NUMERICAL MODEL FOR ANALYSIS AND CONTROL OF THE QUALITY OF BULK-STORED GRAIN USING COLD AIR

BY

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VOLUME 1

ABSTRACT

Food grains that have been cooled can be stored for prolonged periods. This is because the rate of population increase of insect pests can be slowed, seed viability is maintained, dry matter loss is reduced and the persistence of chemical pesticides can be improved.

This thesis reports the development of a mathematical model of ventilated grain stores that enables optimal cooling strategies to be identified and developed. The model describes heat and mass transfer in two dimensions and it enables heat and mass transfer phenomena that occur in the boundary layers of grain stores to be examined in detail. This is achieved by first establishing the air flow distribution in the grain, and then solving the equations that govern heat and moisture transfer. It is believed that this represents an advance on models previously available. In addition to the physical phenomena, the model accounts for biological and chemical phenomena that occur in grain stores.

The thesis also describes the development and operation of commercial mobile refrigerated grain cooling units that have been developed by the candidate. The mathematical model is used to determine the optimum strategy for moving the commercial grain cooler from one aeration duct to the other. The objective function is the number of insects in the grain bulk, although other measures such as seed viability and pesticide residue are also examined. Experiments were conducted on a commercially operated shed type store to validate the model using a commercial instrumentation system also developed by the candidate. The research shows that the optimum strategy is different from that of the grain cooling contractor and grain trader based principally on intuition.

ACKNOWLEDGMENTS

I am grateful to Victoria University of Technology, Melbourne for a Postgraduate Scholarship which enabled me to undertake this research, and to Associate Professor Graham Thorpe for his encouragement, guidance and support throughout the tenure. Various members of the staff of the University and fellow students have assisted with their advice and opinions, particularly when converting programs from BASIC to FORTRAN. The investment made by McBea Grain Protection Services, Melbourne in providing facilities and releasing me for two years to concentrate on the development of this control system research is appreciated, as is the support and encouragement of my wife Jean, and her tolerance in shouldering additional business responsibilities on behalf of McBea. Thanks are due to my younger son Murray for assistance in sourcing references on continued fractions and outlining the number theory involved. Permission to make measurements in the 1500 tonne bulk of barley owned by G & C Cornell, Lockhart, NSW during the progress of a grain cooling contract is gratefully acknowledged. Overseas manufacturers of grain silo cooling equipment have granted permission to copy their commercial literature and relevant exerpts are included in Appendix 5.

W B Elder
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NOMENCLATURE

For list of variables' names used in Fortran program see Appendix 5

Upper case

A_n	numerator of continued fraction
B	coefficient for rate of increase in insect population
B_n	denominator of continued fraction
C	concentration of pesticide, kg/kg of grain
C_0	initial concentration of pesticide, kg/kg of grain
C_1	a coefficient for determining loss of viability
C_2	a coefficient for determining loss of viability
H_W	heat of sorption of water into seed, J/kg
K_{eff}	effective thermal conductivity of bulk, W $m^{-1}K^{-1}$
K_σ	coefficient for standard deviation of seed viability
K_v	seed specific constant for determining loss of viability
M_M	moisture modifier for calculating dry matter loss
M_T	temperature modifier for calculating dry matter loss
N	number of insects
N_O	initial number of insects in the grain bulk
P	static pressure at outlet of McBea Mobile Grain Cooler, Pa
Q	air flow through McBea Mobile Grain Cooler, m^3/s
Q_r	calorific value of seed oxidised, J/kg
R	coefficient of resistance to air flow, Pa s m^{-2}
T	grain temperature, °C
T_{amb}	instantaneous ambient temperature, °C
T_{amp}	amplitude of diurnal swing in ambient temperature, K
T_{MAX}	wet-bulb temperature corresponding to maximum rate of insect population growth, °C
T_{mean}	mean atmospheric air temperature, °C
T_w	wet-bulb temperature of intergranular air, °C

$T_{w_{amb}}$ ambient wet-bulb temperature, °C

$T_{w_{out}}$ wet-bulb temperature of air leaving McBea Mobile Grain Cooler, °C

V germination of seed bulk (living seeds : total)

V_0 initial germination (viability) of seed bulk

W moisture content of seed (dry basis), kg/kg

Lower case

b rate coefficient for increase in insect population

c threshold wet-bulb temperature of increase in insect population, °C

c_1 specific heat of water bound in seed, J kg^{-1}K^{-1}

c_2 specific heat of seed, J kg^{-1}K^{-1}

c_a specific heat of air, J kg^{-1}K^{-1}

c_{i1} a seed specific coefficient in the equation for integral heat of wetting

c_{i2} a seed specific coefficient in the equation for integral heat of wetting

c_{i3} a seed specific coefficient in the equation for integral heat of wetting

c_{i4} a seed specific coefficient in the equation for integral heat of wetting

c_{i5} a seed specific coefficient in the equation for integral heat of wetting

$cx1$ coefficient in expression for temperature gradient at a node

$cx2$ coefficient in expression for temperature gradient at a node

$cx3$ coefficient in expression for temperature gradient at a node

$cx4$ coefficient in expression for rate of change of temperature gradient at a node

$cx5$ coefficient in expression for rate of change of temperature gradient at a node

$cx6$ coefficient in expression for rate of change of temperature gradient at a node

$cy1$ coefficient associated with convection vertically

$cy2$ coefficient associated with convection vertically

$cy3$ coefficient associated with convection vertically

$cy4$ coefficient associated with thermal conductivity vertically

$cy5$ coefficient associated with thermal conductivity vertically

$cy6$ coefficient associated with thermal conductivity vertically

h_s	latent heat of vaporisation of water bound in seed, J/kg
h_v	latent heat of vaporisation of free water, J/kg
hx	distance between nodes in the x direction, m
k	time constant for germination loss
k_0	known value of k at a given temperature or moisture content
m	mass of bulk oxidised, kg
m	moisture content of seed (% wet basis) - equation **2.9**
p	air pressure, Pa
p	half-life of seed - equations **2.9** and **2.10**
q_n	largest integer less than α_n
r	relative humidity of intergranular air
r_n	remainder (α_n-q_n)
r_m	intrinsic rate of increase in insect population
t	time, s
$t_{\frac{1}{2}}$	half-life of pesticide, weeks
t_{eq}	equivalent temperature for calculating dry matter loss, °C
u	face air velocity in the horizontal direction, m/s
v	face air velocity in the vertical direction, m/s
$\mathbf{v}$	face air velocity vector, m/s
w	moisture content of intergranular air, kg/kg of dry air
x	x co-ordinate

Greek

α_0	ratio of duct offset from centre to width of bulk less boundary layers and duct widths
ε_σ	void fraction of bulk material
ϕ_1	volume specific enthalpy of seed, J $m^{-3}K^{-1}$
ϕ_2	volume specific enthalpy associated with bound water in seed and convection, J $m^{-3}K^{-1}$

ϕ_3 change in enthalpy resulting from conduction, combustion and evaporation of water, J $m^{-3}K^{-1}$

ϕ_4 a coefficient in moisture conservation equation

ϕ_5 a coefficient associated with convection

ϕ_6 a coefficient associated with dry matter loss

ρ_a density of air, kg/m^3

ρ_σ density of seed material, kg/m^3

σ standard deviation

Subscripts

$_a$ air

$_i$ node number in x direction

$_j$ node number in y direction

$_v$ vapour

$_\gamma$ gas

Superscripts

^{p} time step counter

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CHAPTER 1

1. INTRODUCTION

1.1. BACKGROUND

When bulk grains are cooled their quality is maintained and damage by insects and other agents of loss is suppressed. Controllers for systems which pass naturally occurring atmospheric air through the bulk take various forms from time-switches to sophisticated feed-back devices. Mobile refrigeration plant is becoming more popular for decreasing the grain temperature more quickly than can be achieved with atmospheric air. The installation of a feed-back loop from a silo to mobile plant presents many practical problems especially when the plant is hired and the various silos in which the sensing equipment is fitted and the mobile plant are owned by different parties. Sufficient is now known about heat and moisture transfer processes in bulk grain for a realistic mathematical model of two-dimensional bulks to be formulated, thus there is an opportunity to eliminate the need for feed-back connections The initial condition of the grain can be input from measurements of temperature and moisture content taken on delivery or once in storage. The subsequent changes in bulk temperature and moisture content can be determined from the known performance characteristics of the cooling plant, biological activity models and measured ambient conditions.

1.2 LITERATURE REVIEW

Grain cooling systems are used in many countries where grain is stored in bulk. Evidence of ventilation systems for grain stores exists in archaeological diggings in Egypt. Early work in the United States of America on grain cooling using naturally occurring atmospheric air (aeration) was outlined by Holman (1966) and various aspects of the process have been studied since by such workers as Burgess and Burrell (1964), Griffiths (1967), Brooker (1969), Elder (1972, 1990 and 1992), Ingram (1979), Sutherland *et al* (1971 and 1983), Williams and Elder (1979), Thorpe *et al* (1982a and b), Hunter(1986a, b, c and 1988), Wilson (1988), Desmarchelier and Wilson (1993) and

Noyes *et al* (1994). Developments in aeration using chilled or refrigerated air have been reported by Sutherland *et al* (1970), Navarro *et al* (1973a and b), Donahaye *et al* (1974), Brunner (1980), Baldo and Brunner (1983), Elder and Ghaly (1983), Hellemar (1993) and Maier (1994).

Control of grain cooling systems using naturally occurring atmospheric air is traditionally by means of a high and low limit thermostat and a high limit humidistat switching the aeration fans. Such systems have been available from the George A Rolfes Company, Boone, Iowa, USA and Foss (AN) of Denmark. Operators measure the progress of cooling by means of either permanently installed thermocouple cables or portable probes with a read-out instrument and adjust the high limit thermostat accordingly. A method of charting to assist operators interpret the large number of temperature readings taken and to identify and respond correctly to the progress of cooling fronts was presented by Elder (1971). Charts of the temperature profile are used by Cargill Australia Ltd, particularly for checking the cooling of oilseeds. Some controllers act on the temperature feed-back signal and such systems have been available from James Watt Electrical in Australia, Eldar in Israel and Foss. The performance of different control methods has been simulated by J W Sutherland (unpublished) and reported by Elder (1984). The time-proportioning control method (Elder, 1972) was shown to have the best performance. A programmable aeration controller involving remote monitoring is under development by Gibbs (1994) and computer control of aeration based on climatic data and feed-back signals is described by Wu and Li (1994). There do not appear to be any grain cooling controllers which depend on predictions of changing conditions in the bulk for feed-back.

1.3 SUPPORTING PAPERS

Recent papers by the candidate which highlight the potential for optimising grain quality parameters when bulk grain is cooled by through flow of air are reproduced with permission in Appendix 1. The first (Elder, 1992) derives an analytical solution for the minimisation of the loss of pesticide applied to the stored grain at intake when aerated using time-proportioning control (Elder, 1972) to select the coldest atmospheric conditions for cooling the bulk. It is shown that the running time for the cooling fan which yields the minimum breakdown of the insecticide can be calculated for each month of operation in a specified climate. The second paper (Elder and Thorpe, 1994) illustrates the use of a numerical model for predicting the cooling patterns generated by through flow of refrigerated air in a shed type grain store in south-eastern Australia and a tall cylindrical silo in southern China, and the resultant potential for grain infesting insect population growth throughout the bulk. The numerical analysis treatment takes into account heat transfer by conduction from outside through the silo walls which was not considered in the former analytical solution for minimising the loss of pesticide.

1.4 OBJECTIVES

The general objective of this research is the development and validation of a numerical model of the cooling of bulk grain and associated processes, and to demonstrate its application to:
(i) devising cooling plant operational strategies which minimise effects of agents of quality loss; and
(ii) optimising air distribution duct layout design and the control of the cooling air flow to minimise the cost of protecting the food from deterioration and loss in value.

The research is to target specific objectives in an ordered sequence as follows:-

- Develop a two-dimensional numerical mathematical model of a bulk of respiring grain involving heat, moisture and momentum transfer. The bulk is subject to an air pressure gradient from air distribution ducting on the floor of the grain store to the grain surface, a cyclical ambient temperature, biological deterioration of the seeds and associated heating, grain infesting insect population growth and chemical breakdown of pesticides that may be applied to the grain. The model is to be capable of determining in detail the temperature and moisture gradients close to the surfaces of the grain bulk which is exposed to the cyclical ambient conditions, and around the air distribution ducting. A non-uniform grid pattern of nodes is to be used to facilitate such detail without invoking an unnecessarily large number of calculations where detail is not required deep in the bulk. A novel feature of the research is the use of continued fractions (Davenport, 1968) to determine automatically the appropriate finite difference grid from the dimensions of any commercial grain store and its air distribution ducting so as to free operators of the model, or of an industrial controller based on the model, from the need to understand the setting up of an appropriate node grid pattern.

