temperature to 50°C to 10.5 hours. The mid point temperatures reached 50°C in 24 hours. The estimated steady state temperature for the mid point was 56°C and the final temperature at the cable was 80°C.

Fig. 5.3.2 Surface temperature distribution at 42 hours



Conclusions

1. The heat input rate is correct at 250 – 300 w/m^2 for solid concrete floors.

2. The cable rating is high. A greater length of lower power cable more closely spaced would produce more uniform temperatures but would cost more

3. The use of higher heat input rates could lead to structural damage – cracking of concrete slabs.

4. An effective means of ensuring good contact between the heat source and the surface to be heated is essential

5. Uninsulated heating cable will not be effective

6. Surface heating of steel structures could be quick and effective if high heat input rates are used.

Further developments needed

1. Development of practical heating elements for floor slabs and wall floor joints

2. Practical test of conductive heating combined with air heating to confirm that heavy structures can be treated effectively.

5.4 Wall floor joint heating trial

Summary

1. Using 152 W/m with cables at 3cm and 13cm from the wall floor joint it was shown that wall floor joint temperatures of 40^{o}C could be achieved in 7.5 hours and 48C in 27.5 hours. The room air temperature was 9 – 10^{o}C.

2. 76 W/m with cables at 3cm from the wall floor joint it took about 33 hours to reach 40^{o}C (the maximum reached)

3. The floor slab heated more slowly and cooled more quickly than the wall when the insulation was removed.

4. Increasing the heat input to 200 W/m and improving the contact between the heater and the structure should ensure a more rapid response without resulting in excessively high temperatures.

The structure

The heating tests were conducted on a section of internal concrete block wall (100 mm thick) and a ground floor dense concrete floor slab. The floor slab is laid on hardcore on a clay subsoil with a high water table.

Heating cable layout

Heating cable rated at 38 W/m was stuck to the wall and floor using aluminium adhesive tape. The cable was secured at about 40 cm intervals and every effort was made to keep it flat and in good contact with the wall. In spite of this contact was not always maintained.

152 Watts/metre (four cables) - Two lengths of cable were attached to the wall and two to the floor. Each pair of cables was positioned 3 and 13 cm from the wall/floor joint.

76 Watts/metre (two cables) - One length of cable was attached to the wall and floor. Both cables were positioned 3 cm from the wall/floor joint.

Insulation

Before starting to heat the wall and floor were covered by strips of commercial reflective insulation which comprised a plastic foam sandwiched between two foil sheets. The overall thickness of the insulation was 6 mm. The insulated area extended 23 cm from the wall/floor joint both up the wall and across the floor. The insulation was held in place by aluminium foil adhesive at intervals. After 33 hours of heating the insulation was removed and heating continued without it.

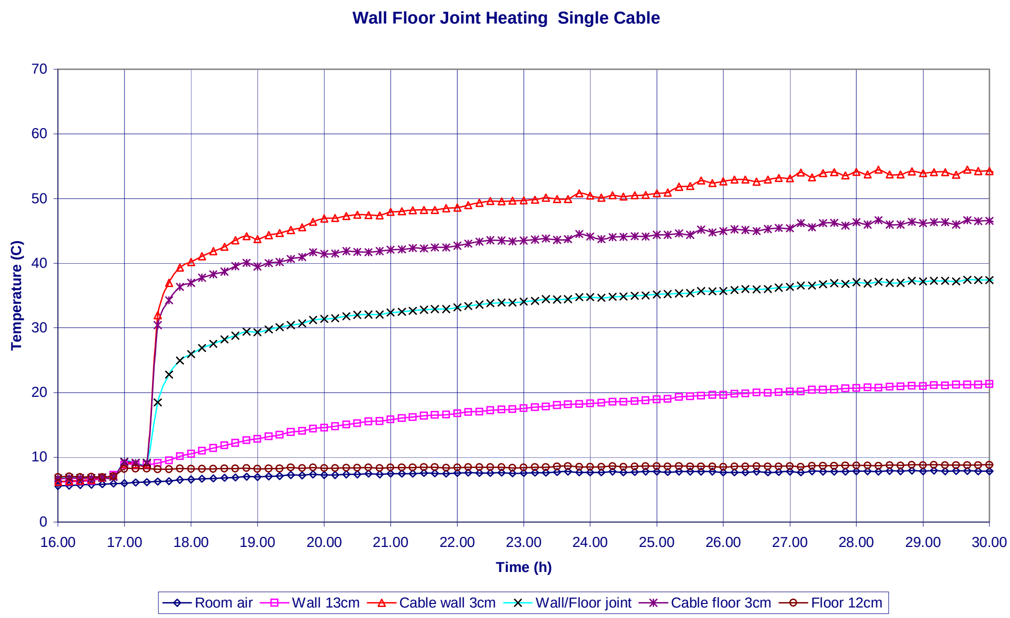
Temperature measurement positions

Temperature profiles at the surface of the wall and floor were measured normal to the heating cables. The temperatures at the mid point between cables and the wall/floor junction were measured in addition to the wall adjacent to each cable.

Results

With the single cable although the wall floor joint heated steadily there was little effect a few cm in either direction (Fig. 5.4.1). Much better results were obtained with the double cable (Fig. 5.4.2).

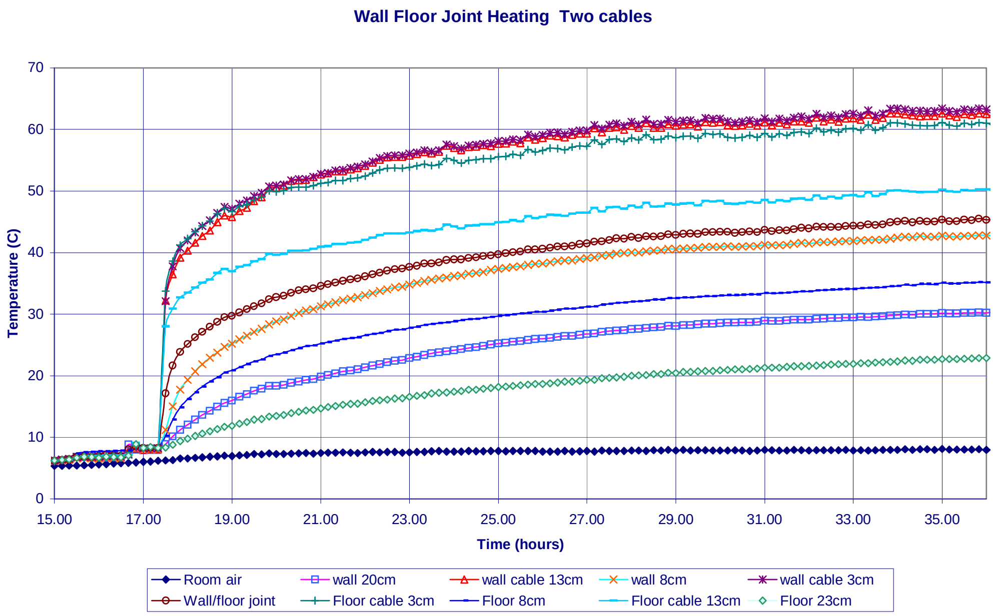
Fig. 5.4.1 Heating concrete with a single cable (76 W/m)



Single cable:

- The wall floor joint reached 40°C in 27.5 hours with 76 W/m input. This temperature fell by about 1°C when the insulation was removed.
- The wall cable stabilised at about 6°C above the floor cable. This reflects the different thermal properties of wall and floor.
- The floor temperature 12 cm from the wall/floor joint was unaffected by the treatment but the wall temperature 12 cm up was influenced, probably as a result of convection from the cable below.
- Removing the insulation had little effect on the measured surface temperatures.

Fig. .5.4.2 Heating with a double cable (152 W/m)



Double cable:

- The section of structure heated with 152 W/m took 7.5 hours for the wall/floor joint to reach 40°C. After 27.5 hours it had reached 48°C.
- When the insulation was removed the wall/floor joint temperature fell to about 45°C after 9 hours (Room air temperature rose about 1degree to 10°C) The wall temperatures were not affected by the removal of the insulation but all the floor temperatures fell 3-4 degrees over a 9-hour period.

Discussion

It is clear from these results that heat does not move laterally in the structures. The most effective heat source will be one that is well distributed over the heated area. Spot checks with the infra red thermometer confirm the importance of ensuring effective contact between the heating cable and the surface.

A flexible, flat heating element that can be pressed into good contact with the floor/wall is required. The importance of insulation to prevent heat being lost from the heated structure is demonstrated. This is particularly important for solid concrete floors.

Higher heat input rates than those used in these trials could be employed particularly if more effective contact can be maintained. Up to 200 W/m^2 could probably be used without local over-heating.

6. MILL BASEMENT HEATING TRIAL, CAMBRIDGE

Summary

- The two ThermoNox 18 kW air heaters used in the trial did not raise the temperature of the basement to 50°C in 48 hours.
- The final air temperature reached was 47°C. The model predicted 49.6°C after 48 hours.
- Un-insulated 250 W/m2 heating mats heated the wall floor joint to 30°C in 45 hours. Multi layer reflective insulation increased the surface temperature to 44°C after 45 hours.
- Un-insulated 500 W/m2 heating mats raised the surface temperature from 17°C to 41°C after 45 hours.
- An un-insulated 500 W/m2 double mat combined with air heating raised the floor surface temperature to 50°C after 20 hours and 64°C after 48 hours.
- An un-insulated 250 W/m2 mat combined with air heating raised the floor surface temperature to 45°C after 32 hours and 47°C after 48 hours.
- A poly-duct delivering room air heated the floor surface to 40°C after 48 hours.

Introduction

Trial objectives

1. Demonstrate the use of heating mats to raise the basement wall floor joint to 50°C
2. Measure the temperature response in a wall floor joint heated by an uninsulated heating mat
3. Measure the temperature response in a wall floor joint heated by an insulated heating mat.
4. Measure the temperature response of all structures in the mill basement when heated by two electric air heaters.
5. Measure the temperature response of a wall floor joint heated by directed warm room air supplied by perforated polythene duct.

Site description

The trial site was the basement of the original Fosters mill (Fig. 6.6). The floor level was about 1 m below outside ground level. The walls were of brick 750 mm thick, the floor was concrete slab and the ceiling was 75 mm thick timber supported on steel frames. Sections of the ceiling where the roller mills stood had been covered by 20mm plywood panels.

Power for the heating mats was drawn from the main distribution board via two 3.3kVA isolating transformers. Three-phase power for the 18.75 kW air heaters was also drawn from the main supply.

Methods

Heating predictions

The heating model was used to estimate the surface temperatures that could be expected after 48 hours with the two electric air heaters. The predicted room air temperature was 49.6 °C and the measured air temperature was 47°C. The floor and walls actually reached 37 – 38°C and the model predicted 39 – 41°C. These differences could be attributed to the use of 'book' values for thermal properties and heat transfer coefficients.

Heating methods and layout

The trial was divided into two periods. During the first the heater mats and insulation were tested without room air heating. The heater mats were rated at 150 W each (2.0 m x 0.3 m) (250 W/m^2) and were daisy chained together and fed by 110 V supply. The mats were placed on the floor as close as possible to the wall floor joint. In one place pairs of mats were placed one on top of another to double the heat input rate (500 W/m2). In another area either single or multiple layer reflective insulation was laid on top of the heater mats.

In the second period two 18.75 kW ThermoNox air heaters were used to heat the whole of the fabric of the room. The ventilation system outlets in the basement were sealed with polythene sheeting to prevent a strong convective flow from the basement. During this period an independent 120 W 240 V axial fan was used to blow room air through perforated poly-ducts on two sides of the room. These ducts were positioned so that air was blown into the wall floor joint. In some places the ducts were laid over double and single heating mats.

Temperature measurements

Temperatures were measured by thermocouple and infra-red thermometer. The thermocouples were recorded by a Campbell datalogger at 10 minute intervals.

In addition to the logged temperatures the heating progress of the structure was checked with the infra-red thermometer. It was found that this instrument gave much more reliable results if it was left in the heated area between uses. There was no delay for the instrument reference temperature to come to ambient.

Results and discussion

The aim of each of the supplementary heating treatments was to reduce the difference between the room air and the surface temperature to ensure effective treatment in potential harbourages. After the initial warming period the surface temperatures of the heated structures reaches a constant difference with the room air temperature. This is an effective measure of the heating performance of the different treatments. A positive value in Table 6.1 shows the surface temperature is higher than the room air temperature. A negative value shows the surface is cooler than room air temperature.

After 19 hours in the air heating phase of the trial, one heater started to modulate and this control became much more frequent after 29 hours (see 67 and 77 hours after start of trials in Fig. 6.1). Air temperatures at 19 hours were about 42°C and at 29 hours were about 45°C. The other heater did not modulate. Both heaters were set to the same recommended control settings of 87 and 90°C.

Results for the different arrangements of mats with and without insulation or supplementary ducted air heating, are shown in Figs 6.2 to 6.4. The combined use of the heating mats and the poly-duct showed that in the first 2-4 hours of air heating the wall floor joint temperature was reduced because room air was much cooler than the mat-heated area. The ventilation initially cooled the heated mat. Results for the use of polyducted heating alone are shown in Fig. 6.5. Nearly 90 hours heating were required for the wall floor join to reach 40°C.

The heating time is a measure of the speed with which the steady temperature difference is reached. The time stated in Table 6.1 is the time for the difference between the surface and the air to halve. In practice this means that the steady temperature difference will be reached in three times the value shown, e.g. the wall floor joint temperature for the single mat with multi layer insulation would take 13.5 hours to reach 17°C above room temperature.

Infra-red measurements revealed variations of 2 – 3 °C between parts of the room where the heater discharge was directed and those where the air was returning to the heaters. It was observed that the cast iron columns stabilised at 29°C at floor level and 44°C at ceiling level.

There was no problem with the fire control sprinklers. The maximum temperature observed at a sprinkler head was 48°C.

Table 6.1 Surface – room air temperature in the basement at Fosters Mill

Heating treatment	Wall/Floor joint (°C)	Floor (°C)	Heating time (h)
Single mat (250W/m^2) No insulation; No room heating	7.0	10.5	2.6
Single mat (250W/m^2) Single insulation; No room heating	12.0	16.0	2.5
Single mat (250W/m^2) Multi-layer insulation; No room heating	17.0	23.0	4.5
Double mat (500W/m^2) No insulation; No room heating	22.0	22.0	0.5
Double mat (500W/m^2) No insulation; Polyduct air heating	7.0	12.0	
Single mat (250W/m^2) Single insulation; Polyduct air heating	-2.8	0.0	
Double mat (500W/m^2) No insulation; Room air heating	19.0	4.0	
Single mat (250W/m^2) No insulation; Room air heating	-6.0	0.0	
Polyduct with room air heating	-7.0	-6.5	
Room air heating No special treatment		-17.6	

Conclusions

1. 250 W/m^2 is not enough to heat the wall floor joint to treatment temperature without insulation and support air heating.

2. With multi-layer reflective insulation and 250 W/m^2 the mat will heat the wall floor joint to between 17 and 23°C above room air temperature.

3. 500 W/m^2 without insulation heats the wall floor joint to 22°C above room air temperature.

4. Poly-duct air distribution to the wall floor joint over heating mats reduces the temperature lift to 7.0°C above room air temperature for 500 w/m^2 and to 2.8°C below room air temperature with 250 W/m^2 mats.

5. Poly-duct blowing room air decreased the difference between wall floor joints and room air temperature by 10°C.

6. Air movement created by the heaters resulted in local variations in the heater mat performance. In general the temperature rise produced by the mat was less with the heaters working than without.

7. Surface temperatures fall quickly when heating stops but recover quickly when heating re-starts.

8. It would be unsafe to assume that 250 W/m^2 heating mats could be used in more than one location during a treatment. Ground floor wall floor joints would fall below lethal levels even with air heating in operation.

9. Predicted heating performance is in good agreement with the measured results.

10. The heaters reached a discharge temperature of 66°C after the 18-h warm-up period.

11. Structural components continued to heat up at a substantially constant rate of 0.171°C /h after the initial warm up period. At this rate the floor slab and lower walls would take a further 64 hours to reach 48°C, a total heating time of 108 hours.

Recommendations

1. Use heating mats on ground floor wall/floor joints for 24 – 36 hours prior to starting air heating.

2. Heating mats should be rated at 500W/m^2

3. Heating mats should be shaped so that they fit into the angle of the corner. They should extend 50 mm up the wall and 150 mm out on to the floor.

4. Room corners need a shaped mat rated at 700 W/m^2 to ensure the corner is treated.

5. Use multi layer insulation to ensure most of the heat goes into the structure not into the air. Remove insulation when air heating starts. Keep insulation and heating mats in place with sand snakes.

6. Use poly-ducts with air heating to ensure that wall floor joints on upper floors are heated.

7. Use enough air heater capacity to raise heater discharge temperature to 65°C within 6-8 hours of starting.

Fig. 6.1 Temperature profiles for heater outputs, air and surfaces.

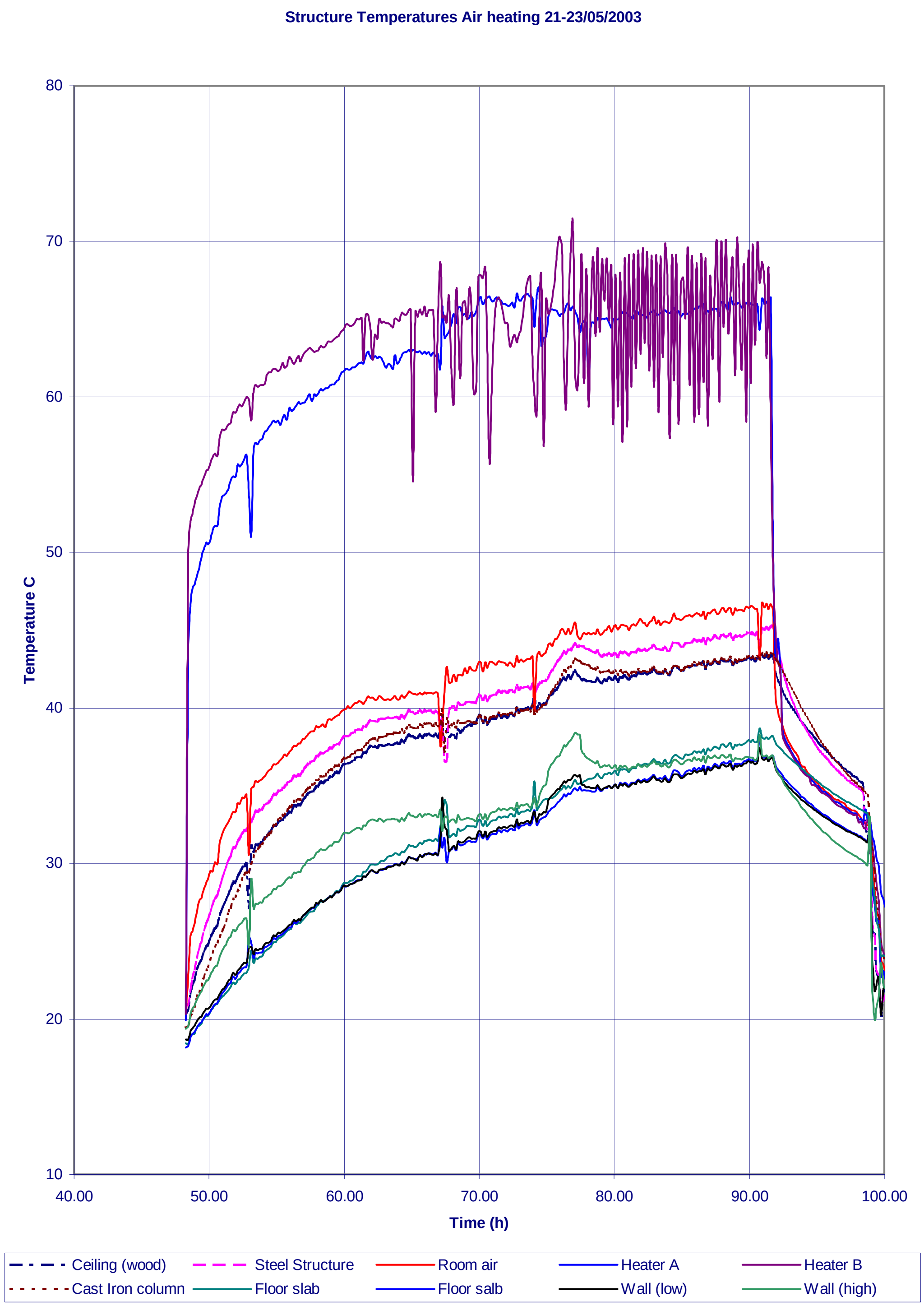
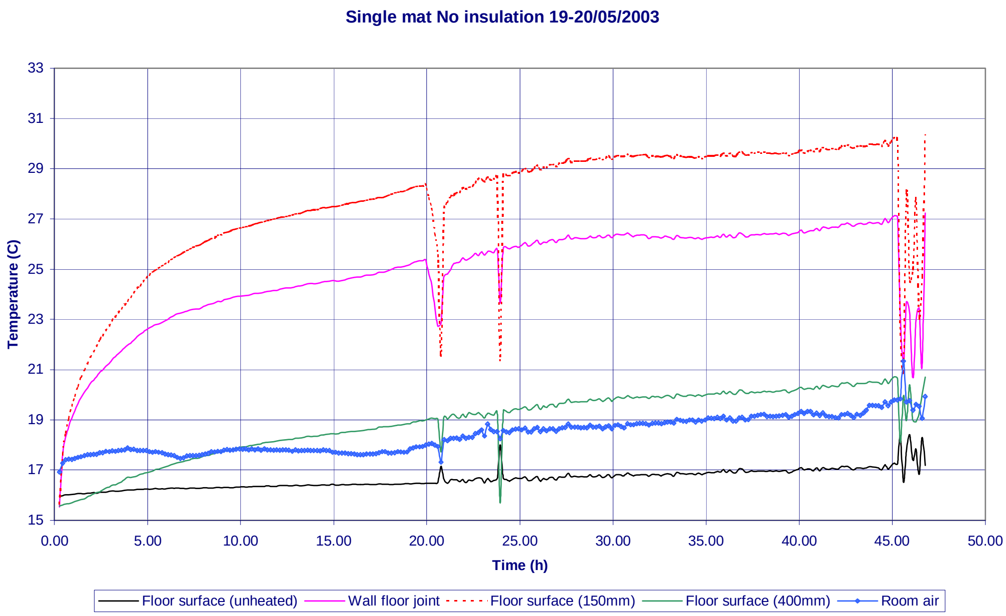
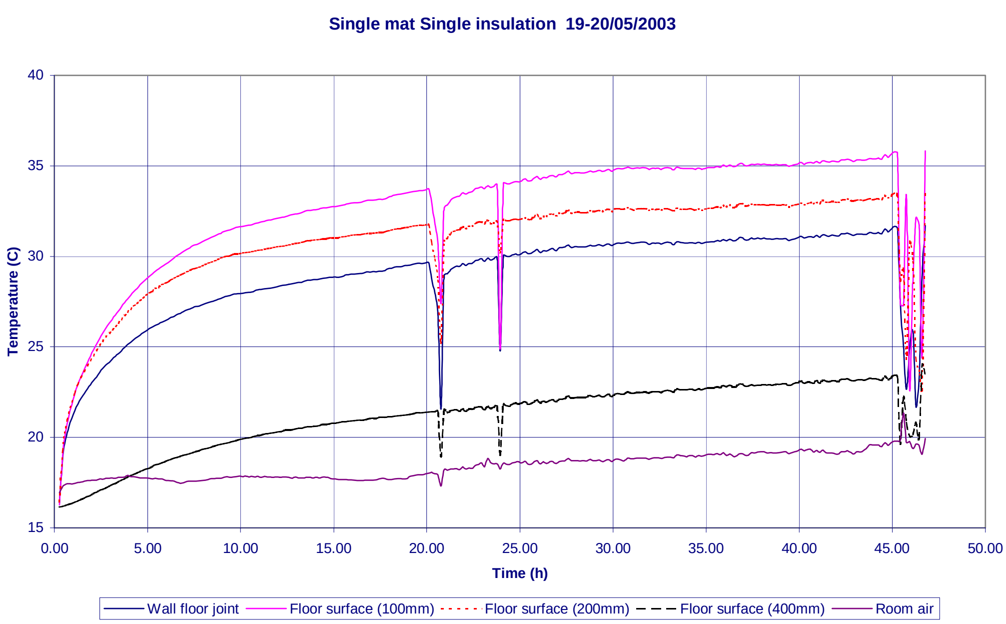


Fig. 6.2 Results with single mats without air heating and A) without insulation, B) with a single layer of insulation and C) with multiple insulation

A



B



(Fig. 6.2 contd.)