- Describe a commercially available mobile air chilling unit developed by the candidate for cooling bulk-stored grain, and determine mathematical models of its performance for interaction with the heat, mass and momentum transfer characteristics of the numerical model of ventilated bulk grain to be developed.
- Carry out experiments in a rural grain store using a commercially available grain temperature and humidity probe system developed by the candidate to validate the model.
- Conduct numerical experiments involving the interaction between the commercial grain cooler and grain store to identify optimum cooling strategies to minimise the potential for insect infestation.
- Examine the potential for novel treatment of duct layout designs facilitated by the model.
- Foreshadow the use of the model in a microprocessor-based controller which automatically varies the air flow through a commercial grain cooling system to minimise the loss of grain quality or other index of commercial loss.
- Signal the opportunities afforded by the model to minimise the over all cost of protecting bulk-stored grain.

The model applies to two dimensional systems that are characteristic of shed type grain stores which represent approximately 60% of Australia's grain storage capacity.

The ultimate goal is to design and build a controller for optimising the operation of any grain cooling system. The present work has in mind grain aeration systems using naturally occurring atmospheric air and mobile grain refrigeration plant; however, the mathematical model will not necessarily be limited to these two types. For example, the operation of a system in which the atmospheric air, before entering the grain bulk, is dried using a desiccant as described by Ismail (1987) could be optimised by the model given the properties of the moisture absorbing material and other system parameters. An objective of the design of the controller should be to make use of the ever increasing speed and capacity of personal computers (PCs) combined with their decreasing cost and physical size, rather than adopt the more sophisticated industrial programmable logic controllers (PLCs) which are now commercially available. The almost universal adoption of PCs by the general community, even in remote areas where grain cooling systems may be installed, represents a good reason for developing a controller based on this technology rather than the traditional PLCs used generally in process industries in major centres. It seems probable that the new generation of plant service technicians is more likely to be competent in the operation of PCs than in the diverse range of PLC systems that are vying for supremacy.

CHAPTER 2

2. MATHEMATICAL MODEL

2.1 RESISTANCE TO AIR FLOW

The present model assumes that the resistance to air flow is proportional to the local velocity of the air, and that the resistance coefficient is isotropic. This may be expressed as

$$\nabla p = - R \, \boldsymbol{v} \qquad \mathbf{2.1}$$

in which $\boldsymbol{v}$ is the face velocity of the air or the air volume flux ($m^3 \, s^{-1} \, m^{-2}$), and R is a resistance coefficient. Hunter (1983) presents values of R for 28 different grains and seeds. Hunter also gives coefficients for an additional term $S|\boldsymbol{v}|\,\boldsymbol{v}$ as in the work of Ergun (1952) which accounts for the departure from a linear pressure-flow relationship. This second term becomes significant at higher intergranular air velocities than would normally be encountered in grain aeration systems. Any refinement of the model may include this effect so that it can deal more accurately with extraordinary circumstances encountered in industry such as the recent refrigeration of a 700 tonne silo of wheat via the emptying auger tube (Fig. 2.1) where the air velocities in the region of the air entry will be sufficiently high to affect the calculation of the pressure drop across the grain bulk. In this study we are concerned with the effect of the velocity distribution on the stored grain ecosystem, and Hunter (1983) reports that omitting the additional term $S|\boldsymbol{v}|\,\boldsymbol{v}$ has little effect on the velocity field.

2.2 HEAT AND MOISTURE EXCHANGE

Much of the past work on heat and mass transfer during ventilation of bulk grain assumes that the seeds are inert hygroscopic particles. This model however includes the effect of respiration of the seeds involving the liberation of heat and additional gases (carbon dioxide and water vapour) that mix with the ventilating air altering its speed, and the removal of oxygen from the ventilating air. To simplify the equations governing this reactive process, Thorpe (1995) has made order of magnitude assumptions to derive the thermal energy equation which follows. The derivation is detailed in Appendix 2 in which the symbols are defined.

$$\varepsilon_\sigma \rho_\sigma \left\{ (c_2)_\sigma + (c_1)_\sigma W + \frac{\partial H_W}{\partial T} \right\} \frac{\partial T}{\partial t} - h_s \varepsilon_\sigma \rho_\sigma \frac{\partial W}{\partial t} - \rho_a \frac{\partial \varepsilon_\sigma}{\partial t} \int_0^W h_s dW$$
$$+ \rho_a \Big(c_a + w \big((c_1)_\gamma + c_{2v} \big) \Big) \ v. \nabla T$$
$$= K_{eff} \nabla^2 T + \varepsilon_\sigma \rho_\sigma Q_r \frac{dm}{dt} - 0.6 \varepsilon_\sigma \rho_\sigma h_v \frac{dm}{dt} \qquad 2.2$$

The first term represents the net rate of increase in enthalpy per unit volume, the second the heat associated with the change in state of bound water to vapour. The third term accounts for the binding energy of the water in the grain which is oxidised into non solids as a consequence of respiration processes. The final term on the left hand side of the above equation represents the difference between the flow of heat in and out of a specific volume of the bulk resulting from convection of all the gasses including those generated by respiration. The terms on the right hand side represent respectively heat conduction, the heat of combustion of dry matter and the associated heat of vaporisation of the water produced. The calorific value of substrate material Q_r used is 15 778kJ/kg.

The moisture balance on an elementary region of the grain bulk is expressed as

$$\varepsilon_\sigma \rho_\sigma \frac{\partial W}{\partial t} + \rho_a v. \nabla w = \varepsilon_\sigma \rho_\sigma \frac{dm}{dt} (1 + 1.66W) \qquad 2.3$$

The terms denote the rate of accumulation of water, the effect of convection of moisture in and out, and the water produced as a result of respiration.

The integral heat of wetting for a given moisture content is given by Thorpe *et al* (1990) as follows:-

$$\int_0^W (h_v - h_s) \, dW = \left(c_{i1} + c_{i2} W + c_{i3} W^2 + c_{i4} W^3 + c_{i5} W^4 \right) h_v \qquad 2.4$$

where the coefficients for a number of grains are shown in Table 2.1, and h_s is the heat of sorption and h_v is latent heat of vaporisation of free water.

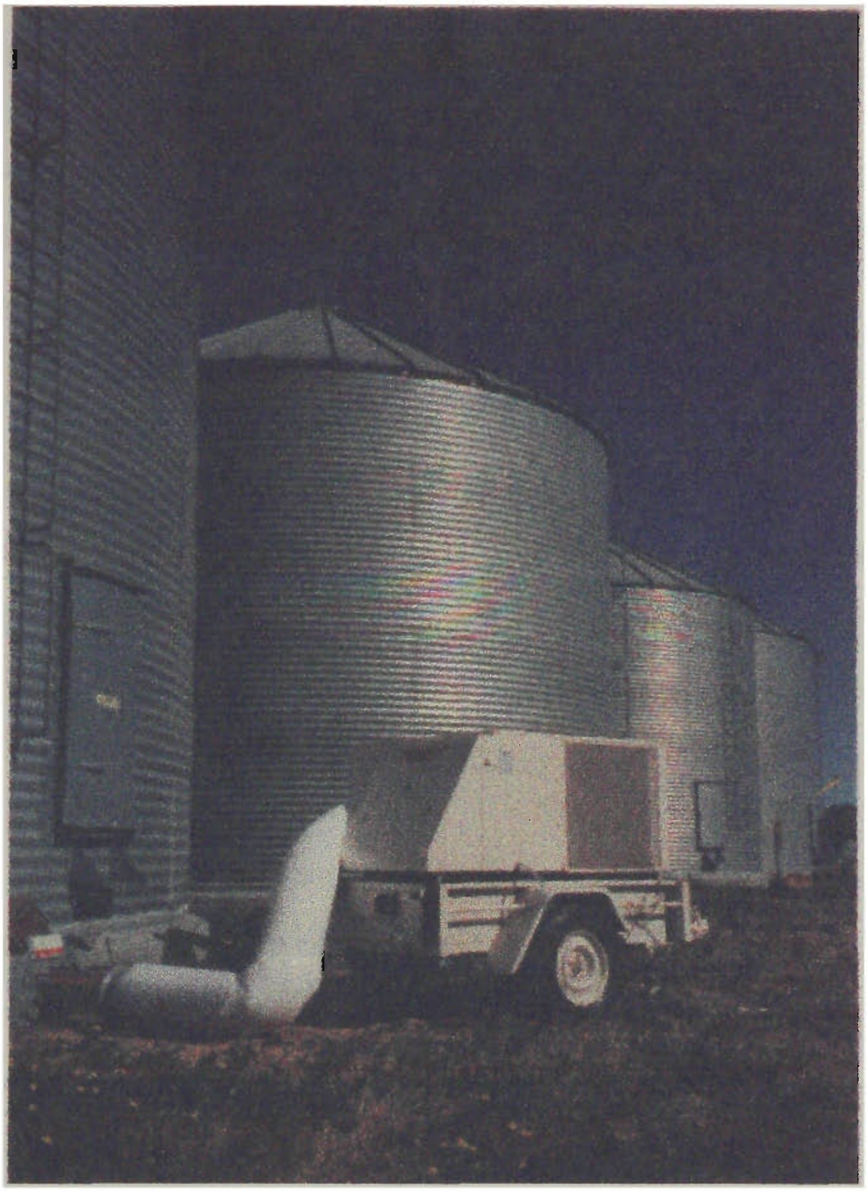


Fig. 2.1 - Cooling wheat in a 700 tonne capacity steel silo via the emptying auger tube using the high air pressure, low air temperature characteristic of a M[c]Bea Mobile Grain Cooler
Courtesy L G Moore Holdings, Horsham, Victoria

TABLE 2.1

Coefficients for calculating the integral heat of wetting for a number of grains

Grain	c_{i1}	c_{i2}	c_{i3}	c_{i4}	c_{i5}
Barley	-0.26249	4.6097	-0.00910	1.2485	8.4783
Canola	-0.22976	10.5894	-0.01706	2.4416	7.3356
Peanuts	-0.30395	7.4899	-0.07120	3.9970	11.2951
Sorghum	-0.17662	5.1872	-0.06118	4.2819	56.3811
Sunflower	-0.27797	12.6731	-0.04931	4.4794	6.0718
Wheat	-0.21133	4.7403	-0.03483	2.6210	17.6706

2.3 DRY MATTER LOSS AND RESPIRATION HEAT

The dry matter loss calculated in the model is based on the respiration of maize reported by Thompson (1972). From this work, the rate of loss of dry matter has been reported by Thorpe (1994) in the following form:-

$$\frac{dm}{dt} = \left\{ 14.72 \times 10^{-10} \exp\left(1.667 \times 10^{-6} t_{eq} - 1\right) + 2.833 \times 10^{-9} \right\} / \left(M_M M_T\right) \qquad \textbf{2.5}$$

where the temperature modifier M_T is calculated using three moisture ranges namely below 19% (dry basis), from 19 to 28%, and above 28%, and based on the deviation from 15.5°C (60°F) as described in detail by Thorpe (1986). The moisture modifier M_M applies over the full temperature range studied.

It is assumed for the time being that this model of dry matter loss will be adequate for other grains. The respiration of moist bulks is likely to be dominated by the respiration of micro flora attacking the seeds. Researchers in this science such as Gibson *et al* (1994b) and Magan and Baxter (1994) use water activity as a measure of the growth of moulds suggesting that their response is governed more by the equilibrium relative humidity of the air at the surface of the seeds (water activity) than by the overall water content of the bulk, much of which may be inaccessible to moulds. It is therefore possible that the model of dry matter loss would be more accurate for other seeds if the equivalent maize moisture content was used, ie. the maize moisture which will generate the same equilibrium relative humidity as the other seed at its moisture content. Some approximate equivalent values are given in Table 2.2. For the model, it may be preferable to later derive an expression for dry matter loss in terms of intergranular relative humidity which may be calculated from the grain type, moisture content and temperature. A recent paper by Lacey *et al* (1994) reports oxygen consumption for wheat at equilibrium relative humidities from 80-95%, and compares it with the rates for barley, canola (rapeseed) and linseed at 25°C with water activity held between 0.88 and 0.90. This and similar new work could be used to enhance the accuracy and versatility of the respiration model.