C

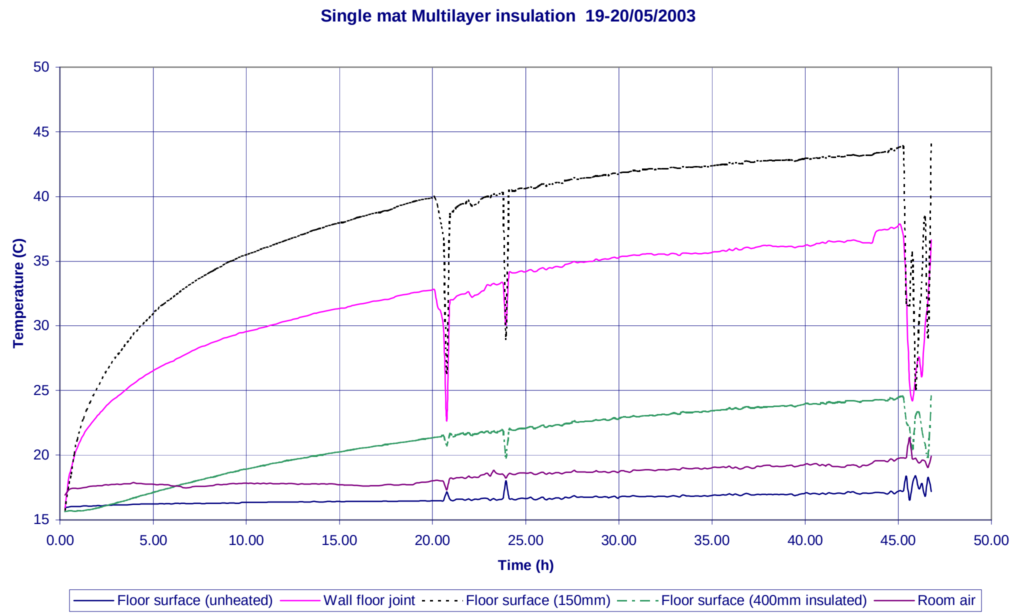


Fig. 6.3 Results with double mats and poly-ducted heating

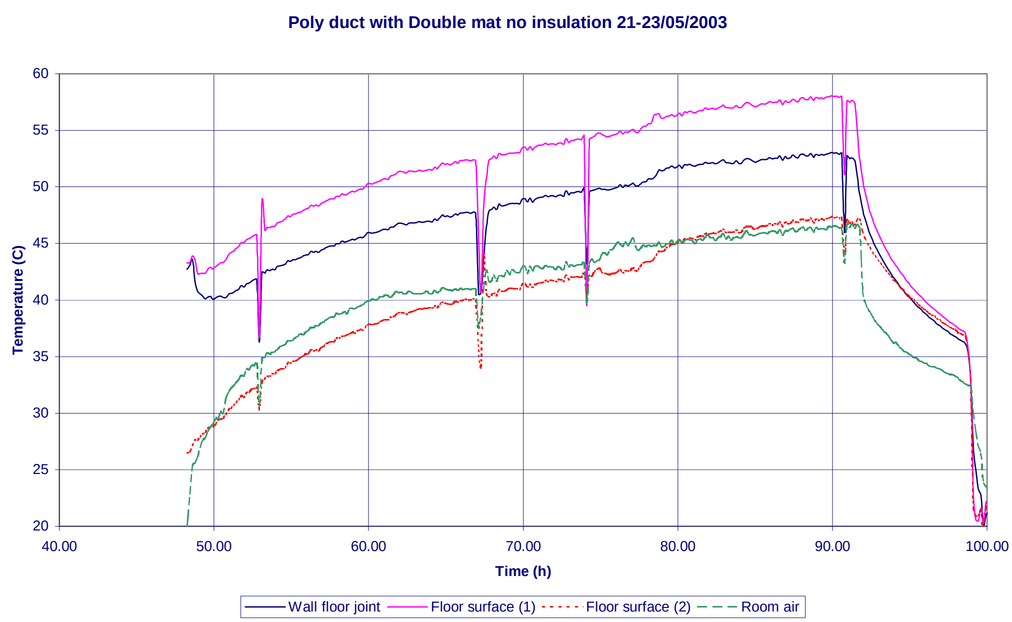
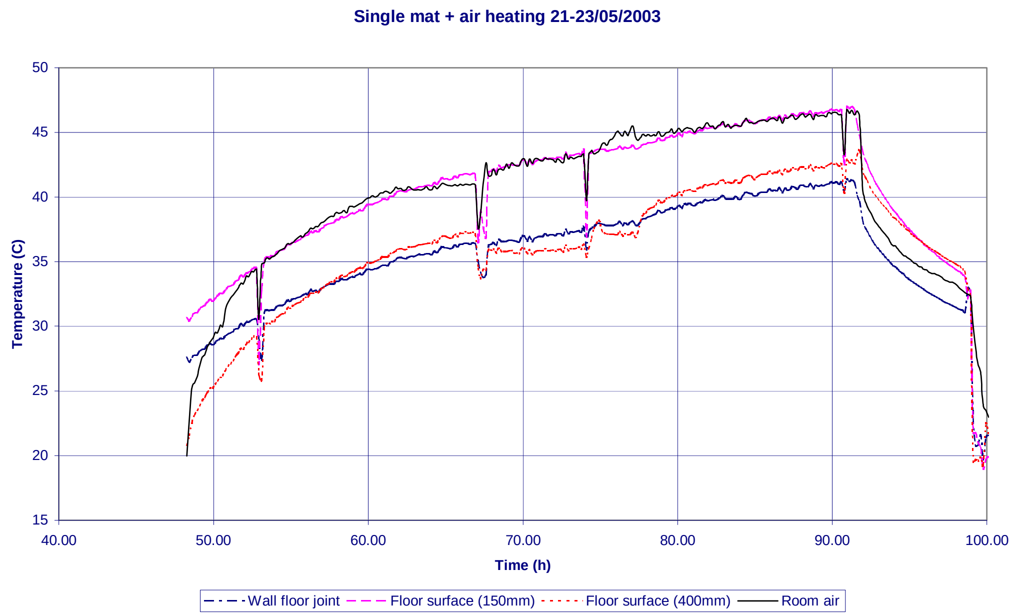


Fig. 6.4 Combination of mats and air heating for wall floor join heating, A) single mat and B) double mat

A



B

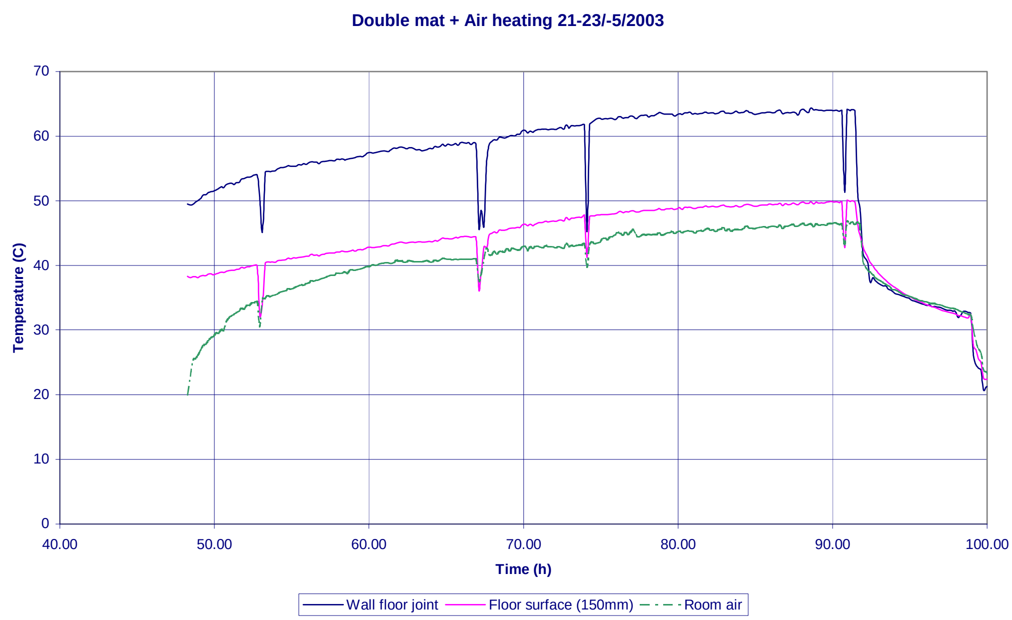


Fig. 6.5 Heating of wall floor join with poly-duct heating alone

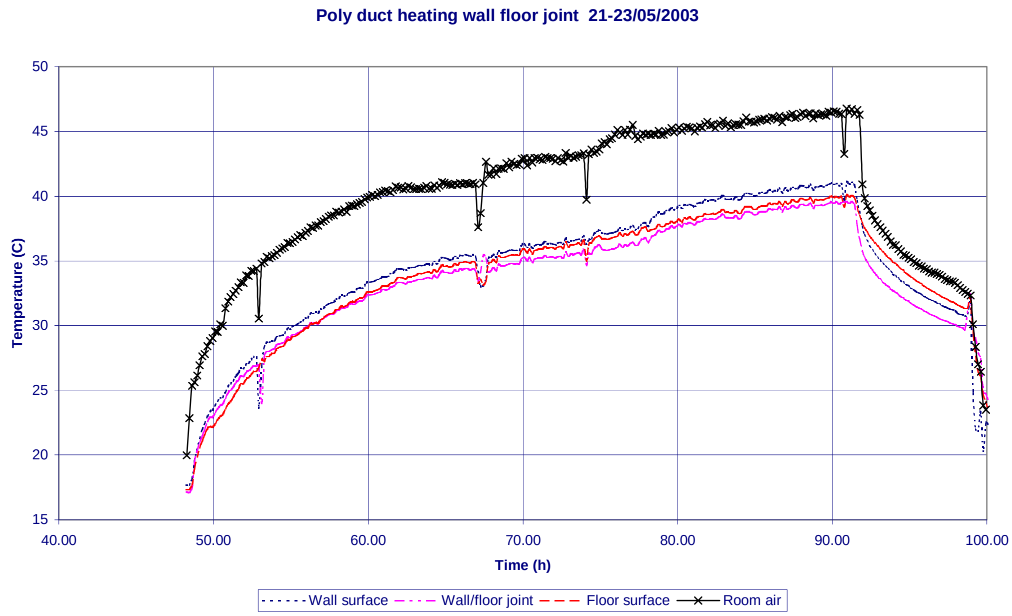
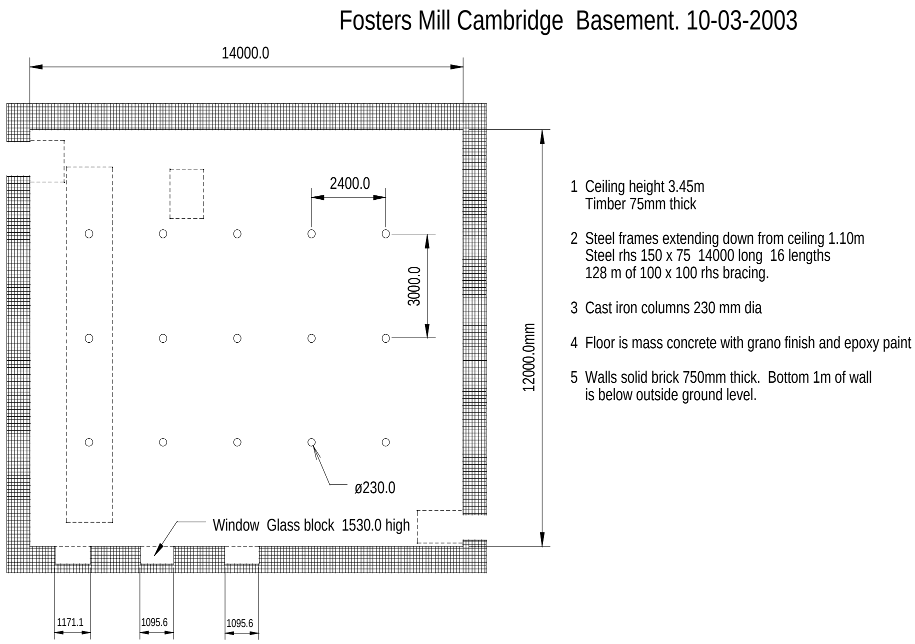


Fig. 6.6 Trial floor plan



7. WHOLE MILL TRIAL AT HOLBEACH

Summary

- The treatment was performed on the whole mill building.
- The average air temperature was held after the first 10 hours at 48 – 51°C for a 30-hour period.
- All the upper floors were raised to 50°C and held there for 12 hours or more.
- Much of the ground floor was raised to 50°C but some sheltered areas only reached 38°C.
- The insulated wall floor joint heating mats warmed the edge of the floor to 71°C (700 W/m2), 61°C (400 W/m2), and 47°C (250 W/m2) after 14 hours. An unheated section of floor perimeter remained at 23°C. The average external air temperature was 22°C.
- The poly-duct heated wall floor joint was maintained at 5°C below the duct air temperature (52.5°C). The control section of wall floor joint was maintained at 11°C below air temperature.
- Heater capacity on upper floors, with three 18 kW units on the top floor and two each on the first and second floors, was just adequate.
- Heater capacity on the ground floor with five 18 kW heaters was inadequate. Two more 18 kw heaters would have improved the ground floor heating.
- Some insect survival occurred indicating that a lethal temperature exposure was not achieved in the basement and that the pre-treatment floor spraying was of limited effectiveness.

Introduction

The mill at Holbeach is constructed of brick with an internal steel frame and two internal brick dividing walls so that the space is divided into 3 vertically. The upper floors are supported on 100 mm thick timber. The ground floor is a concrete plinth and features two levels. The roof is slate over close boarded timber. There are substantial areas of single glazed window in one side wall. The walls and roof of the area above the grain bins are of insulated steel clad panels. The basement area below these bins is constructed of uninsulated sheet steel panels.

The volume of the building is 3328 m^3 with overall dimensions of 17.7 m height, 7.3 m width, and 25 m length.

Objectives

1. To carry out a full scale thermal disinfestation of a mill under commercial time constraints.
2. To monitor effectiveness by placing live insects at selected locations within the building.
3. To measure the temperature response of the structure and compare this with model predictions.

4. To test the effectiveness of heating mats and poly-duct ventilation for raising the temperature of wall floor joints.

5. To test a dust applicator for treatment of voids with inert dust as an adjunct to the heat treatment providing some residual protection.

Methods

During the week leading up to the treatment the building was thoroughly cleaned. Obvious cracks in the structure were sealed with silicon sealant. All floors were sprayed with an approved pyrethroid insecticide. Electrical preparations included the preparation of the power connection point and the provision of the 110 V supply for the heating mats. An application of a commercial formulation of diatomaceous earth (DE) was blown into a 5 mm gap between a 36m ^{2} chimney breast shaped wall lining and the wooden storage bin behind using the same gas powered applicator as that used in the trial at Langley mill (see section 3 above). Holes were again drilled at 2-3 m intervals and the dust injected as before.

The principal components of the heating equipment were 12 ThermoNox 18kw three phase electric fan heaters. These were deployed, 3 on the top floor, two on floors 1 and 2, and 5 on the ground floor. In addition, on the ground floor two fans blowing room air directly onto the floor slab were used to heat inaccessible places. After 26 hours two heaters were moved from the top floor, one each to the 1st floor and ground floor.

The edge of the floor slab was pre-heated by silicone rubber electric heating mats. A range of heating power density was used (250, 400 and 700w/m2) The total power input to the mats was 5.37 kW at 110v. Power was supplied via three isolating transformers.

On the second floor a fan and polythene duct were deployed to blow room air into the wall floor joint on one side of the building.

The trial heating times

Heating mats were positioned round the edge of the ground floor and with the mill still running. They were switched on 15 hours before the start of the air heating treatment. The mill was shut down 12 hours later at 0400 hrs (day 1). Fire extinguishers were removed from the building and compressed air system vented to atmosphere. Heating power supply was connected and all the heaters were plugged in and positioned. Heating started at 0700 hrs and continued uninterrupted until 0930 hrs the next day when two heaters were removed from the top floor. One was placed on the first floor and the other on the ground floor. At 2000 hrs on day 2 the remaining heater on the top floor was turned off.

Heating continued until 0130 hrs on day 3 when all the heaters were turned off (fans continued to run for 40 minutes) and the windows were all opened to allow the building to cool.

At 0530 hrs day 3 work started to transfer the electric supply back to the mill. By 07.00 am temperatures are low enough to prepare to start the mill. Heaters, power cables and temperature monitoring equipment were removed and the mill was restarted at 09.30 am. There were problems with the PLC after 2 hrs running. This fault was cleared by 8.00 pm.

Temperature measurements

Temperature monitoring equipment was installed 4 days before treatment was due to start. Temperatures were recorded at 10 minute intervals in 64 locations throughout the structure for the duration of the treatment. The temperature into and out of each heater was recorded. Floor temperatures under different sample heating mats were recorded.

In addition to the automatic records, manual records of surface temperatures were taken at 2-3 hour intervals throughout the treatment. These were obtained with an infra-red hand held thermometer. A representative temperature of each wall, floor and ceiling of each room in the mill was taken.

The bioassay

The bioassay comprised cultures of the rust-red flour beetle *T. castaneum* set up with 50 adults two days prior to heat exposure on 40 g of a 20 to 1 mixture of wholemeal flour and dried yeast. The cultures were contained in fine mesh (30 m) nylon bags heat sealed to prevent escapes. The day before the 7.00 am start of air heating, bags were placed in pairs at each of eight positions throughout the mill from the top floor to the basement. Two further bags were returned to the laboratory for incubation at 25°C to act as controls.

Results

Air temperatures

Fig. 7.1 shows the average delivery and return air temperatures on each level for the treatment period. The average (between machine input and output temperatures) air temperature on all floors rose to 60°C in 7h (top) 10h (2^{nd}) 15h (1^{st}) 27h (ground). The model predictions were an air temperature of 60°C in 24 h (top) 7h (2^{nd}) 7h (1^{st}) 7h (ground). The time errors are due to no allowance for heat convected from lower floors, an underestimate of roof insulation and an extra heater used in the model on floors 1 and 2. The thermal properties of the structure were taken from literature, not measured.

Heating of surfaces

The surface temperature observations for each level are plotted in Figs 7.2-5, revealing the same pattern as in previous trial with the heating of concrete surfaces lagging behind others. Locations for these temperature records are shown in Fig.7.6.

Mats benefitted from insulation to restrict heat loss when air temperatures were low and proved capable at the higher power densities in raising underlying surface temperatures within a few hours. Fig. 7.7 shows the floor temperatures under the heating mats during the test and Fig. 7.8 the locations of the mats in the basement area.

The poly-duct heated wall floor joint showed that this was a much slower option for heating than mats with temperatures lagging behind ducting air temperature by about 4°C on reaching maximum temperature after 48 hours (Fig. 7.9).

Cool spots

Heat distribution was controlled by moving the fan heaters from time to time. The limited number of heaters and the constraints on where they could be placed meat that some wall floor joints and shielded areas of the plant did not reach treatment temperature. Towards the end of the heating period when stable temperature gradients had been established in the structure a search for the lowest temperatures on each floor was made. The most common place to find low surface temperatures was in the corners of rooms at the wall floor joint. Typical values are shown in Table 7.1. The cool spots had a surface heat transfer coefficient about half that of an exposed wall. The observed values were equivalent to those quoted in the literature for still air conditions.

Bioassay results

Adults and eggs survived at one position only, in the basement near the corner between position A and heater 1 in Fig. 7.6, above the point where a temperature of 31°C was recorded under a mat 8 hours after the start of floor heating (Fig. 7.8). Controls indicated a survival of up to 25% of eggs exposed at this position while over 95% of adults survived.

The dust application

Despite the large area, and such a thin gap, the DE gave good penetration and was seen to blow out from injection points up to 3 m from the point of application.

Discussion

The use of 12 18 kW heaters for this mill of 3,300 m^3 capacity supplemented by the use of heat conducting mats for the basement concrete wall floor joints showed the potential success of a heat-based disinfestation procedure. For this relatively small mill it was apparent that about one heater per 300 m^3 of volume was required to achieve optimal results, and that probably 14 rather than 12 18 kW heaters were required, the extra heat energy being needed for the lower region of the basement where access was restricted. A log of the temperature of the air leaving and returning to each heater provided a good indication of heater performance and the response of the building to heating, but did not give detailed information about the distribution within each heated space. The true air temperature on each floor is best represented by the temperature of the return air as it enters the heater.

The current trial used 64 temperature monitoring positions. Critical point monitoring could reduce the number of temperature sensors required for routine monitoring of commercial heat treatments. Selection of critical points should be based on known infestation locations and the expected thermal response of that part of the structure. The aim of the heat mats on the ground floor to raise temperatures was to kill any insect stages present in the wall floor joints and to provide a barrier to prevent insects falling onto the floor taking refuge in cool corners. However it is impractical to raise such floor temperatures high enough to kill insects during the first 12 hours of a treatment, and spraying floors with insecticide in recommended to control insects that fall there from above when the structure starts to warm up. The heating mats required insulation to build temperatures up prior to air heating.

Results showed that internal walls and floor/ceilings that are heated from both sides reached lethal temperatures relatively quickly. Wall floor joints on upper floors can be heated by directing hot air into the angle between the floor and wall. Plant and structural members inside the treated space will also stabilise near to room air temperature. Wall floor joints of upper floors are influenced by heat loss through the outer wall. Places where structural steel work or ducts pass through outer walls, and dead spaces behind insulation or concrete structures, will not reach lethal temperatures. These areas should be sprayed with insecticide and/or treated with DE if appropriate.

The use of targeted DE treatments to supplement heat for UK mills is showing promise, corroborating studies in North America (Fields et al., 1997; Dowdy, 1999; Dowdy and Fields, 2002). Future studies need to include a wider range of insect species and investigate effects against different stages. Since there can be variation in efficacy between different DEs (Dowdy, 1999), these studies should also include other DE products.

Effective temperature monitoring is the key to the shortest and most reliable treatment. The installation of fixed automatic sensors connected back to a central point is time consuming. A log of surface temperatures in each ‘room’ required 85 observations at each time interval. The use of radio remote sensors in all these locations would save time but be expensive.