TABLE 2.2

Equivalent maize moisture contents for a number of other grains

Seed	Moisture content % wet basis	Maize equivalent moisture content % wet basis
Canola	10	19
	13	22
	16	26
Peanuts	10	15
	13	22
	16	26
Sorghum	14	17
	16	24
	18	28
Sunflower	10	18
	13	22
	16	27
Wheat	14	17
	18	19
	22	28

2.4 GERMINATION LOSS

The loss of germination of different seeds is not a simple function of temperature and moisture. However, a general rule based on work by Banks (1992) for barley states that for every 4 kelvin decrease in temperature, the life of the seed over the range of common moisture contents is doubled. Banks (1992) also indicates that a 1% decrease in moisture content of the malting barley studied increases seed life by a factor of three. The general relationship may be expressed as follows:-

$$\frac{V}{V_0} = e^{-kt} \qquad \textbf{2.6}$$

where V is the germination after time t seconds, and V_0 is the initial germination. Given a known value of the time constant k at a certain temperature, its value at other temperatures can be evaluated given the above relationship. It can also be modified for changes in moisture content.

Temperature modification:-

k is a function of temperature T (and moisture content). From the above rule, as t is doubled, k must halve for a given V/V_0. Now t doubles for every 4K drop in temperature, thus k must halve for every 4K drop. Thus, if the value of k (k_0) is known at one temperature T_0, its value at a new temperature T_1 will be as follows:-

$$k = k_0 \times 2^{\left(\frac{T_1 - T_0}{4}\right)} \qquad \textbf{2.7}$$

Similarly, the moisture modification is:-

$$k = k_0 \times 3^{100\,(M_1 - M_0)} \qquad \textbf{2.8}$$

The total change in viability is obtained by treating each effect in turn.

More precise modelling of viability is provided by Roberts (1960) and Roberts and Abdalla(1968) using equations of the following form:-

$$\log p = K_v - C_1 m - C_2 T \qquad \textbf{2.9}$$

where p is the half life of the seed in weeks,

m and T are respectively the seed moisture content (%) and temperature (°C), and

K_v ,C_1 and C_2 are coefficients for a specific seed

and

$$\sigma = K_\sigma p \qquad \textbf{2.10}$$

where σ is the standard deviation of the frequency of deaths against time, and

K_σ is a constant for a specific seed

The coefficients for some seeds are shown in Table 2.3

The model uses the above equations of Roberts and Abdalla (1968). The coefficients in Table 2.3 are for the half viability expressed in weeks. In the computer program, K_v is converted for expression of half viability in days, ie for wheat K_v becomes 5.067.

TABLE 2.3

Coefficients for determining the loss of viability of a number of seeds
(Source:- Roberts and Abdalla, 1968)

Seed	K_v	C_1	C_2	K_σ
Barley	6.745	0.172	0.075	0.301
Broad beans	5.766	0.139	0.056	0.379
Peas	6.432	0.158	0.065	0.384
Wheat	4.222	0.108	0.050	0.350

2.5 GROWTH OF GRAIN INFESTING INSECT POPULATIONS

Desmarchelier (1988) has shown that the intrinsic rates, r_m of population growth of eight species of stored-product Coleoptera are linearly related to the intergranular wet-bulb temperature, T_W. This may be expressed mathematically as

$$r_m = b\,(T_w - c) \tag{2.11}$$

where b and c are species specific constants which are shown for number of insects in Table 2.4.

The objective in cooling grain is to bring the intergranular wet-bulb temperature below c, the threshold value to stop multiplication. For values of T_w below c, the value of r_m is taken as zero.

The number, N, of insects after a time, t, is thus given by

$$N=N_O \exp(r_m t) \tag{2.12}$$

where N_O is the number of insects initially in the grain.

TABLE 2.4

Rate of population increase coefficients and threshold wet-bulb temperatures for a number of grain infesting insects ranked by threshold value (Source:- Desmarchelier, 1988)

Insect	b $°C_{WB}^{-1}$	c threshold $°C_{WB}$
Tribolium castaneum (Herbst)	0.034	17.6
Oryzaephilus surinamensis (L.)	0.073	16.4
Oryzae zea-mais Motschulski	0.018	14.0
Lasioderma serricorne (F.)	0.122	13.9
Rhyzopertha dominica (F.)	0.0435	13.0
Sitophilus oryzae (L.)	0.048	9.8

At high grain temperatures, the rate of increase of some species of grain infesting insects reaches a maximum defined by Desmarchelier (1988) at a wet-bulb temperature T_{MAX}, and then declines as the temperature increases further. The data for r_m above T_{MAX} presented by Desmarchelier (1988) for *Sitophilus oryzae* (L.) when plotted on a psychrometric chart (Fig. 2.2) show that r_m goes to zero at a dry-bulb temperature of about 33°C. It is obvious that the decline in r_m is not a simple function of any psychrometric property of the intergranular air. As a compromise, the model puts r_m for *Sitophilus* species at zero above 32°C dry-bulb.

2.6 BREAKDOWN OF GRAIN PROTECTANTS

The loss of pesticide concentration has been related by Desmarchelier and Bengston (1979) to the temperature T and the relative humidity r of the intergranular air and is expressed as

$$\frac{C}{C_0} = \exp\left(\frac{-1.386rt \ast 10^{B(T-30)}}{t_{\frac{1}{2}}} \right) \qquad \mathbf{2.13}$$

in which the coefficient B and $t_{1/2}$ (the half-life) are specific to each compound. The model includes these coefficients for five grain protectants currently in use commercially as shown in Table 2.5.

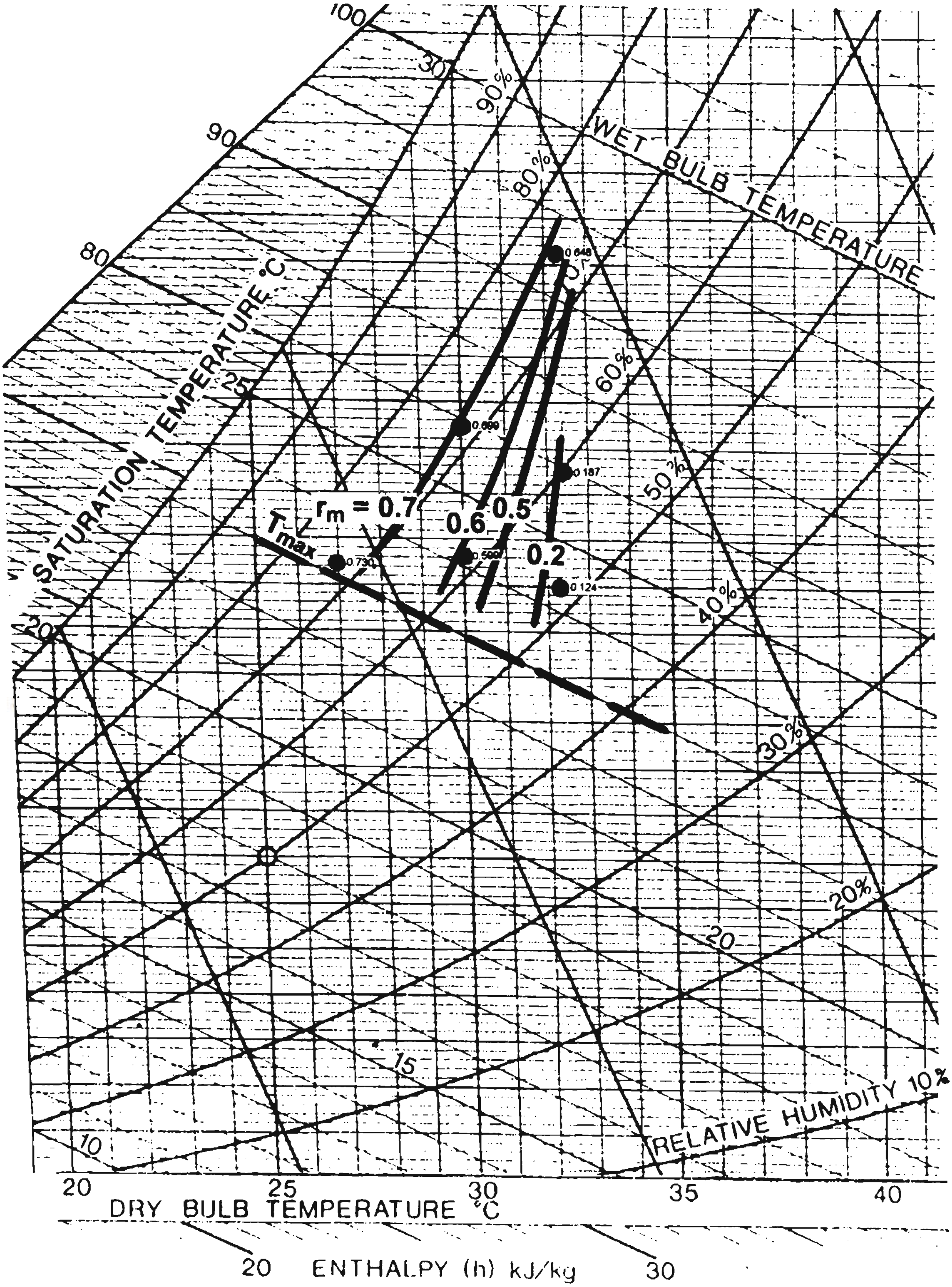


Fig. 2.2 - Decrease in the intrinsic rate of increase of *Sitophilus oryzae* (L.) above the maximum rate at the corresponding wet-bulb temperature T_{max} (Desmarchelier 1988) showing trend to zero at a dry-bulb temperature of 33°C

TABLE 2.5

Decay coefficients for chemical pesticides applied to stored grain

Pesticide	Half-life (weeks)	B (per degree C)
Bioresmethrin	24	0.033
Bioresmethrin + pip.but.	38	0.031
Chlorpyrifos-methyl	19	0.04
Fenitrothion	14	0.036
Methacrifos	8	0.055

2.7 CLIMATIC DATA

The mean daily temperature and humidity for each month under consideration is used with a sinusoid superimposed having an amplitude representing the mean diurnal swing. This is the condition of the air entering the grain cooler.

$$T_{amb} = T_{mean} + T_{amp} \sin\left(\frac{2\pi\, t}{3600 * 24}\right) \qquad \textbf{2.14}$$

where time t is in seconds

The necessary data for sites throughout Australia and some neighbouring islands are given by Bureau of Meteorology (1988).

2.8 GRAIN COOLER CHARACTERISTICS

2.8.1 REFRIGERATION SYSTEM PERFORMANCE

The thermal performance of the M^c^Bea Mobile Grain Cooler is shown in Fig. 2.3 and has been modelled as follows:-

$$T_{w_{out}} = 167Q^3 - 262Q^2 + 148Q - 43.3 + 1.2T_{w_{amb}} - \frac{0.045(35 - T_{amb})}{Q} \qquad \textbf{2.15}$$

M^CBEA MOBILE GRAIN COOLER
MODEL RM180GC
PERFORMANCE CHARACTERISTICS

COOLING RATE DEPENDS ON SIZE OF SEED, DUCTING AND SILO

COEFFICIENT OF RESISTANCE TO AIR FLOW (R)

Alfalfa	7%	16 318 $Pa.s.m^{-2}$
Barley	12%	1 676
Clean ear corn	16%	6.19
Flax	11%	10 421
Linseed	7.9%	14 907
Lupin seed	7.5%	512
Maize	12.4%	719
Oats	13%	1 816
Pea beans	15%	435
Peanuts in shell	4.4%	29.0
Rapeseed	5.7%	7 097
Rough rice	13%	1 952
Safflower	5.9%	1 207
Sorghum	13%	2 664
Soybeans	10%	646
Sunflower	7.9%	1 593
Wheat	11%	3 131

APPROXIMATE PRESSURE OF AIR IN DUCT AT RATED FLOW (400L/s)

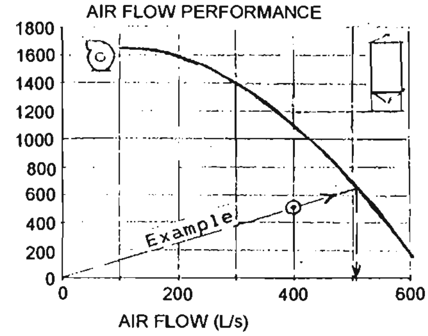
Silo floor area served by duct = A
Height of grain above duct = H
Length of air distribution duct = L

$$P = 0.4R\left(\frac{H}{A} + \frac{1}{2L}\right) \quad Pa$$

Add 20% for compaction
Allow 200Pa for losses

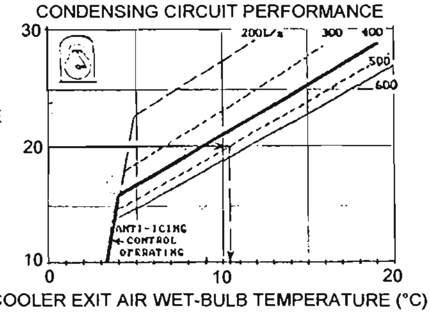
All distances in metres

AIR FLOW PERFORMANCE

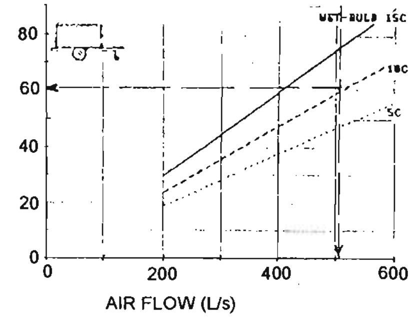


COOLING RATE DEPENDS ON AIR FLOW AND CLIMATIC CONDITIONS

CONDENSING CIRCUIT PERFORMANCE

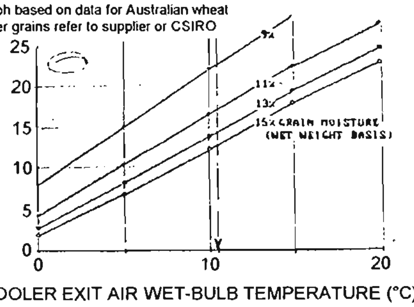


GRAIN COOLING CAPACITY



GRAIN TEMPERATURE PRODUCED

This graph based on data for Australian wheat
For other grains refer to supplier or CSIRO



CAPACITY CORRECTION FACTOR

DEDUCT "C" FROM EXIT AIR WET-BULB TEMPERATURE

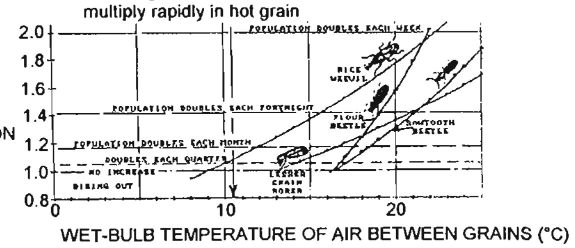
$$C = 45 * \left(\frac{35 - T}{Q}\right)$$

T=Ambient dry-bulb temperature (°C), Q=Air flow (L/s)

FINAL GRAIN TEMPERATURE DEPENDS ON MOISTURE CONTENT

GRAIN INFESTING INSECT POPULATION GROWTH

Insects, including those resistant to insecticides, multiply rapidly in hot grain



Example

Silo diameter	14m	Floor area $154m^2$
Grain height	15m	
Duct length	5m	

Grain typewheat (R=3131)
Average wet-bulb temperature of air entering Cooler 20°C

Estimate of air pressure in duct at rated flow (400L/s):-

$$P = 0.4 * 3131 * \left(\frac{15}{154} + \frac{1}{2*5}\right) = 247 \, Pa$$

Add 20% for compaction:	0.2*247 = 49 Pa	
Allow 200Pa for supply duct losses:		200 Pa
Air pressure at Cooler connection		496 Pa (400L/s)

On "Air Flow Performance" graph:-
- Mark 496Pa point on 400L/s verticle line
- Draw a line from zero through this point to the curve
- Where sloping line meets curve, read Air Flow (500L/s)
  - This is the actual air flow through the system
- Draw a verticle line from this point to the bottom graph

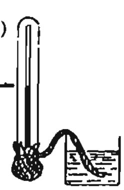
On "Condensing Circuit Performance" graph:-
- Draw a horizontal line from 20°C (Wet-bulb of entering air) to the 500L/s sloping line (Actual air flow)
- Draw a verticle line from this intersection down to the bottom graph axis (Wet-bulb of air between grains)
- Note Cooler's Exit Air Wet-bulb Temperature (10.5°C)

On "Grain Cooling Capacity" graph:-
- Using actual air flow (verticle line drawn from top graph), estimate 10.5°C between 10 and 15° wet-bulb lines
- Draw a horizontal line from this point to Tonnes/24 hours Grain Cooling Capacity (60 tonnes/day)

Capacity Correction Factor: The temperature (dry-bulb) of the outside air has a small effect on the Cooler's Exit Air Wet-bulb Temperature. The Exit Air Wet-bulb will be lower if the outside air is less than 35°C. The number of degrees lower can be calculated from the formula given for "C".

WET-BULB TEMPERATURE

The wet-bulb temperature of air may be measured by wrapping a piece of muslin or similar around a thermometer bulb, and allowing the air to circulate over the bulb to evaporate the water. This evaporation cools the thermometer bulb to a temperature which eventually stablilises at some value below the air temperature. The wet-bulb temperature of the air between the seeds of a bulk of grain is a very good quality control index for the rates of germination loss, chemical protectant breakdown and insect population growth.



c. McBea Services, 2 Gilbert Court, Parkdale Victoria 3195, Australia

Fig. 2.3 - Performance chart for M^CBea Mobile Grain Cooler Model RM180GC relating grain store characteristics to cooling rate based on fan performance and condensing rate under given ambient conditions, grain temperature achieved and level of control over insect populations
Published with the permission of M^CBea Grain Protection Services, Melbourne

Fig. 2.3 - Performance chart for M^cBea Mobile Grain Cooler Model RM180GC relating grain store characteristics to cooling rate based on fan performance and condensing rate under given ambient conditions, grain temperature achieved and level of control over insect populations

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If $T_{w_{out}} < 5°C$, then $T_{w_{out}} = 5°C$ representing the action of the automatic anti-freeze-up control signified by the discontinuity in the condensing circuit performance curves in Fig. 2.3. The first four terms represent the influence of air flow on the temperature drop across the refrigerant evaporator.

The curves for different air flows are substantially parallel and provide a simple conversion from input to output air wet-bulb temperature as seen in the fifth term of equation 2.15. The last term is an ambient temperature dependent capacity correction factor to account for operation away from the ambient conditions at which the plant is specified, namely 35°C.

2.8.2 AIR FLOW CHARACTERISTIC

The refrigeration system performance depends on the air flow Q (m³/s) through the Cooler which is dependent on the resistance offered by the grain bulk and ducting system, plus any controls varying the air flow to meet certain criteria. The Cooler's fan/coil/filter characteristic as shown in Fig. 2.3 is represented by the following polynomial:-

$$P = 1000\left(3.33Q^3 - 9Q^2 + 1.97Q + 1.54\right) \qquad \textbf{2.16}$$

where P is the static pressure in pascals at the outlet of the Cooler.
The air flow performance curve shown in Fig. 2.3 can be seen to approximate a parabola which was tried initially; however, the cubic equation above was found to more accurately model the Cooler's fan characteristic.

The performance chart in Fig. 2.3 was devised and compiled by the candidate to link the performance of the M^{c}Bea Mobile Grain Cooler with the dimensions of any grain store with its air distribution ducting. It also accounts for the variation in grain cooling capacity under different climatic conditions, and determines the grain temperature that can be expected. In addition, based on the work of Desmarchelier (1988), it indicates the individual rates of growth of populations of four species of grain infesting insects at the expected final conditions.

Separate allowances need to be made for supply duct losses and as these will be different in almost every case this effect has not been included in the modelling. These losses are usually very small by comparison with the loss through the grain and therefore they have very little effect on the Cooler's performance. Where the connecting duct work includes a large fan as shown in Fig. 2.4, the transfer of heat through the steel casing will be significant when the ambient temperature is high. Conduction of heat into sub-floor air distribution ducting as discussed in Section 6.5 will also influence the condition of the air entering the grain.

Fig. 2.4 - Stabilising the moisture content of paddy rice in a 300 tonne capacity section of a large drying and storage shed under the influence of a hot dry climate using a M^c^Bea Mobile Grain Cooler supplying controlled humidity air via the large grain ventilation fan housing. The aeration fan is switched off during this procedure

Courtesy Ricegrowers' Cooperative Limited, Leeton, New South Wales

CHAPTER 3

3. NUMERICAL SOLUTION OF EQUATIONS

3.1 MATRIX EQUATIONS

The thermal energy and mass conservation equations are solved by expressing them in finite difference form. The domain of interest is divided into a non-uniform mesh as shown in Fig. 3.1. Instabilities in the numerical solution are avoided by expressing derivatives involving convection as upwind differences (Patankar and Spalding, 1970), ie.

$$\frac{\partial T}{\partial x} = \frac{T_{i+1,j} - T_{i,j}}{hx(i)} \qquad \text{if } u \geq 0 \qquad \mathbf{3.1}$$

and $$\frac{\partial T}{\partial x} = \frac{T_{i,j} - T_{i-1,j}}{hx(i-1)} \qquad \text{if } u \langle 0 \qquad \mathbf{3.2}$$

This can be expressed as

$$\frac{\partial T}{\partial x} = cx1(i)T_{i-1,j} + cx2(i)T_{i,j} + cx3(i)T_{i+1,j} \qquad \mathbf{3.3}$$

where *cx1(i), cx2(i)* and *cx3(i)* assume values appropriate to the direction of the local flow. Second derivatives with respect to *x*, say, may be expressed as

$$\frac{\partial^2 T}{\partial x^2} = cx4(i)T_{i-1,j} + cx5(i)T_{i,j} + cx6(i)T_{i+1,j} \qquad \mathbf{3.4}$$

as described by Graham *et al* (1994). A forward difference scheme is used for the derivatives with respect to time, ie.

$$\frac{\partial T}{\partial t} = \frac{T_{i,j}^{p+1} - T_{i,j}^{p}}{\Delta t} \qquad \mathbf{3.5}$$

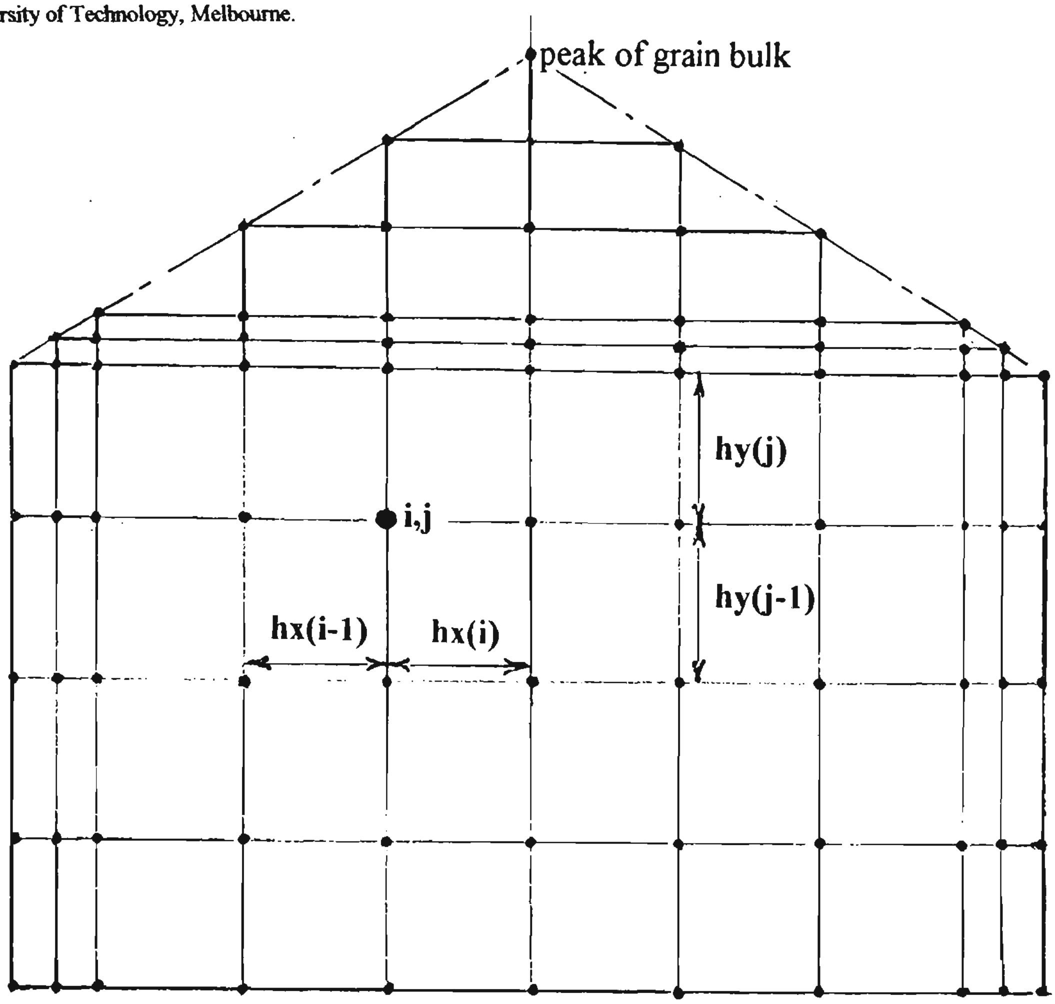


Fig. 3.1 - Scheme of nodes representing a bulk of grain or other porous substance in which nodes are coincident with the sloping top surface