The heating model gave optimistic projections of heating time for the ground floor and indicated more heat would be needed for the top floor than was actually the case. The air temperature predictions were accurate and the response of each type of structure was correctly predicted though the time to reach lethal temperatures was longer than observed. The model treats the whole area of each type of structure as one so cannot predict variations in response near individual heaters.

Recommendations

- Ensure effective cleaning of the ground floor.
- Ensure effective spraying of all floors. Special attention to corners of rooms because insects will migrate to these cool areas.
- Use high power heat mats (400 Wm^2/ or 700 W/m^2 for corners) and insulation to pre-heat ground floor wall floor joints. Effective contact between heating mats and floor is essential.
- Remove insulation from heating mats when the return air temperature has stabilised at 50 °C.
- Use poly-ducts to blow hot air into wall floor joints on upper floors when the return air temperature has stabilised at 50°C (will bring surface temperatures to within 3°C of ducted air temperature).
- Close the building up to prevent excessive air exchange during treatment.
- Develop a remote process monitoring system to manage the heating treatment. Include temperature logging of selected sites and air on/off temperatures for each heater.
- Use an infra-red hand held thermometer to check on progress and distribution of heat.
- Use measured thermal properties of the structure to improve model predictions.

Table 7.1 Observed low temperatures

Av. Room air (°C)	Av. Wall (C)	Cool spot (C)	Heat flux (W/m^2)	Cool corner h_{so} (W/m^2 °C)
Ground floor; 61.4	47.0	38.0	117.1	5.00
1st Floor; 61.8	49.0	38.0	104.1	4.37
2nd Floor; 58.1	46.5	37.0	94.3	4.47

Fig. 7.1 Average air temperatures at the heaters (TC)

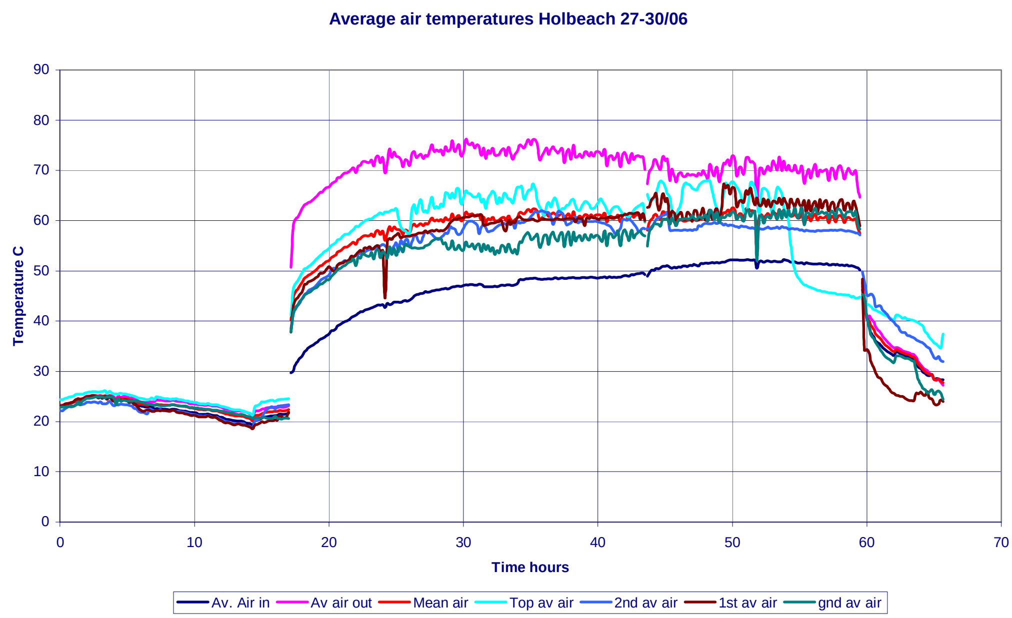


Fig. 7.2 Ground floor structure temperatures (IR)

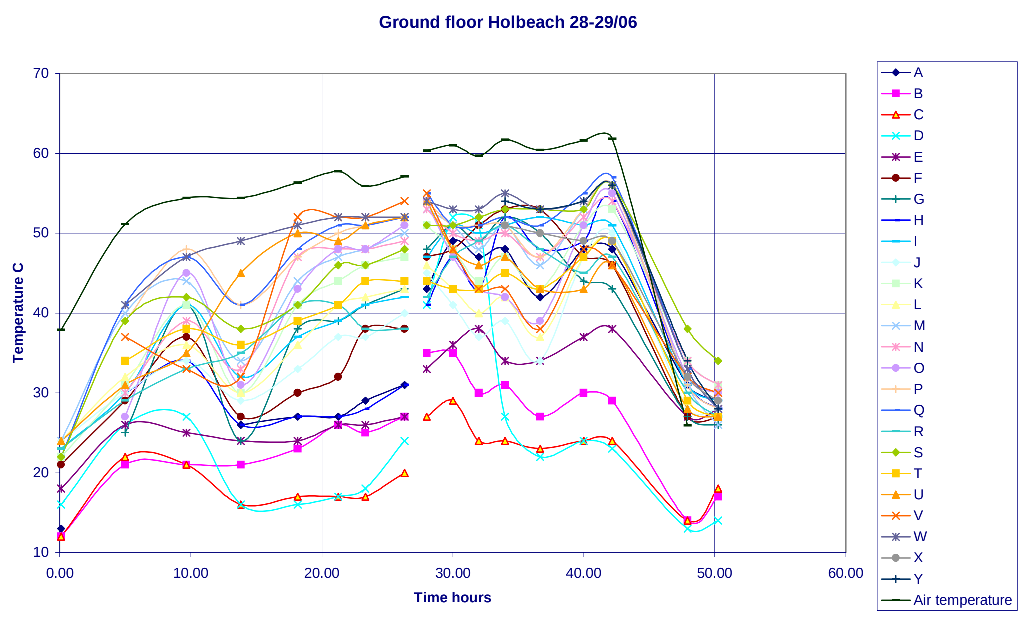


Fig. 7.3 First floor structure temperatures (IR)

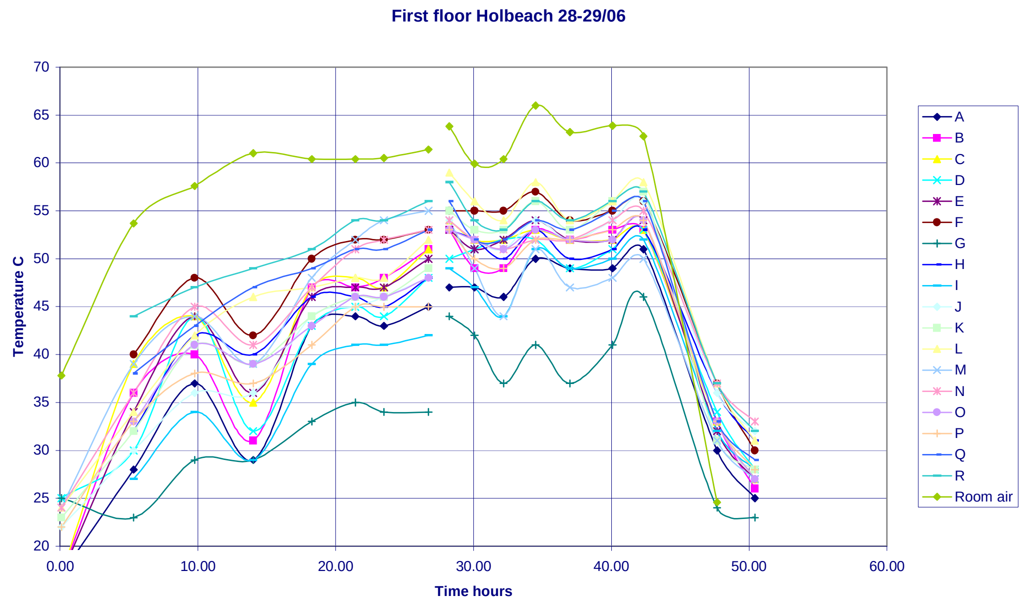


Fig. 7.4 Second floor structure temperatures (IR)

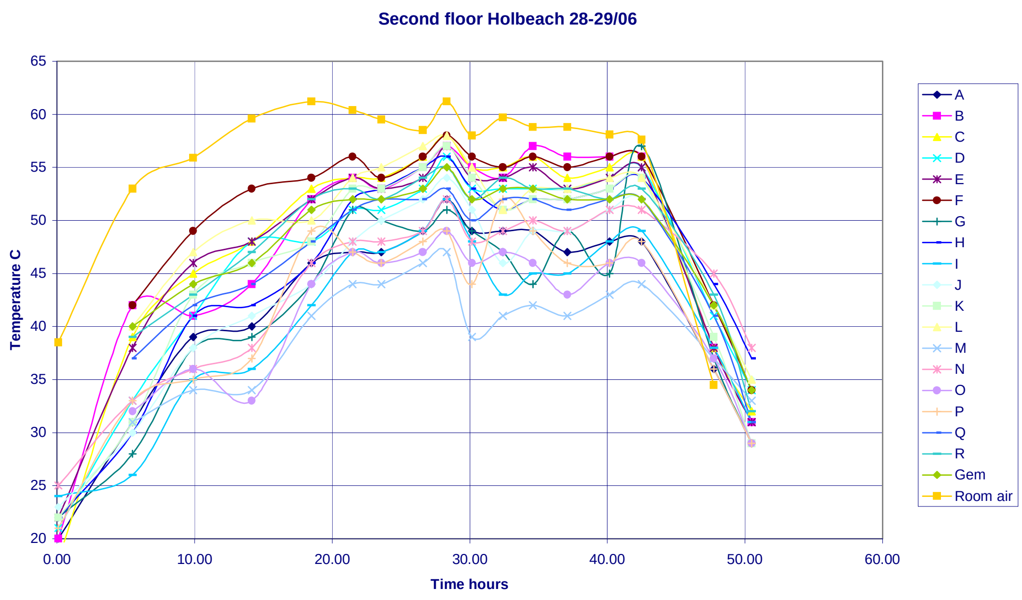


Fig. 7.5 Top floor structure temperatures (IR)