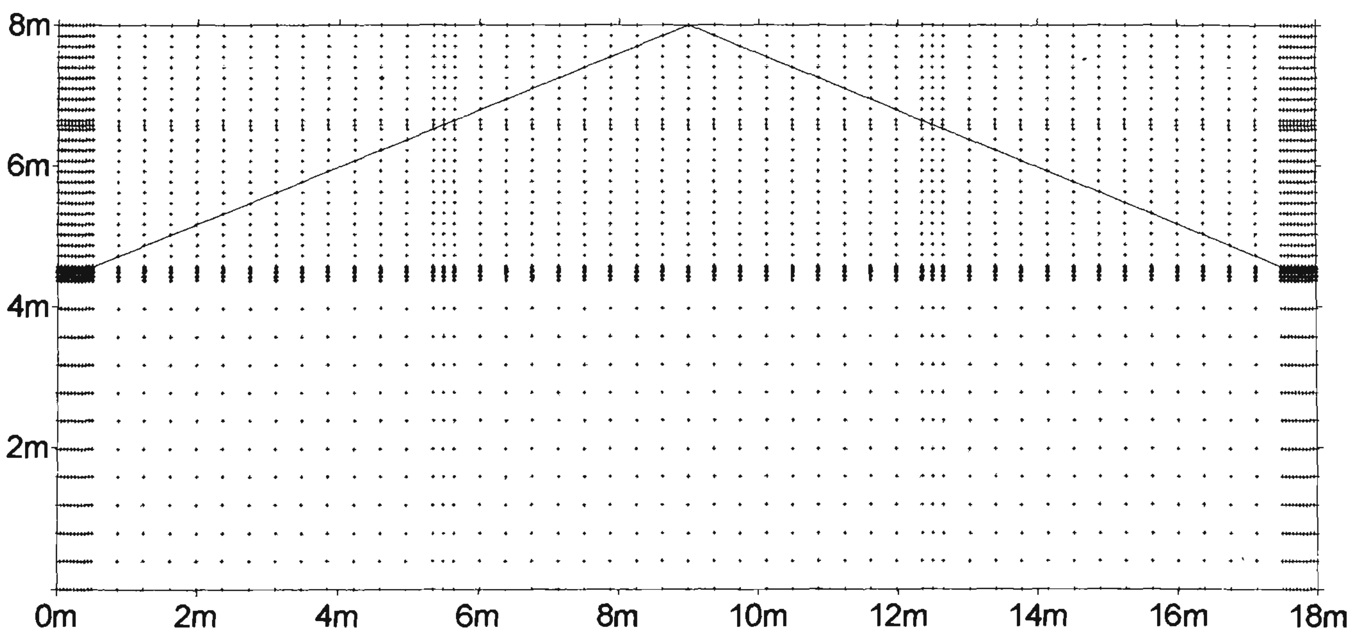


Fig 3.2 - The non-uniform mesh determined by the program from the dimensions of the shed type store simulated showing a common node spacing for all positions deep in the bulk, unique node positions identifying the exact width and accurate location (within 5mm) of ducts, and closer node spacing at the walls for more accurate calculation of peripheral effects

Using these finite difference approximations, the thermal energy conservation equation may be written in the form

$$\phi_1 \frac{T_{i,j}^{p+1} - T_{i,j}^{p}}{\Delta t} + \phi_2 = \phi_3 \tag{3.6}$$

where $\phi_1 = \rho_\sigma \varepsilon_\sigma \left\{ (c_2)_\sigma + (c_1)_\sigma W + \frac{\partial H_W}{\partial T} \right\}$

$$\phi_2 = - h_s \rho_\sigma \varepsilon_\sigma \frac{\partial W}{\partial t} - \rho_\sigma \frac{\partial \varepsilon_\sigma}{\partial t} \int_0^W h_s dW$$
$$+ \left\{ \rho_a \left[c_a + w \left((c_1)_\gamma + (c_2)_v \right) \right] \right\} \left\{ u \left(cx1T_{i-1} + cx2T + cx3T_{i+1} \right) + v \left(cy1T_{j-1} + cy2T + cy3T_{j+1} \right) \right\}$$

$$\phi_3 = K_{eff} \left\{ cx4T_{i-1} + cx5T + cx6T_{i+1} + cy4T_{j-1} + cy5 + cy6T_{j+1} \right\}$$
$$+ \rho_\sigma \varepsilon_\sigma Qr \frac{dm}{dt} - 0.6 \rho_\sigma \varepsilon_\sigma h_v \frac{dm}{dt}$$

in which the absence of a subscript or superscript implies we are considering the $(i,j)^{th}$ node at the p^{th} time step

ie. $T_{i,j}^{p} \equiv T$

$T_{i+1,j}^{p} \equiv T_{i+1}$

and $T_{i,j}^{p+1} \equiv T^{p+1}$

The updated temperature of the $(i,j)^{th}$ node is thus calculated from

$$T^{p+1} = T + \Delta t \left(\phi_3 - \phi_2 \right) / \phi_1 \tag{3.7}$$

The discretized form of the moisture conservation equation is

$$\phi_4 \frac{W^{p+1} - W^{p}}{\Delta t} + \phi_5 = \phi_6 \tag{3.8}$$

where $\phi_4 = \rho_\sigma \varepsilon_\sigma$

$\phi_5 = \rho_a \left\{ u \left(cx1w_{i-1} + cx2w + cx3w_{i+1} \right) + v \left(cy1w_{j-1} + cy2w + cy3w_{j+1} \right) \right\}$

$\phi_6 = \rho_\sigma \varepsilon_\sigma \frac{dm}{dt}$

hence $W^{p+1} = W + \Delta t \left(\phi_6 - \phi_5 \right) / \phi_4$ **3.9**

The pressure distribution in the grain bulk was found by solving Laplace's equation using the Alternating Direction Implicit method (Peaceman and Rachford, 1955).

3.2 THE COMPUTATIONAL GRID

The number of nodes selected for the mathematical model depends on the order of accuracy required, and in this respect the selection is somewhat arbitrary. However, in practical systems it is necessary to ensure that nodes coincide with actual physical features such as a cooling air inlet duct, a steel door in a concrete wall or a tunnel, or other feature which will influence the behaviour of the cooling process. One method of locating these features is to introduce non-uniform node spacing. This has been done in the present work as shown in Fig. 3.1 to more accurately determine peripheral effects within 0.5m from the surface of the bulk particularly where heat enters through the wall. The remaining internal space can be divided into larger modules to reduce the number of calculations to be processed. Where there are multiple air inlet ducts, some of these will be off-set from the centreline of the bulk and their position must correspond to a node. For uniform node spacing between the ducts and boundary layers therefore, a rational number as close as possible to the ratio of duct location to net width of the internal space (after deducting the widths of the ducts) must be determined. This is achieved using the following continued fractions described by Davenport (1968) and summarised by Selkirk (1991).

Let α be the real number ratio representing the distance from the boundary to the duct and the bulk width, and q be the largest integer less than α.

Then $\alpha_0 = q_0 + r_0$ where r denotes the remainder. **3.10**

If $r=0$ then calculation finished.

If $r \neq 0$, $\alpha_0 = q_0 + \dfrac{1}{1/r_0}$ **3.11**

Let $\alpha_1 = 1/r_0$

$$\text{Thus } \alpha_0 = q_0 + \frac{1}{\alpha_1}$$

$$= q_0 + \cfrac{1}{q_1 + \cfrac{1}{1/r_1}} \qquad \mathbf{3.12}$$

etc

The continued fraction form of α is $[q_0, q_1, q_2, \ldots]$

To obtain rational approximations for α, define $A_{-1} = 1,\quad A_0 = q_0,\quad A_n = q_n A_{n-1} + A_{n-2}$

$$B_{-1} = 0,\quad B_0 = 1,\quad B_n = q_n B_{n-1} + B_{n-2}$$

Rational numbers $\frac{A_n}{B_n}$ for a choice of number of node spacings to duct and across the bulk are shown by completing the Table 3.1 below:-

TABLE 3.1

Continued fractions $\frac{A_n}{B_n}$ obtained by multiplying q_n by A_{n-1} and adding A_{n-2} and likewise with B_n starting at $n = 1$

n	-1	0	1	2	3	4	5
q_n		q_0	q_1	q_2	q_3	q_4	q_5
A_n	1	q_0	A_1	A_2	A_3	A_4	A_5
B_n	0	1	B_1	B_2	B_3	B_4	B_5

The choice will be determined by the speed and memory limitations of the micro-computer employed. Where the model incorporates a boundary layer at the walls with fixed node spacing, and a duct or ducts with a finite width, the dimensions of these and other features must be deducted from the bulk width to determine the length to be evenly divided by the above procedure.

Example:- In the grain store simulated, the two aeration ducts were 300mm wide and offset 3.5m each side of the centreline, the store being at total of 18m wide. Using the model's programmed boundary layer of 0.5m in from each side wall, the space remaining to be divided into equal node spacings is 16.4m. The distance from the inner edge of the boundary layer to the outer edge of the nearest duct is 4.85m. The ratio of this distance to the space to be divided is 0.2957317 (α_0), thus

$q_0 = 0$. Using the reciprocal of the remainder, α_1 becomes 3.381443 yielding $q_1 = 3$, thence α_2 is 2.621622 yielding $q_2 = 2$ and so on as shown in Table 3.2

TABLE 3.2

Continued fractions for selecting equidistant node spacings for an adequate level of accuracy of the model's duct position to the duct locations in the grain store simulated

n	*-1*	*0*	*1*	*2*	*3*	*4*	*5*
q_n		0	3	2	1	1	1
A_n	1	0	**1**	**2**	**3**	**5**	**8**
B_n	0	1	**3**	**7**	**10**	**17**	**27**

The bold quotients represent progressively more accurate approximations to the decimal fraction specified by the dimensions of the grain store. The actual matrix selected by the program is shown in Fig. 3.2 in which the duct position is only 5mm different from the actual duct locations. The quotient used is the next one in the above Table, namely $\mathbf{\frac{13}{44}}$ resulting in 69 nodes in the x direction after the duct and boundary layer nodes are added to the denominator plus the node at $x = 0$. In the computer program, the spacing of the nodes in the y direction is made approximately equal to the spacing of the x nodes determined by the above procedure; however, if there is some feature in the vertical direction such as a steel access door or an emptying conveyor between the floor and the grain surface, continued fractions could again be determined for an appropriate y node spacing to locate most accurately within computational limits the discontinuity in thermal conductivity up the wall of the grain store. Above the intercept of the grain surface with the wall of the grain store, the spacing of the nodes in the y direction is determined by the angle of repose of the bulk so that nodes coincide with the top surface of the grain. As angles of repose of most materials are less than 45°, this procedure has the advantage of providing automatically closer node spacing in the peak region of the bulk which is most vulnerable to heating and loss of quality control. This effect can be seen in Fig. 3.2.

Continued fractions have been used previously by the candidate in the cutting of helical gears on a milling machine in the absence of a more modern gear generator. The task is to determine the most accurate combination of a limited selection of change gears connecting the mandrel rotating the gear blank to be machined and the work table feed screw. The decimal to approximate is a function of the relative leads of the work table feed screw and of the helix of the gear to be cut. Continued fractions can also be used to obtain rational numbers approximating π.

3.3 THE COMPUTER PROGRAM

The program is written in Fortran 77. Appendix 6 defines the variables. The listing in Appendix 7 consists of the main program for heat and mass transfer calculations with numerous subroutines for input data manipulation, physical, chemical and biological properties of the interacting components and for determining the air pressure distribution. Subroutines included for speeding up the convergence of the pressure field were introduced when the program was written in QBasic; but as the calculation now takes only about five minutes, these are no longer called. A complete list of the subroutines is given in Appendix 8. Common variables are compiled in a file listed in Appendix 9.

3.4 DATA INPUT

When mobile grain cooling plant is relocated to a different climatic region and applied to stores of different dimensions containing different types of grains, the relevant information about the new situation must be supplied to the mathematical model or the plant controller using the model to optimise operation. The operator must also provide initial temperatures, moisture contents, pesticide concentrations (if any), the quantity or height of grain and the month in which the plant is started. Where there are multiple ducts, the duct receiving chilled air must be identified. It is envisaged that, with further development, the input of data will be accomplished using a PC which will generate an input data file on a removable disk for transfer to the cooling plant controller or computer being used for optimisation studies. In the case of a cooling plant controller, this same disk would also accumulate predicted cooling data for later transmission to a centre for analysis and comparison with physical measurements that may be made in the grain bulk from time to time. In the present work, an input data file is provided for the above variables, and basic data for moist air, a number of grains, insects and pesticides, and cooling plant characteristics are contained in relevant subroutines.

The main dimensions of the grain store, the aeration ducting and the properties of the grain bulk are entered on a file shown in Appendix 10. Climatic data are also entered together with the initial temperature, moisture and germination of the grain. The initial insect density is assumed to be 1 per tonne, and initial pesticide concentration 1mg/kg. If desired, other values may be inserted in the relevant subroutines.

Program control variables and loop specifiers are also entered in the data input file. The time steps "dt" and "dtg" may need to be decreased if instability or numerical data processing errors occur; but this will inevitably increase program execution time. The re-activation and appropriate editing of the instability detecting subroutines may be required to keep execution time within practical limits.

Cooling plant identification and control data are also included in the data input file, and currently provide for up to five different air flows for a specified period entering each aeration duct. In the simulation of the barley shed store with two aeration ducts, the RM180GC M^{c}Bea Mobile Grain Cooler model is invoked with its rated air flow of 400 L/s into one duct, whilst zero flow is specified for the other. When the number of days for the initial cooling run has been reached, eg. the 7 day optimum to minimise numbers of the lesser grain borer, the chilled air flow is transferred to the other duct with zero flow imposed at the first duct and the new pressure field determined before continuing with the heat and mass transfer calculations. The file also provides for an air flow modulation damper with thermostat control which is an option offered for M^{c}Bea grain coolers.

CHAPTER 4

4. DEVELOPMENT OF COMMERCIAL GRAIN COOLERS

4.1 BACKGROUND

The need for grain cooling plant arises from the recognition of the benefits of decreasing the temperature of bulk-stored grain. Once cooled, the bulk remains at the low temperature for many months and therefore, if the refrigeration plant can be moved easily, operators can use the same equipment on a number of silos and at different sites if required.

Cooling bulk grain prevents common grain storage problems which are traditionally thought to result from the grain being stored at an unacceptably high moisture content. This misconception arises because the visible moisture problems result from invisible physical processes which are generated by high grain temperatures. High temperatures also promote the multiplication of grain infesting insects which produce heat when oxidising carbon as part of their normal respiratory processes. Likewise moulds and the grain itself are respiring and generating heat to raise grain temperatures further. Where insecticides are used, high temperatures cause them to decay rapidly, they become ineffective and insects soon become evident. Cooling eliminates all these problems and more by its effect on some fundamental physical properties of a bulk of grain as follows:-

- Decreases the **partial pressure of the water vapour** between the seeds thus greatly reducing the vapour pressure gradient towards the silo wall and other cooler boundaries where the pressure of the water vapour is lower. In silos of hot grain, it has been shown by Griffiths (1964) that this vapour pressure gradient causes the accumulation of moisture from the hot centre at the walls and floor of grain stores. The candidate has discovered that this is still a common experience for many who store grain, despite the care taken over ensuring that the grain is initially dry, and some accept this phenomenon as a normal outcome even after repeated fumigation.

- Increases the **density** of the air between the seeds thus reducing the difference in air densities across the bulk which in turn suppresses the movement of air by convection within the bulk. This eliminates the moisture accumulation at the peak of bulks observed by Griffiths (1964) to result from the upward movement of hot moisture-laden air from the hot centre driven by the downward movement of heavier cooler air at the walls when the ambient is at a lower temperature than that of the bulk. Caked grain at the peak of uncooled bulks is still a common occurrence in Australia, with most operators reporting to the candidate that clods of matted grain sometimes obstruct the flow during emptying.
- Decreases the **absolute moisture content** of the air in the bulk thus reducing the rate at which the convection currents described above can transfer moisture. Cooling therefore has a compounding effect on the mechanisms which lead to moisture damage.
- Decreases the **dew-point temperature** of the air above the grain surface, particularly important in sealed silos and plastic covered bunker type stores, thus diminishing greatly the potential for condensation under the silo roof or tarpaulin and consequent spoilage. This characteristic sweating, particularly of steel silos, can result even if wheat as dry a 10% moisture content is stored at a typical temperature at harvest of 35°C if the roof temperature is less than 20°C. The air in such a bulk of grain cooled to 20°C has a dew-point of 3°C.
- Decreases the **grain temperature** thus slowing all biological and chemical activity

As a consequence of the above effects and the lower grain temperature, cooling delivers further benefits as follows:-

- Reduces the risk of toxins produced by moulds on moistened grain by suppressing the mechanisms which give rise to the accumulation and concentration of moisture as discussed above.
- Suppresses the activity of moulds on grain stored at elevated moisture contents by the reduction in grain temperature thus reducing the potential for heating and the consequent high temperatures which generate all the characteristic grain storage problems discussed above.

- Suppresses the activity of grain infesting insects by decreasing the **wet-bulb temperature** of the intergranular air. The significance of the wet-bulb temperature as an accurate measure for determining the arrest of insect population growth is discussed by Desmarchelier (1988) and the results are used in Section 2.5.
- Decreases the rate at which any contact insecticides applied to the grain break down and lose their effectiveness against susceptible insects.
- Forestalls significantly the development of resistance by insects to pesticides by not only maintaining the lethal effect as above for longer; but also by inhibiting their multiplication.
- Maintains the quality and freshness of the grain throughout the storage period.
- Retards the deterioration of wet grain in storage, and facilitates the exploitation of the heat of respiration for drying the bulk by expelling hot moisture-laden air during ventilation.

As an aid to operators of bulk grain stores, the candidate has developed a system of long probes with connecting inserting rods. These are available commercially. This equipment enables one to measure grain temperature (°C), the intergranular air wet-bulb temperature (°C), dew-point (°C), absolute moisture content (g/kg) and the partial pressure of the water vapour (hPa) as well as the intergranular relative humidity (%) which is related to mould activity and grain moisture content. This hand-held battery-operated instrument has been developed in collaboration with the Australian distributor, ETMC Technologies, for Novasina, Switzerland. Features of this equipment are described in Section 4.4. Equipped with such a system, any bulk of grain can be probed to determine the urgency of the need for cooling bearing in mind any chemical treatment applied, the end use of the grain, and the viability of ventilating the bulk with naturally occurring atmospheric air if mobile refrigeration plant is not accessible at the time.

Grain is normally harvested and stored during hot weather so it is therefore unlikely that passing naturally occurring atmospheric air through the bulk will decrease the grain temperature sufficiently to completely suppress the growth of insect populations. Chilled air becomes necessary in such circumstances and not only provides the air condition required; but also gives much greater confidence than could be expected with climate dependent systems. The overall cost per unit mass of grain for aeration is 5 to 10 times less than that for chilling, typically 15 to 25c/tonne.

The chilling of bulk stored grain with conditioned air has been used in various parts of the world for a number of different reasons (Navarro *et al*, 1973a and b). Grain silo coolers are manufactured in Germany, Sweden, Italy, Russia and Australia. The Australian mobile grain coolers were developed by the candidate with private research and commercialisation funding, and are unique in that they can be towed at normal road speeds, because they incorporate an independent rubber suspension system which absorbs shock and minimises fatigue of the copper piping of the refrigeration system. All known grain coolers supply chilled air to ducting on the floor of grain stores and are intended to be operated continuously until inspection shows that the grain has been cooled to the desired level. It is rare for grain temperature feed-back from a sensor in the bulk to be employed to control the refrigeration plant. However, one such case is reported by Sutherland *et al* (1970) in which the difficulty of determining the proper location for the sensor for the research study involved is discussed. This difficulty is compounded when dealing with normal commercial situations, such as partly filled silos, and is suspected to be one of the main reasons an automatic feed-back loop does not form part of present day grain cooler applications. The operator is therefore left with two options: namely to leave a cooler connected to a silo for a period determined by the rated cooling capacity in tonnes per 24 hours, or to determine the completion of cooling by inspection. The former may not always be a good guide since in some cases the resistance of the bulk and duct work may be sufficiently high to decrease the flow of air through the grain cooler to a value less than the rated flow.

4.2 COMPUTER CONTROL

The motivation behind the mathematical model developed in this thesis is the provision of all the necessary feed-back information for the most efficient control of the grain cooling plant without the need of wiring to delicate sensors in the grain mass. The accuracy of the model's information will be only as good as the input data on the stored product such as its initial temperature and moisture content at various levels. When the model is incorporated in the controller of an aeration system that uses naturally occurring atmospheric air, during the passage of the first cooling wave it is possible to estimate the grain temperature and moisture profiles from the monitored condition of the air used.

4.3 M^c^BEA MOBILE GRAIN COOLERS

In the model, the simulation of refrigeration plant conditioning the air entering the grain is based on the Australian made 18kW Model RM180GC of the M^{c}Bea Mobile Grain Coolers of which there is a fleet available for hire to grain storage operators and others in Australia. The M^{c}Bea brochure (Appendix 3) rates the cooling capacity of these units at 1800 tonnes of grain (or other bulk material) per month assuming uniform air flow through the mass. A general assembly is shown in Fig. 4.1.

The Cooler comprises a refrigerant condensing circuit using Freon 22 ($CHClF_2$ - R22), an interim HCFC refrigerant recommended under the United Nations Environment Program's *Montreal Protocol on Substances that Deplete the Ozone Layer* and its Declaration on Transitional Substances. Freon 22 has an Ozone Depletion Potential one twentieth that of the CFC Freon 12 (CCl_2F_2 - R12) used in domestic refrigerators and automotive air conditioners (Harris, 1990). The circuit is completely hermetic with the compressor and its driving motor encased in the sealed system of pipework. The motor is cooled by the flow of refrigerant and there is therefore no shaft outside the refrigerant circuit such as on an air conditioned motor vehicle which would require a seal to prevent the loss of gas. The flow of ambient air through the air cooled condenser is modulated in accordance with the compressor head pressure to prevent flooding with refrigerant and lubricant. This feature, negotiated by the candidate in the design stages, has now become a standard on the roof-top air conditioners on which the M^{c}Bea Mobile Grain Coolers are based. New models of the M^{c}Bea Grain Coolers are charged with a lubricant which is compatible with the refrigerants currently under development which have no effect on the ozone layer, so that such a gas, as soon as it is available commercially, may be exchanged for the R22 without any other modifications being required. This far-sighted design feature has been instituted by the candidate to meet concerns