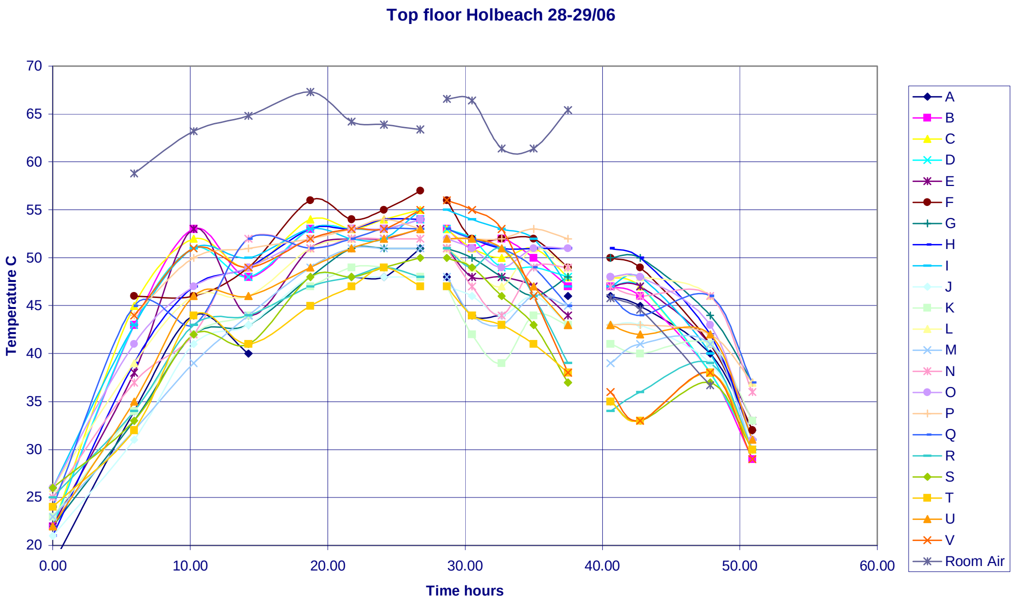


Fig. 7.6 Key to surface temperatures

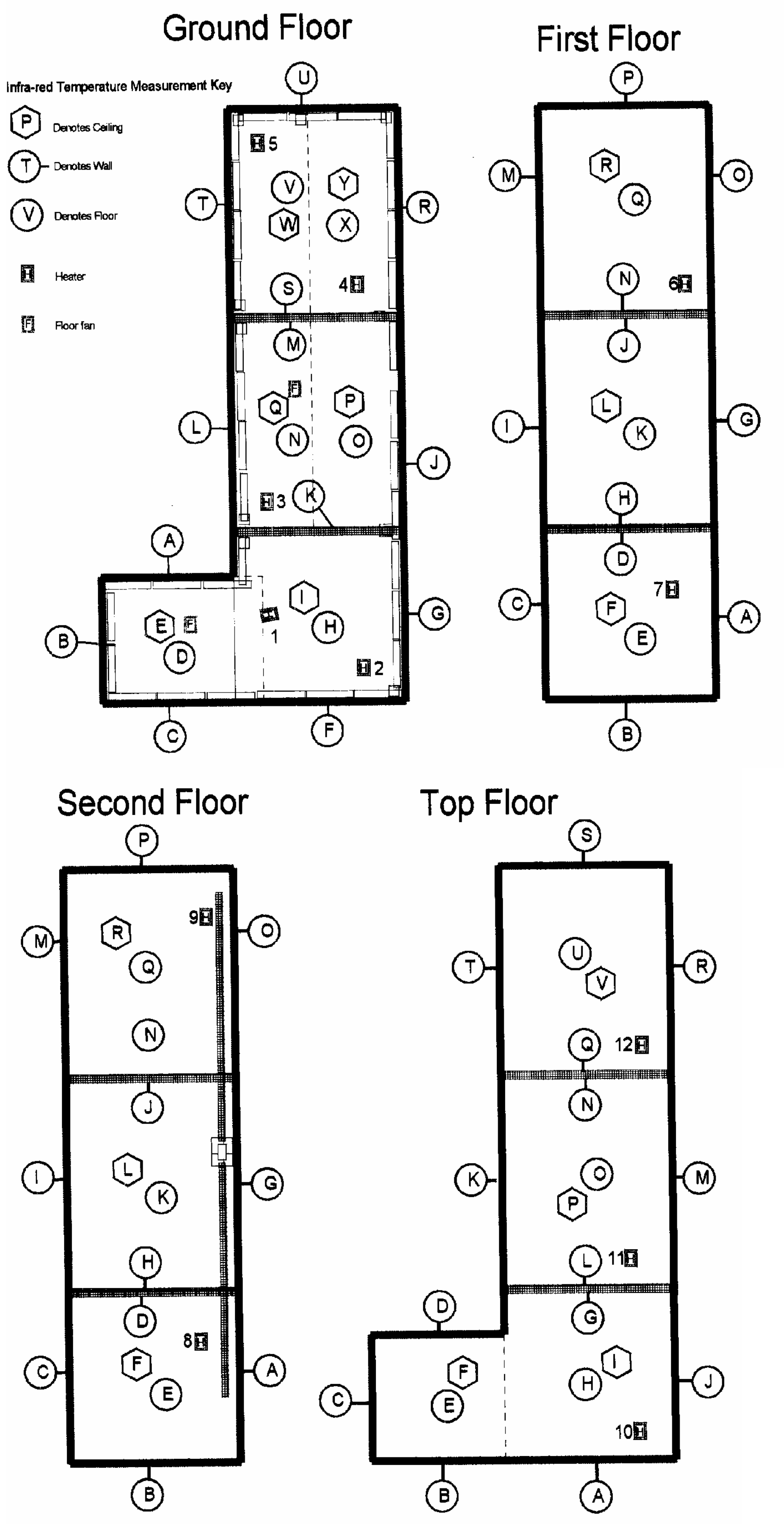


Fig. 7.7 Floor temperatures under heating mats (TC)

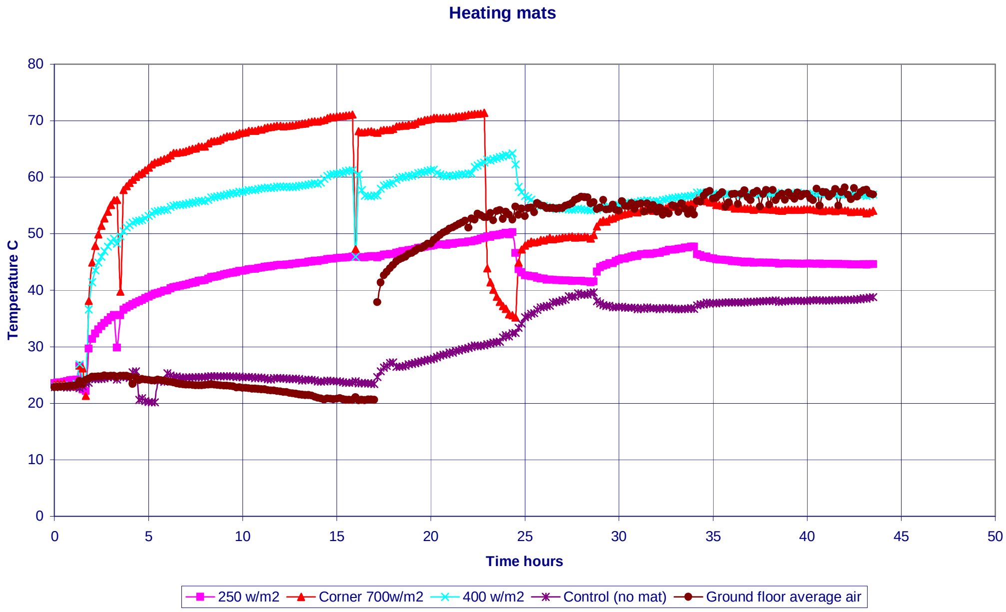


Fig. 7.8 Floor temperatures under heating mats after 8 hrs (IR)

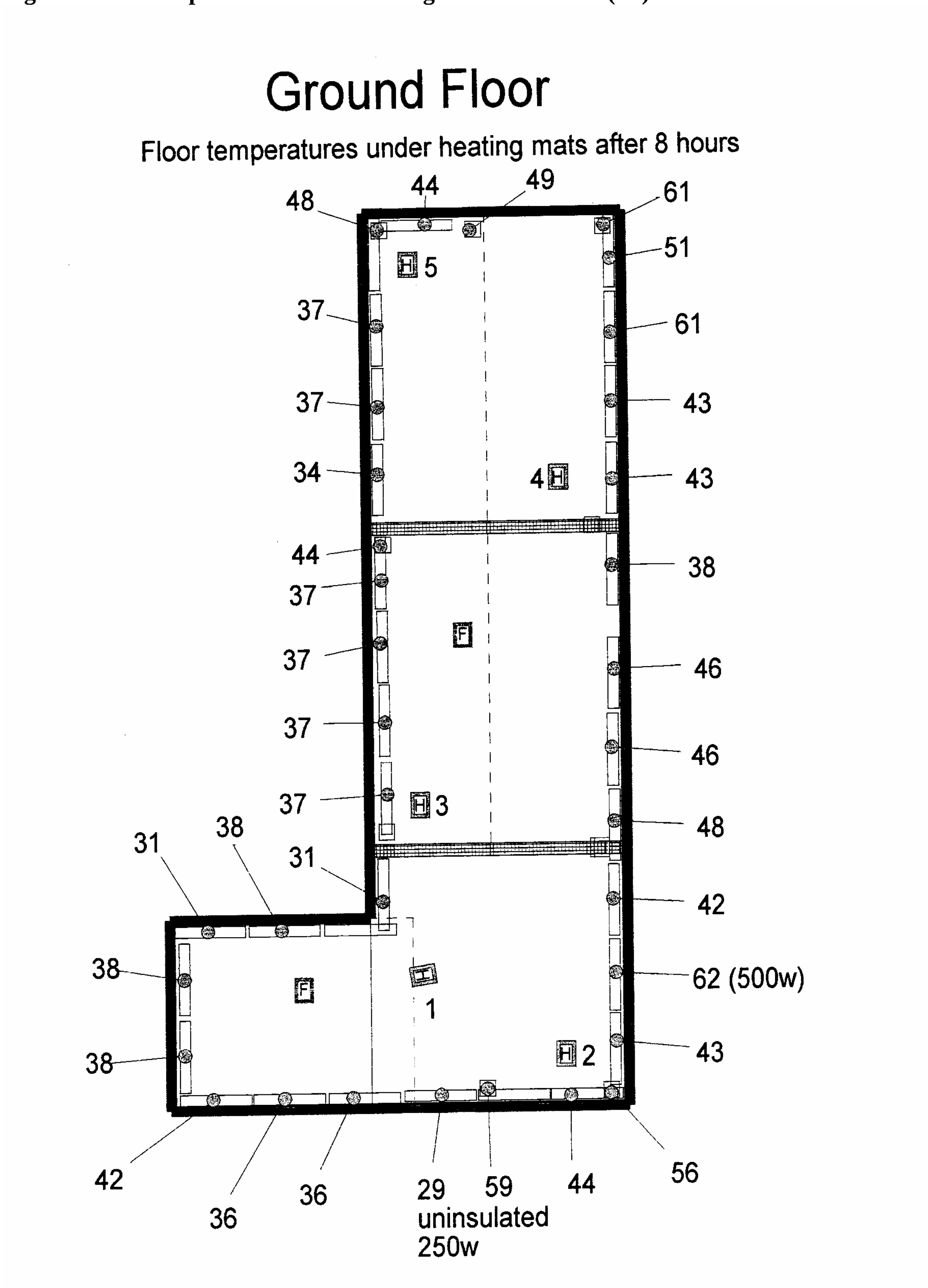
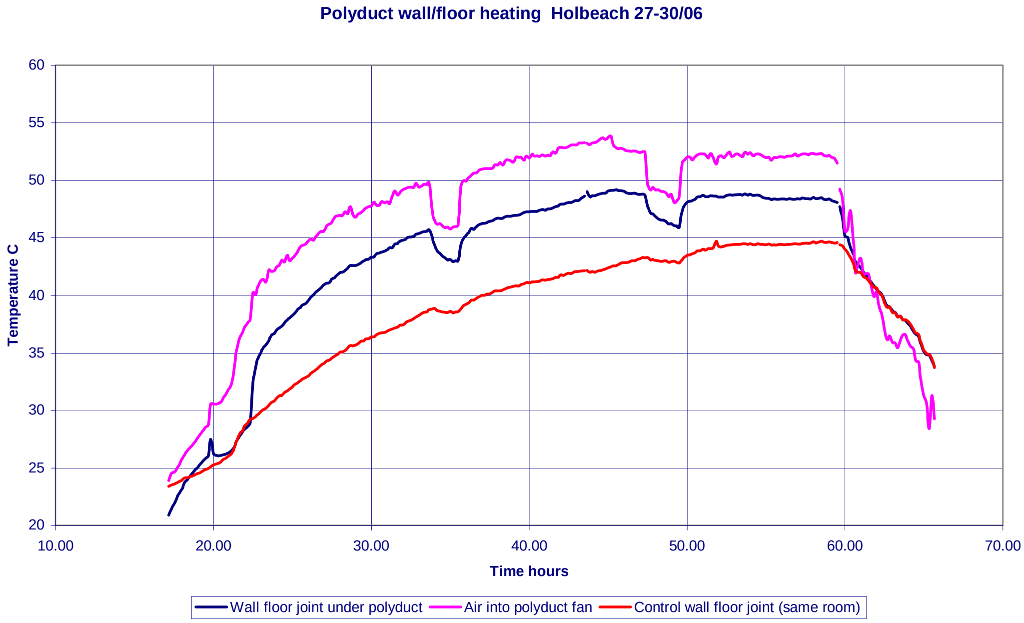


Fig. 7.9 Wall floor joint heating with and without polyduct (TC)



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APPENDIX 1.