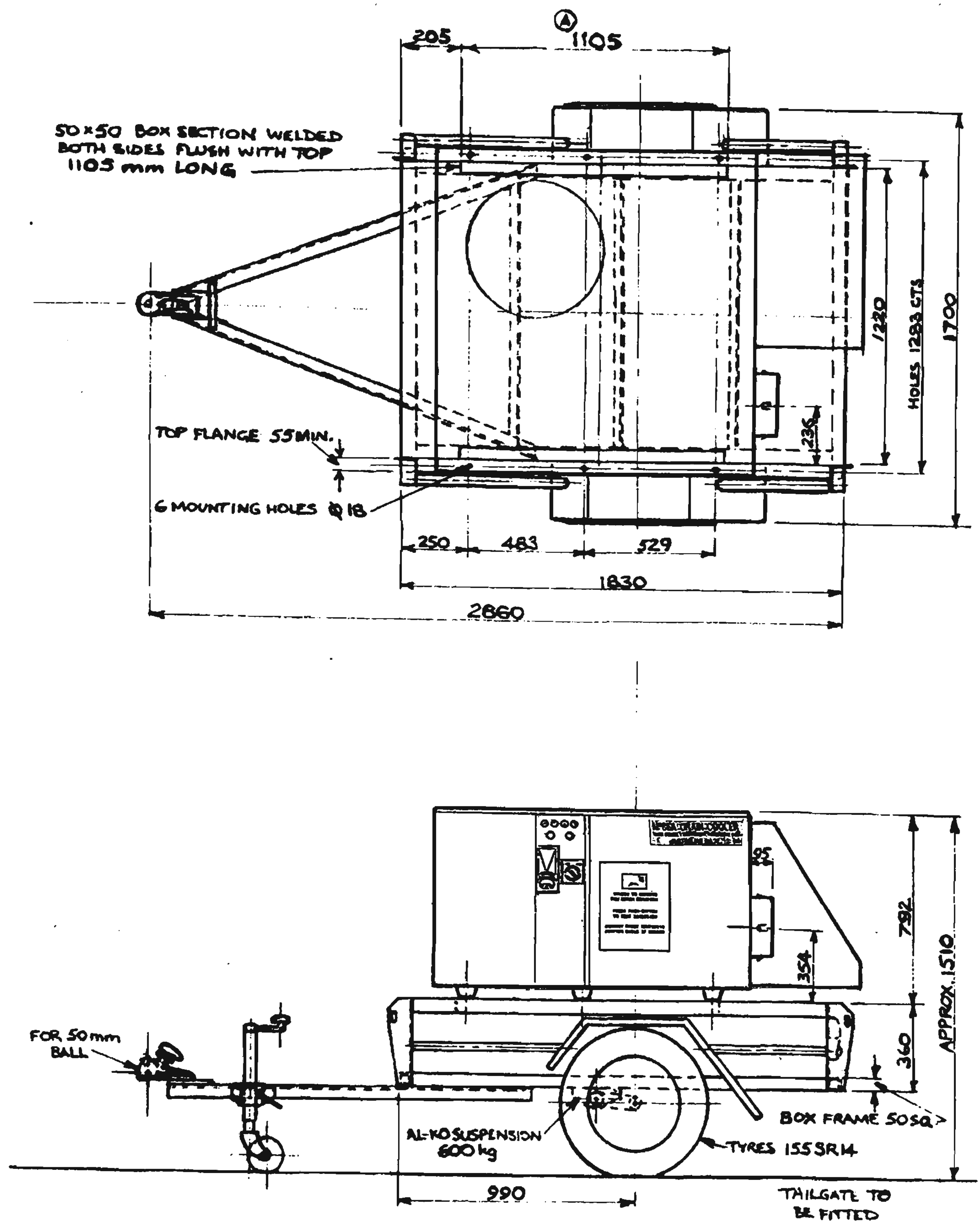


Fig. 4.1 - General assembly of M^cBea Mobile Grain Cooler Model RM180GC showing 20 amp connection for three-phase 415 volt power supply, chilled air outlet spigot for connecting flexible insulated ducting and the integrated roadworthy trailer providing storage for the electrical extension cable, flexible ducting, fittings and condensate drain hose
Published with the permission of M^cBea Grain Protection Services, Melbourne, Victoria

expressed by Solomon and Albritton (1972) at the short-term effects of releasing increased amounts of HCFCs recommended as replacements for CFCs.

The evaporator is designed to bring the air passing through it to the lowest possible temperature without icing of the condensate. This necessitates a deep coil with fin spacing adequate to free ice should it occur. The control of icing is accomplished by varying the flow of gas automatically using a valve controlled from the suction pressure to by-pass hot refrigerant gas from the compressor direct to the evaporator. The easily understood concept of applying hot gas to remove ice is an important feature initiated by the candidate in that it instils confidence in grain store operators to make adjustments to this valve should the need arise. Those who do are very successful in remedying ice-up problems when the coolers have been faced with conditions for which they were not designed such as the application shown in Fig. 2.1.

The relative humidity of the air leaving the Australian grain cooler is controlled to ensure that levels which may give rise to the development of mould and aflatoxin are avoided. The relative humidity of the air leaving the cooler is from 70-75% which is below the levels at which experiments on fungal growth such as those of Gibson *et al* (1994a) were conducted. This is achieved by making use of the compression of the cooled air in the high pressure fan downstream of the evaporator and, at the higher air flows, supplementing the heat so provided with small electric elements switched sequentially according to the pressure rise across the fan. This novel feature was introduced by the candidate to avoid complicated relative humidity sensing instrumentation and control systems which are subject to calibration drift and which may engender uncertainty and lack of confidence by refrigeration service personnel in remote rural communities, which in turn can lead to delays and added costs.

The flow of air through the evaporator is dictated largely by the resistance of the grain bulk and duct work to air flow. A manually adjustable damper plate is provided as an optional extra for situations where the resistance to air flow is so low that the quantity of air delivered exceeds the rated air flow of the Cooler. A feature recently introduced by the candidate is a motor-controlled damper which adjusts in accordance with a set Cooler outlet temperature. This control over the Cooler's air flow foreshadows the integration of this facility with a microprocessor-based operation optimising system. Provision for this Cooler outlet temperature set point is made in the data input file (Appendix 10) for the numerical mathematical model of bulk grain developed for this thesis.

A special feature of the Cooler is the provision of a cold air fan that is capable of generating sufficient pressure for users to be able to refrigerate their grain via extremely restrictive openings such as a fumigation duct or the emptying auger tube as shown in Fig. 2.1 without significant loss of cooling capacity.

In many remote areas of Australia where grain is grown, the three-phase power required to operate the Australian grain cooler is not available from the electricity supply grid. Various systems for converting single-phase power to three-phase have been studied by the candidate. It is concluded that this is not a practical option because of voltage variation in remote areas and the tendency for each situation to be unique requiring special consideration every time the Cooler is relocated. Furthermore, this solution does not address another frequent problem of silos being far away from any electricity supply. There is therefore a need for a self contained system independent of the power grid yet retaining the manoeuvrability of the plant. This need is accommodated by equipping one of the Coolers on the hire fleet operated by M^c^Bea with a 20kVA three-phase alternator which can be driven via the power take-off of an agricultural tractor. This facilitates the cooling of field bins or of silos at sites where three-phase power is not available or too expensive to connect. A single-phase mobile grain cooler of much lower grain cooling capacity has also been developed by the candidate based on the design concepts of the larger M^c^Bea Mobile Grain Coolers. The two models now available for use where three-phase electricity is not available are shown in Fig. 4.2

M^c^Bea Mobile Grain Coolers have been protecting bulk stored grain in Australia for some six years at locations ranging from Kununurra in the north east of Western Australia to Melbourne, Victoria, 3

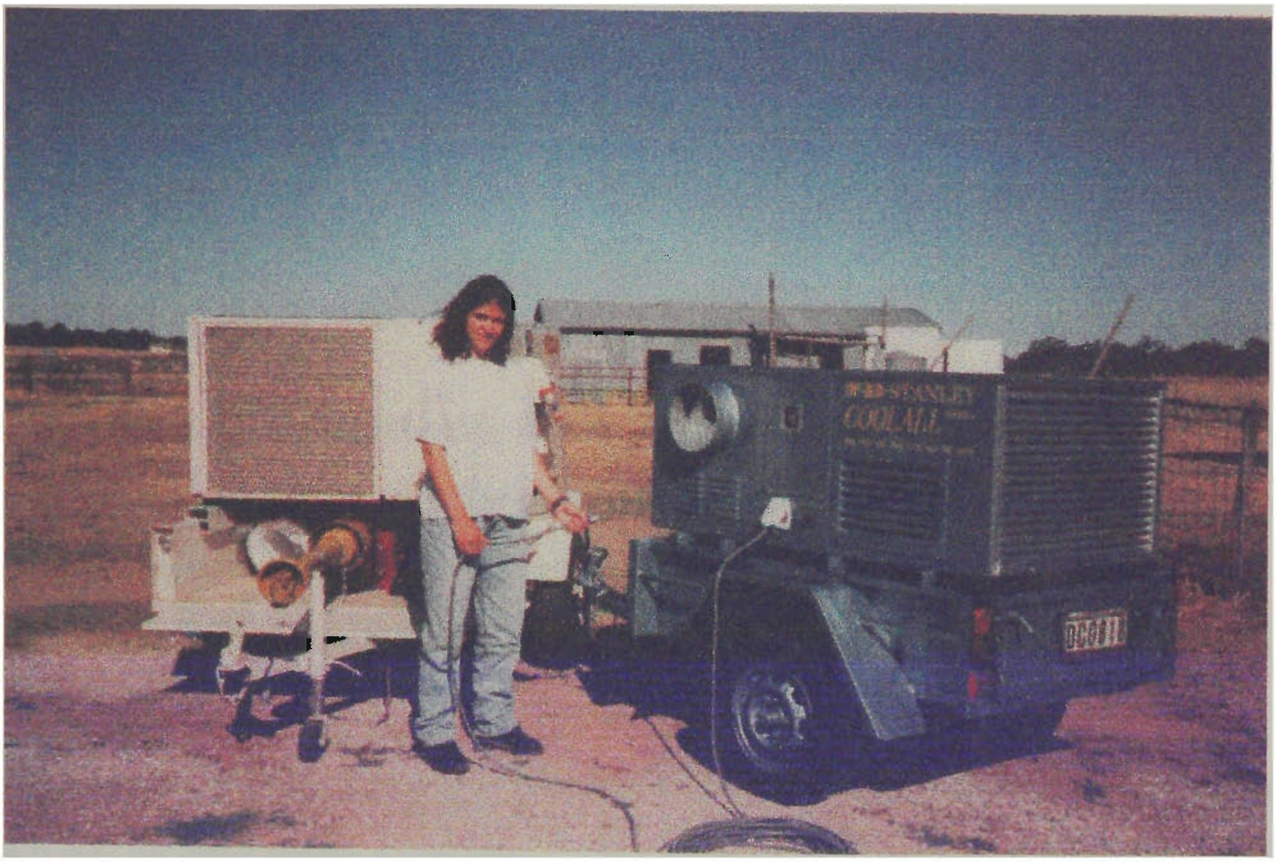


Fig. 4.2 - McBea Mobile Grain Cooler with power take-off driven 20kVA three-phase alternator for connection to an agricultural tractor, and McBea-Stanley *COOLALL*$^{MARK-1}$ for connection to a 15 amp, 240 volt single-phase electricity supply.

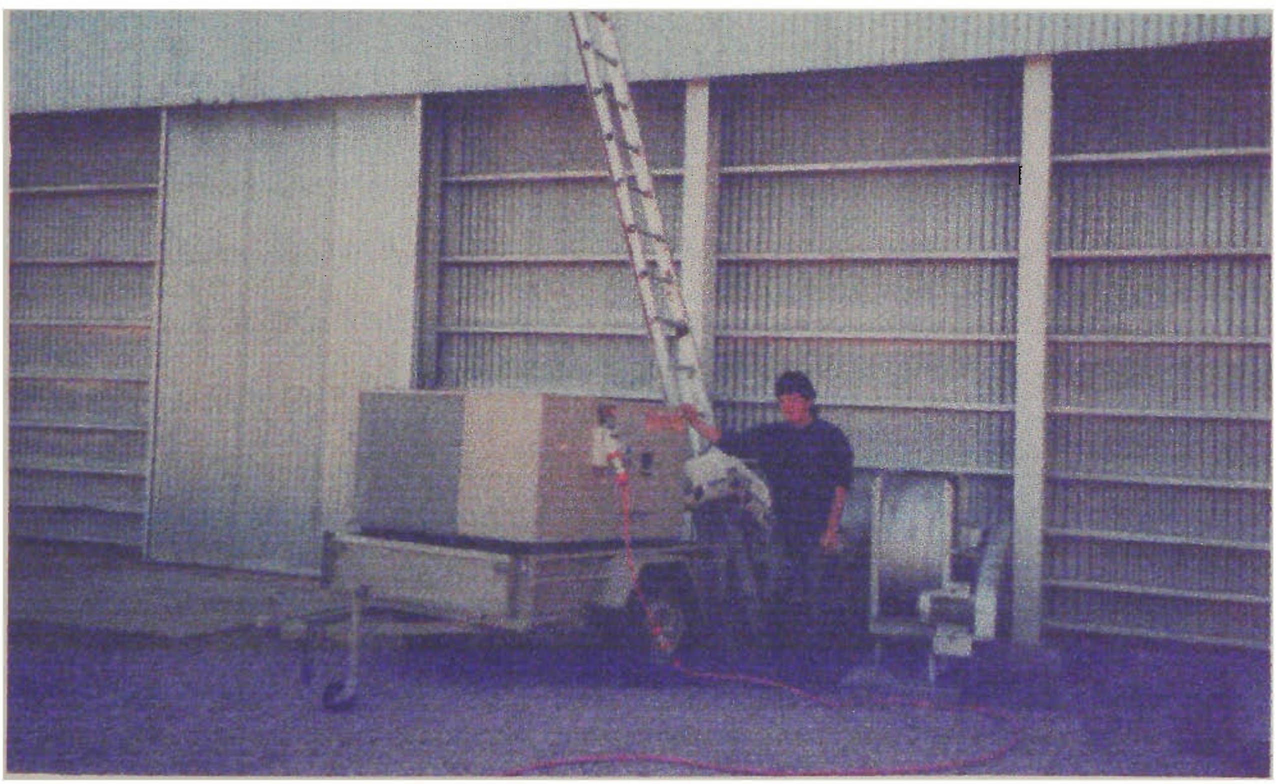


Fig. 4.3 - McBea Mobile Grain Cooler Model RM180GC supplying chilled air via existing aeration fan (not operating) to 1500 tonnes of wheat in a shed type grain store after breakdown of the pesticide applied some months earlier

Courtesy Frankling Grains Pty Ltd, Barham, New South Wales and in the North Island of New Zealand since 1991. Some photographs of applications are shown in Figs 4.3-4.7.