MILL HEATING THERMAL MODELLING

Theoretical Outline

When a large mass is heated temperature gradients are set up and the thermal diffusivity of the mass and the surface heat transfer rate controls the rate at which heat is stored. A simple model of a single slab with one dimensional heat flow has been written and used to investigate the relative importance of thermal properties such as specific heat, thermal conductivity and density. The model is used to predict the temperature distribution history during a heating process. One side of the slab is heated by convective and radiative heat transfer. The other surface of the slab is in contact with a constant sink temperature through a convective and radiative surface.

Each of up to 10 different slabs is modelled by dividing them into slices through which the heat flows. The model balances the heat flux from the heat source with the flow into each different slab by adjusting the room air temperature The present model uses only a single material for each slab but there is no difficulty in adapting the solution to represent composite walls composed of several materials.

In order to include the effects of heating mats on parts of the structure the model allows the user to specify heat inputs direct to the inside surface of the structure, bypassing the convective transfer from the room air. Heat is also allowed to flow from the surface into the room air through a surface resistance if the structure surface is warmer than the room air.

This model only deals with one heated space at a time so in order to investigate the heating performance of a space that is bounded, in part by other heated spaces, the user can specify that a structure is heated from both sides. The energy input to such a structure may be counted from one side (when it is an external division adjoining another heated zone) or both sides (when it is contained within the heated zone). It is assumed that the temperature in the adjacent zone is the same as that in the heated zone.

SLAB5.FOR 20/09/2003

Composite slab transient heating and cooling

```
     COMMON slices,hi,temperature,e_in,rad_in,      *
U,in_flux,temp,dt,capacity,ho,air_out,e_out,rad_out,out_flux,
    *  sink_flux,heater_power,slab,slabs,surface,area,
    *  leak,air_heat,air_ambient,contact

     DIMENSION temperature(30,10),temp(30,10),U(30,10),
    *  capacity(30,10)
     REAL dt,ho(10),hi(10),air_in,air_out(10),rad_in,
    *  rad_out(10),e_in(10),e_out(10),in_flux(10),out_flux(10),
    *  k(10),cp(10),ro(10),thick(10),dl(10),temp_monitor(10),
    *  area(10),average_surface,heater_power,
    *  heater_set,total_area,average1(10),av_count,point,
```

```
    *  temp_log,error,sink_flux,XL,XR,     *
heat_low,heat_hi,heat_dif,time,dtt,sample,air_heat,
    *  air_ambient,energy,contact(10),direct_heat
     INTEGER I,J,slices(10),report,interval,end,sample_time,
    *  slabs,slab,control,off_time,leak_time
     LOGICAL heat_trace,detail,surface,leak,internal(10)
     EXTERNAL AIRTMP
```

Read the problem parameters **OPEN** (UNIT=5, FILE = "**TEST.DAT**", STATUS ="OLD") **OPEN** (UNIT=6, FILE = "**OUT.DAT**", STATUS = "UNKNOWN")

Global data READ(5,*)slabs,dt,heat_hi,heat_low,heater_set,heat_dif,

```
    *  control,interval,end,off_time,heat_trace,
    *  sample_time,detail,point,     *  air_heat,air_ambient,leak_time
```

Convert air_heat (m3/s) to heat capacity rate J/s degC air_heat = air_heat * 1208.4

```
     leak = .TRUE.
     air_in = 0
     total_area = 0
     DO 10 I=1,slabs
```

Slab specific data

```
          READ(5,*) temperature(1,I),k(I),cp(I),ro(I),thick(I),
    *  ho(I),hi(I),air_out(I),rad_out(I),e_in(I),e_out(I),
    *  slices(I),area(I),contact(I),internal(I)

          average1(I) = 0          dl(I) = thick(I) / FLOAT(slices(I))     U(1,I) = k(I) / dl(I)
          capacity(1,I) = dl(I) * cp(I) * ro(I)     air_in = air_in + temperature(1,I)
          total_area = total_area + area(I)10    CONTINUE
     air_in = air_in / FLOAT(slabs)
     average_surface = air_in
     heat_hi = heat_hi * 1000
     heat_low = heat_low * 1000
     heater_power = heat_hi
     energy = 0
     direct_heat = 0
     time = 0
     rad_in = air_in
     av_count = 0
     report = interval
     sample = sample_time
```

Fill the arrays with the starting values **DO 12 J=1,slabs DO 1 I=1,slices(J)**

```
temperature(I,J)=temperature(1,J)       temp(I,J)=temperature(1,J)     U(I,J)=U(1,J)
capacity(I,J)=capacity(1,J)1   CONTINUE
```

Calculate minimum time step for stability

```
          dtt = (ro(J)*cp(J)*((thick(J)/slices(J))**2))/(2*k(J))
          IF(dtt.LT.dt) THEN
            dt = dtt
          ENDIF
12    CONTINUE
```

```
      CALL HEATER(control,heater_power,heater_set,heat_low,
     *  heat_hi,heat_dif,air_in)

      XL = average_surface
      XR = heater_set

      DO WHILE (IFIX(time).LT.end)
         DO WHILE (IFIX(time).LT.report)
```

Converge heat sink capacity and heat input by varyingair_in temperature using ZEROIN

```
         surface = .TRUE.
         CALL ZEROIN(air_in,AIRTMP,XL,XR)
         XR = air_in * 1.8
```

Calculate the layer temperatures using AIRTMP with the current value of air_in

```
         surface = .FALSE.
         error = AIRTMP(air_in)
```

Time step complete so copy new temp() to temperature()

```
         DO 5 J=1,slabs
           DO 3 I=1,slices(J)
             temperature(I,J) = temp(I,J)
3          CONTINUE
           IF(internal(J)) THEN
             air_out(J) = air_in
             rad_out(J) = air_in
           ENDIF
5        CONTINUE
```

Update averages of slab temperatures
Surface temperatures

```
         average_surface = 0
         DO 18 slab=1,slabs
           average1(slab) = average1(slab) + temperature(1,slab)
           average_surface = average_surface + temperature(1,slab)
     *              * area(slab)
18       CONTINUE
         av_count = av_count + 1
```

Radiant room temperature should track weighted slab surface temperature

```
         average_surface = average_surface / total_area
         rad_in = average_surface
         XL = average_surface * 0.5
```

The air temperature in the room is air_in after convergence

Switch off the heater after a set heating time by changing control to 0 Set to end of run if not needed.

```
         IF(time.GE.off_time) THEN
           control = 0
         ENDIF
```

Switch off air leaks when the leak_time is exceeded Set to 0 for no leaks at all.

```
      IF(time.GE.leak_time) THEN
        leak = .FALSE.
        leak_time = end
      ENDIF
```

Heater control

```
      CALL HEATER(control,heater_power,heater_set,heat_low,
     *     heat_hi,heat_dif,air_in)
```

Calculate energy input to the process kw

```
      energy = energy + (heater_power * dt / 1000)
```

Calculate the direct heat input from mats

```
      DO 23 slab = 1,slabs
        direct_heat = direct_heat +
     *           (contact(slab) * area(slab) * dt / 1000)
23    CONTINUE
```

Next time step

```
      time = time + dt
```

---Heat-trace output---

```
      IF(heat_trace.AND.(time.GE.sample)) THEN
        sample = sample + sample_time
```

Calculate the average surface temperature for each slab

```
        DO 19 slab=1,slabs
          average1(slab) = average1(slab)/av_count
19      CONTINUE
        WRITE(6,17) time/60,air_in,sink_flux/1000,
   *            (average1(J),J=1,slabs)
17      FORMAT( F10.1,F10.2,F10.2,10F8.1)
```

Reset the average1 array and average counter

```
        av_count = 0
        DO 20 slab=1,slabs
          average1(slab) = 0
20      CONTINUE
      ENDIF
   END DO
```

---Detail output----

Report temperature profile and time at reporting intervals

```
   IF(detail) THEN
      WRITE(6,4)time/60,air_in,(in_flux(J),J=1,slabs),
   *   (temperature(1,I),I=1,slabs)
4     FORMAT( F5.0,F9.1,(20F8.1))
      IF(point.GT.0) THEN
        DO 22 slab=1,slabs
          CALL MONITOR(temperature,dl,thick,point,slab,temp_log)
          temp_monitor(slab) = temp_log
22      CONTINUE
        WRITE(6,21)(temp_monitor(J),J=1,slabs)
21      FORMAT(10F8.1)
      ENDIF
   ENDIF

   report = report + interval
```

---End of test run---

```
   END DO
```

Report total heat used MJ

```
   WRITE(6,6)energy/1000,direct_heat/1000
6   FORMAT( /'Energy used....   ',F10.2,' MJ'/
   *    'Heat mat energy   ',F10.2,' MJ')

   CLOSE (5)
   CLOSE (6)
   STOP
   END
```

Subroutine to interpolate temperature at specified depth within a slab

```
      SUBROUTINE MONITOR(temperature,dl,thick,point,slab,temp_log)
      REAL temperature(30,10),dl(10),point,temp_log,thick(10),mp,
     *  fraction
      INTEGER slab,slice

      IF(point.GE.thick(slab)) THEN
          temp_log = 0
          RETURN
      ENDIF
```

Offset the monitoring point by half the slab thickness. If detailed temperatures are needed at the surface of the slab the number of slices should be increased. This routine will not monitor temperatures closer than slice/2 to the surface.

```
      slice = 0      mp = point + dl(slab)/2      DO WHILE (mp.GE.0.0)
          mp = mp - dl(slab)
          slice = slice + 1
      END DO
      IF(mp.EQ.0) THEN
          temp_log = temperature(slice,slab)
          RETURN
      ENDIF
      IF(slice.EQ.1) THEN
          temp_log = temperature(1,slab)
          RETURN
      ENDIF
      fraction = (mp+dl(slab))/dl(slab)
      temp_log = temperature((slice-1),slab) +
     *    ((temperature(slice,slab)
     *              - temperature((slice-1),slab)) * fraction)
      RETURN
      END
```

Convervence routine for finding air temperature

```
      FUNCTION AIRTMP(air_in)
```

Calculate the heat flux for each slab in one time step with given air temp and sum them. Subtract heater flux to find the error.

```
      COMMON slices,hi,temperature,e_in,rad_in,
     *    U,in_flux,temp,dt,capacity,ho,air_out,e_out,rad_out,out_flux,
     *      sink_flux,heater_power,slab,slabs,surface,area,
     *      leak,air_heat,air_ambient,contact

      DIMENSION temperature(30,10),temp(30,10),U(30,10),capacity(30,10)
      REAL Q,Qs,Qr,Qc,sink_flux,heater_power,area(10),
     *    dt,ho(10),hi(10),air_in,air_out(10),rad_in,
     *    rad_out(10),e_in(10),e_out(10),in_flux(10),out_flux(10),
```

```
     *     air_heat,air_ambient,contact(10),Qd

      INTEGER I,J,slices(10),slabs,slab
      LOGICAL surface,leak


      DO 14 slab=1,slabs
C If converging air temperature only compute inside surface.
      IF(surface) THEN
         J = 1
      ELSE
         J = slices(slab) - 1
      ENDIF
C Calculate the temperatures in the slab after dt
         DO 2 I=1,(slices(slab) - 1)
          IF(I.EQ.1) THEN
           Qs = hi(slab) * (air_in - temperature(1,slab))
           Qr = e_in(slab) * 5.67E-8 * ((rad_in + 273)**4 -
     *               (temperature(1,slab) + 273)**4)
           Qc = U(1,slab) * (temperature(2,slab) - temperature(1,slab))
C Direct heat input from conduction heating Qd w/m2
           Qd = contact(slab)
           Q = Qs + Qr + Qc + Qd
           in_flux(slab) = Qs + Qr
C Surface slice temperature
           temp(1,slab) = temperature(1,slab)
     *             + ((Q * dt)/(capacity(1,slab)))
          ENDIF
C Calculate the heat flux between internal slices
           IF(I.GT.1) THEN
            Q = U((I-1),slab) * (temperature((I-1),slab)
     *            - temperature(I,slab))
     *            + U(I,slab) * (temperature((I+1),slab)
     *            - temperature(I,slab))
           temp(I,slab) = temperature(I,slab)
     *            + ((Q * dt)/capacity(I,slab))
           ENDIF
2        CONTINUE
```

```
      IF(.NOT.surface) THEN
```
Calculate the heat escape from the outside surface
```
        Qs = ho(slab) * (air_out(slab)
 *        - temperature(slices(slab),slab))
        Qr = e_out(slab) * 5.67E-8 * ((rad_out(slab) + 273)**4
 *        - (temperature(slices(slab),slab) + 273)**4)
        Qc = U((slices(slab)-1),slab)
 *        * (temperature((slices(slab)-1),slab)
 *        - temperature(slices(slab),slab))
        Q = Qs + Qr + Qc
        out_flux(slab) = Qs + Qr
```
Outside surface temperature
```
        temp(slices(slab),slab) = temperature(slices(slab),slab)
 *        + ((Q*dt)/capacity((slices(slab)-1),slab))
   ENDIF
```

Next slab

14 CONTINUE

Calculate the total sink flux at this time step
```
   sink_flux = 0
   DO 6 I=1,slabs
      sink_flux = sink_flux + in_flux(I) * area(I)
```
6 CONTINUE

Calculate the heater power lost through air leakage
```
   IF(leak) THEN
      sink_flux = sink_flux+(air_heat*(air_in - air_ambient))
   ENDIF
```
Calculate the value of the convergance function and return
```
   AIRTMP = sink_flux - heater_power
   RETURN
   END
```

End of convergance routines----------------------------

SUBROUTINE ZEROIN (X, FUNCT, XL, XR)

```
   INTEGER   I, END
   REAL      X, XL, XR, F, FL, FR, EPS
        EPS = 1.0E-5
     FL = FUNCT (XL)
        FR = FUNCT (XR)

     IF (FL .EQ. 0)
 +     THEN
        F = FL
        X = XL
        RETURN
     END IF
```

```
      IF (FR .EQ. 0)
    +    THEN
          F = FR
          X = XR
          RETURN
      END IF

      IF (FL*FR .GT. 0)
    +    THEN
              WRITE (6,50) XL,XR
          RETURN
      END IF

      IF (FL .GT. FR)
    +    THEN
          X  = XL
          XL = XR
          XR = X
          F  = FL
          FL = FR
          FR = F
      END IF

      X   = (XL+XR) / 2.0
      F   = FUNCT (X)
      END = 1 + INT (ALOG(ABS(XR-XL)/EPS) / ALOG(2.0))

      DO 40 I = 1, END
        IF (F .EQ. 0) RETURN

        IF (F .GT. 0)
    +       THEN
             XR = X
             FR = F
           ELSE
             XL = X
             FL = F
        END IF

        X = (XL+XR) / 2.0
        F = FUNCT (X)
40     CONTINUE

     RETURN
50   FORMAT(' W A R N I N G  EVEN NO OF ROOTS BETWEEN ESTIMATES'
    +        /' XL ',F10.2,'     XR ',F10.2)
     END
```

```
      SUBROUTINE HEATER(control,heater_power,heater_set,heat_low,
     *     heat_hi,heat_dif,air_in)
```

Control the heater on a timed or thermostat or high low power.This routine resets heater_power according to the selected control strategy.

control = 0 No heat on
1 Thermostatic control on/off using heat_dif differential and heater_set as high limit
2 Switching between heat_hi and heat_low.
heat_dif is the switching differential3Heat on at heat_hi all the time4 Heat modulated by heat_low steps between heat_hi and 0Use heat_hi as max, heat_low as step, heater_set and heater_dif are controls

```
      REAL air_in,heater_power,heater_set,heat_low,heat_hi,heat_dif
      INTEGER control

      SELECT CASE (control)
        CASE (0)
          heater_power = 0
          RETURN

        CASE (1)
          IF(air_in.GE.heater_set.AND.heater_power.GT.0) THEN
              heater_power = 0
              RETURN
            ELSE IF(air_in.LT.(heater_set - heat_dif)
     *               .AND.heater_power.LT.heat_hi) THEN
              heater_power = heat_hi
          ENDIF
        RETURN

        CASE (2)
            IF(air_in.GE.heater_set
     *               .AND.heater_power.GT.heat_low) THEN
              heater_power = heat_low
              RETURN
            ELSE IF(air_in.LT.(heater_set - heat_dif)
     *               .AND.heater_power.LT.heat_hi)THEN
              heater_power = heat_hi
          ENDIF
          RETURN

        CASE (3)
          heater_power = heat_hi
            RETURN

          CASE (4)
```

```
        IF(air_in.GE.heater_set.AND.heater_power.GT.0) THEN
          heater_power = heater_power - heat_low
          RETURN
        ELSE IF(air_in.LT.(heater_set - heat_dif)
*                .AND.heater_power.LT.heat_hi) THEN
          heater_power = heater_power + heat_low
        ENDIF
        RETURN

    END SELECT
    RETURN
    END
```

Program Input File Format

Global parameters

6 30 72 36 60 8 2 3600 172800 172800 T 3600 F 0.01 0 10 0
Slab Specific parameters
14 0.13 2300 600 0.1 1.3 4.0 18 18 0.95 0.95 8 182.5 0 T
14 0.84 830 1700 0.35 3.3 8.3 18 18 0.95 0.95 10 72 0 T
14 0.84 830 1700 0.27 3.3 8.3 18 18 0.95 0.95 10 331.6 0 F
14 45 480 7900 0.02 4.3 8.3 18 18 0.95 0.95 2 22.4 0 F
14 0.026 1000 30 0.04 3.3 8.3 18 18 0.95 0.95 3 109.1 0 F
14 0.13 2300 600 0.035 4.3 8.3 18 18 0.95 0.95 3 200 0 F

A description of input parameters can be appended to the end of the data as an aide memoir.

Mill Top floor Heated with 2 Thermonox heaters at 18 kw each control algorithm 2

wooden floor heated from both sides, energy from one side.
brick walls internal heated from both sides 350mm thick
brick wall outside wall 270mm thick
Steel structure bin tops internal
Insulated cladding
Roof structure

Description of input parameters

Global Parameters

Variable Name	**Description**	**Units**
slabs	Number of slabs in model (max 10)	-
dt	Basic initial time step (eg 60 but recalculated by program)	s
Heat_hi	Maximum heater power	kw
Heat_low	Low rate heater power	Kw
Heater_set	Heater set point	C
Heat_dif	Switching differential to switch back to high power	C
Control	Heater control algorithm 0 = heater always off	

	1 = heater switches between high power and off 2 = heater switches between high and low power 3 = heater on maximum full time 4 = Heat modulated by heat_low steps between heat_hi and 0. Use heat_hi as max, heat_low as step, heater_set and heater_dif are controls	
interval	Reporting interval	s
end	Length of simulation	s
off_time	Elapsed time after which heaters are to be set to off (control = 0)	s
heat_trace	Report surface temperatures and air temperatures	L
sample_time	Time interval between heat trace reports	s
detail	Report surface temperatures and heat flux for each slab at sample time	L
point	Distance from surface to monitoring point (0 if not to be used)	m
air_heat	Air exchange rate between inside and outside the structure expressed as a volume flow rate	m^3/s
ambient_air	Outside air temperature to be used for air exchange	C
leak_time	Air exchange starts at time=0 and continues until leak_time when it stops.	s

Slab Parameters One set for each slab type

Variable Name	Description	Units
Temperature	Starting temperature of all slices in slab	C
k	Thermal conductivity	w/mC
cp	Specific heat of slab	J/kgC
ro	Density of slab	kg/m^3
thick	Thickness of the slab	m
ho	External surface heat transfer coefficient (convection)	w/m^{2}C
hi	Internal surface heat transfer coefficient (convection)	w/m^{2}C
air_out	Air temperature at the external surface	C
rad_out	Radiant sink temperature at the external surface	C
e_in	Emissivity of the internal surface	-
e_out	Emissivity of the external surface	-
slices	Number of slices in the slab model (max 30)	-
area	Total area of this type of slab exposed inside the room Where the structure is heated from both sides inside the room the total area exposed is used. Where both sides are heated but only one is inside the room only the internal exposed area is used	m^2
contact()	Rate of direct heat input to a surface from a heating mat	w/m^2
internal()	Internal element heats from both sides. True when structure is heated from both sides False when structure is only heated from one side	L

Result File layout

The result layout depends on the settings of heat_trace and detail. The example below shows the format that results from heat_trace TRUE and detail FALSE. Slab surface temperatures and total heat input are reported at the set interval.

time m	air	kw	slab1	slab2	slab3	slab4	slab5	slab6
60.0	40.42	75.00	28.2	25.9	25.5	30.0	33.1	31.5
120.0	43.11	75.00	33.3	29.6	29.4	33.1	36.4	33.4
180.0	45.26	75.00	36.2	32.1	31.9	35.2	38.7	35.2
240.0	47.10	75.00	38.6	34.2	33.9	36.9	40.5	36.8
.								
2820.0	59.62	57.00	56.3	56.2	50.2	49.3	54.0	49.1
2880.0	59.66	57.00	56.3	56.2	50.3	49.3	54.0	49.2

Energy used.... 11038.41 MJ
Heat mat energy .00 MJ

Material properties

Table 1 Thermal properties of materials found in mills

Material	Thermal conductivity w/m°C	Specific heat J/kg °C	Density kg/m^3
Brick	0.65	830	1700
Concrete	2.4	920	2300
Timber	0.13	2300	600
Steel	45.0	480	7900
Glass (window)	1.05	750	2600
Slate	1.9	920	2700
Polyurethane panel	0.026	1000	30

APPENDIX 2. A SKELETON PROTOCOL FOR MILL HEAT TREATMENT

This protocol is presented in the form of a check-list which can form the basis of a site specific detailed work plan and resource budget.

1. Site Survey

- Building dimensions
- Structure
- Access
- Monitoring sites
- DE dust sites
- Power supply location
- Insect evidence – problem areas

2. Calculation of heating requirement

- Numbers of heaters
- Locations for heaters
- Numbers of mats
- Locations for floor fans and poly-ducts
- Cable lengths

3. Pre shutdown

- Clear all loose materials and product
- Clean thoroughly – particularly infestation sites
- Position heaters and distribution equipment
- Position heating mats and insulation Switch on 24 hrs before shut down
- Mark monitoring locations

4. Post shutdown

- Remove fire extinguishers and pressurised spray cans
- Vent pneumatics
- Close all windows, doors and vents
- Connect heater power supplies
- Position and connect heaters
- Position and connect floor fans and poly-ducts
- Spray floors with approved insecticide

5. Heating

- Turn on all heaters
- Check all monitoring point temperatures at 2 – 3 hour intervals
- Remove heat mat insulation when air temperature reaches 50^{o}C
- Adjust heater positions as required

6. Cooling

- Stop heating when the prescribed exposure has been achieved
- Monitor temperature decline

7. Plant re-start

- Restore power to the mill machinery
- Remove heaters, cables, fans and ducts
- Replace fire extinguishers
- Restart milling process

8. Quality report.

- Report thermal dose given at each monitoring point
- Report any signs of insect activity