4.4 COOLING A GRAIN SHED

In December 1993, an old grain store of the shed type in southern New South Wales was filled with 3000 tonnes of malt grade barley. A partition divided the shed into two sections. Each section was equipped with two aeration ducts equally spaced across the floor and connected to a manifold painted dark green supplied with air from a belt-driven aeration fan. Sections of the aeration ducting are shown in Fig. 4.8 ready for laying on the floor to connect to the horizontal spigot through the wall shown in the background. The grain shed is shown in Fig. 4.9. The majority of grain stored in Australia is held for many months in this type of structure, and a very large one is shown in Fig. 4.10.

The manifold on each section was removed and the aeration duct connections fitted with starting collars to receive the 250mm flexible insulated duct from a McBea Mobile Grain Cooler which was connected first to the eastern duct in the northern section of the shed.
During the cooling process, measurements were made in the barley in the northern section of the shed using an instrumentation system developed by the candidate. The portable package including inserting rods is known as the McBea Services' MS1 Deep Probe Wet-bulb Temperature Measuring System. It is shown in Section 4.1 that this system provides measurements of all the important physical properties of bulk grain which influence the consequential response of biological agents of deterioration and commercial loss. Information on this specialised equipment for bulk grain quality control illustrated in Fig. 4.11 is given in Appendix 4. The candidate's motivation for developing this portable and easily used instrumentation and launching it on the grain storage industry emanates from the belief that it is in the long term interest of grain storage operators to identify and remove the cause of the emergence of organisms which damage the grain, rather than simply attack the organisms themselves as a short term palliative treatment. The organisms of chief concern to the Australian grain storage industry are grain infesting insects, and this is why the name of the

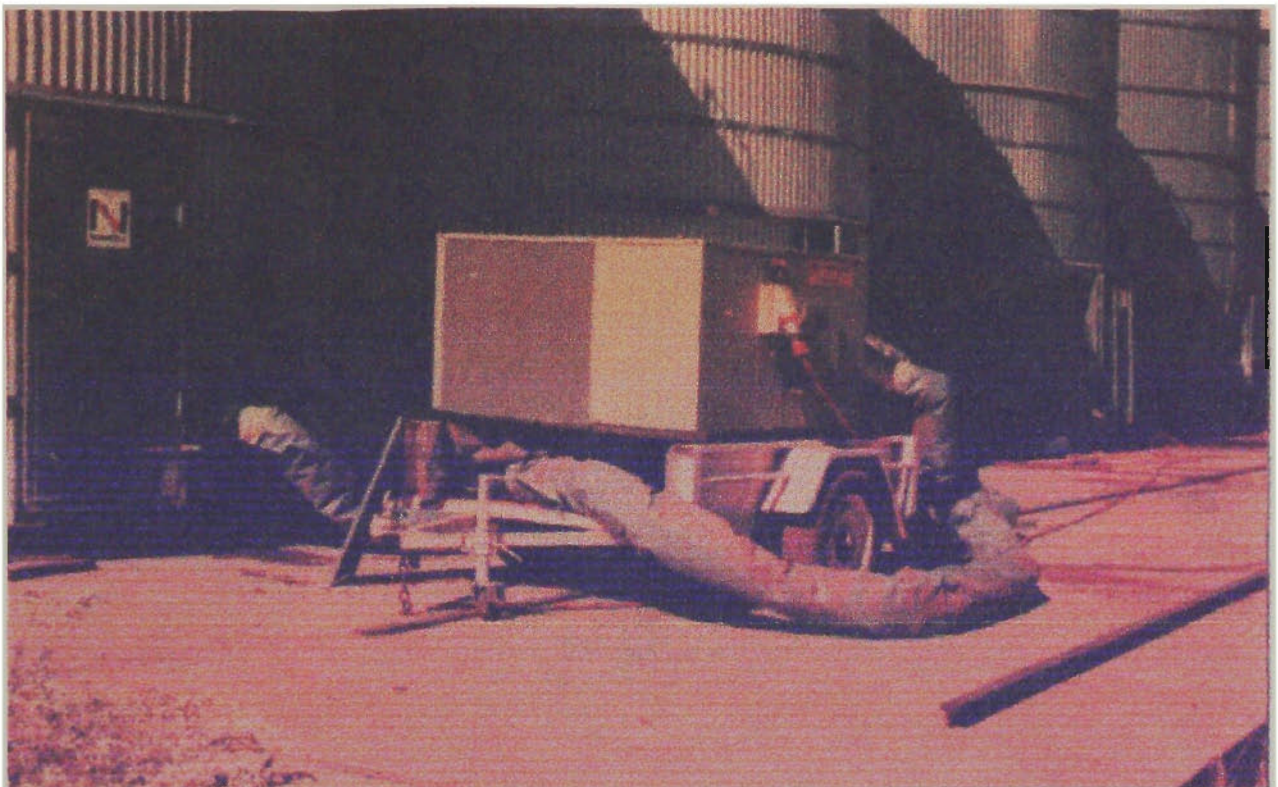


Fig. 4.4 - Maintaining the germination of seed grains in steel silos near Kununurra in the north east of Western Australia using the first production RM180GC M[c]Bea Mobile Grain Cooler
Courtesy Agseed Pty Ltd, Dubbo, New South Wales

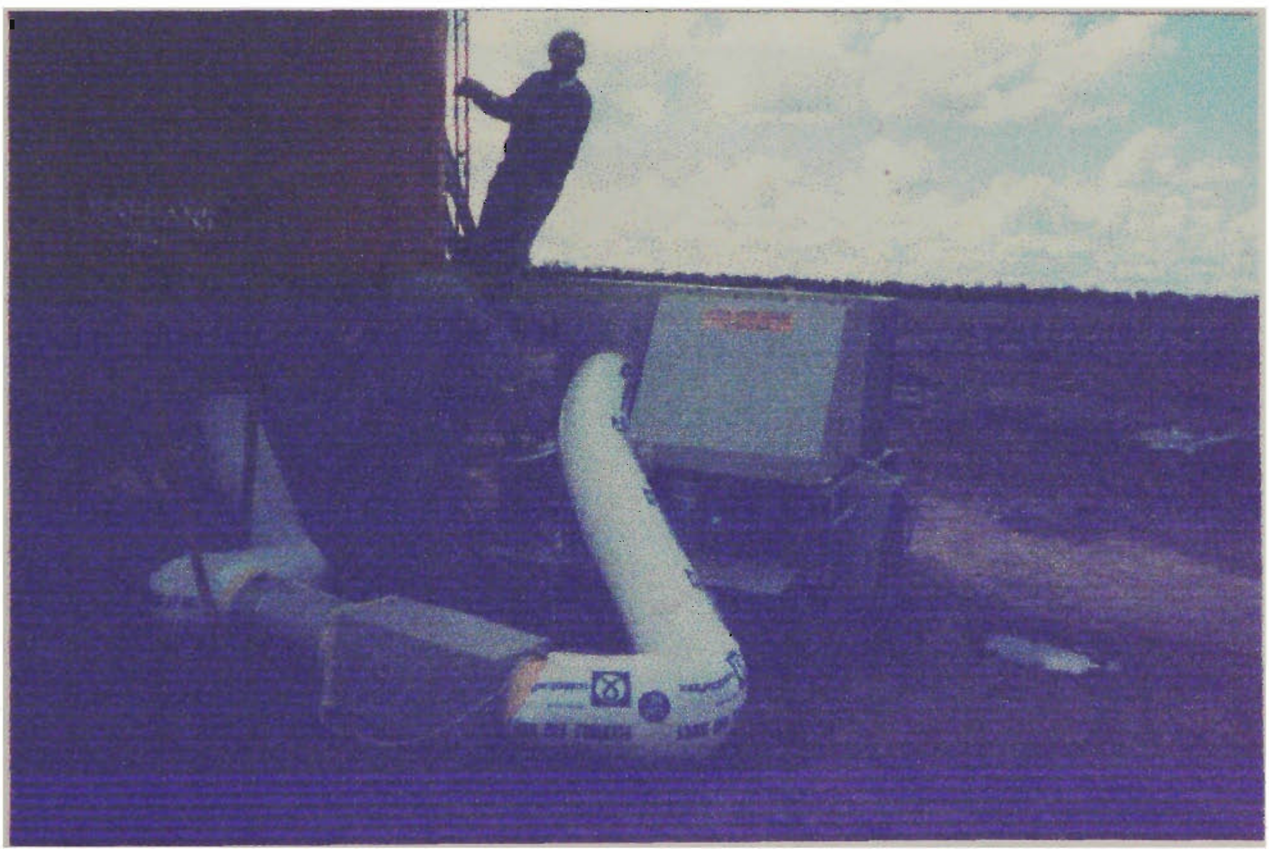


Fig. 4.5 - Drying maize in a field bin at low temperature to prevent cracking of grits using a M[c]Bea Mobile Grain Cooler with an after-heater shown in foreground
Courtesy A E & E M Toynton & Hiltcard Pty Ltd, Blayney, New South Wales

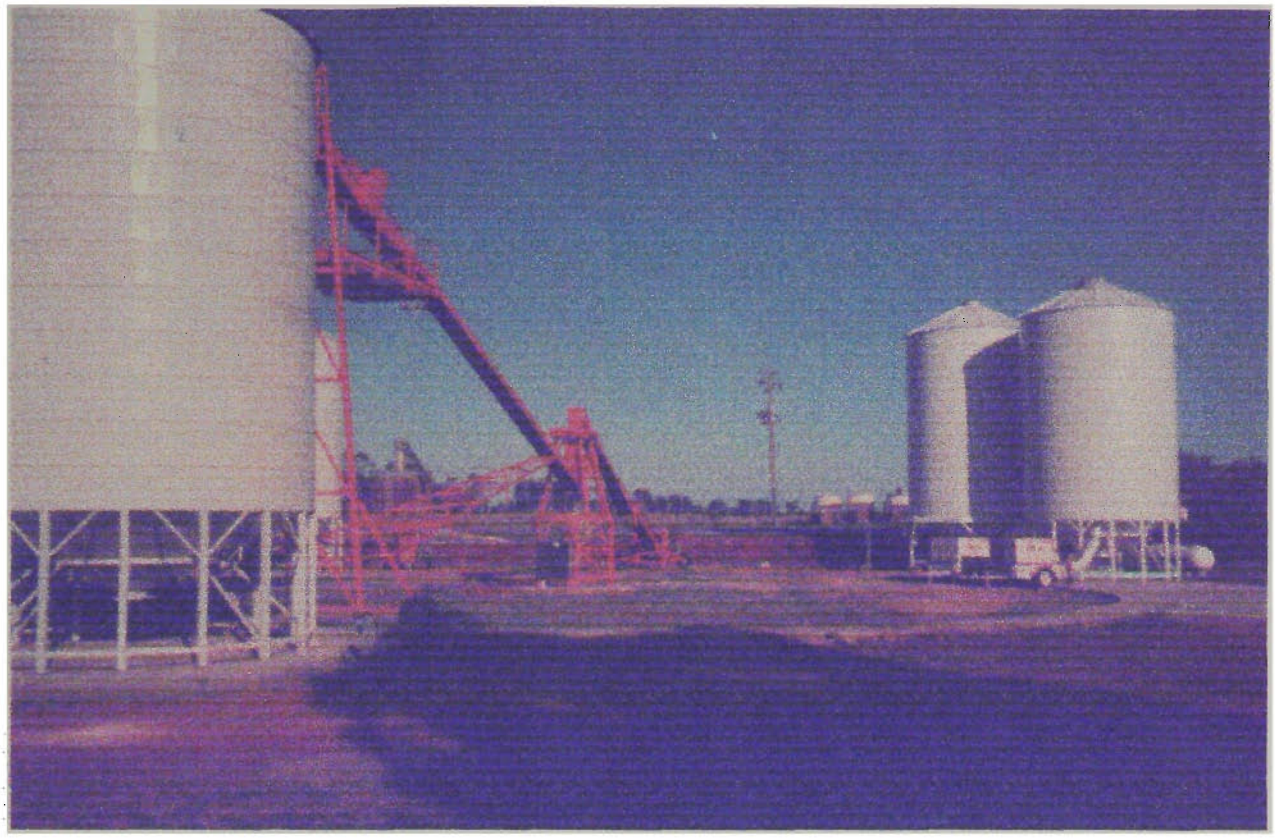


Fig. 4.6 - Maintaining the quality of undesirably moist adzuki beans in 120 tonne steel silos using M^c^Bea Mobile Grain Coolers

Courtesy Buckwheat Enterprises Pty Ltd, Parkes, New South Wales

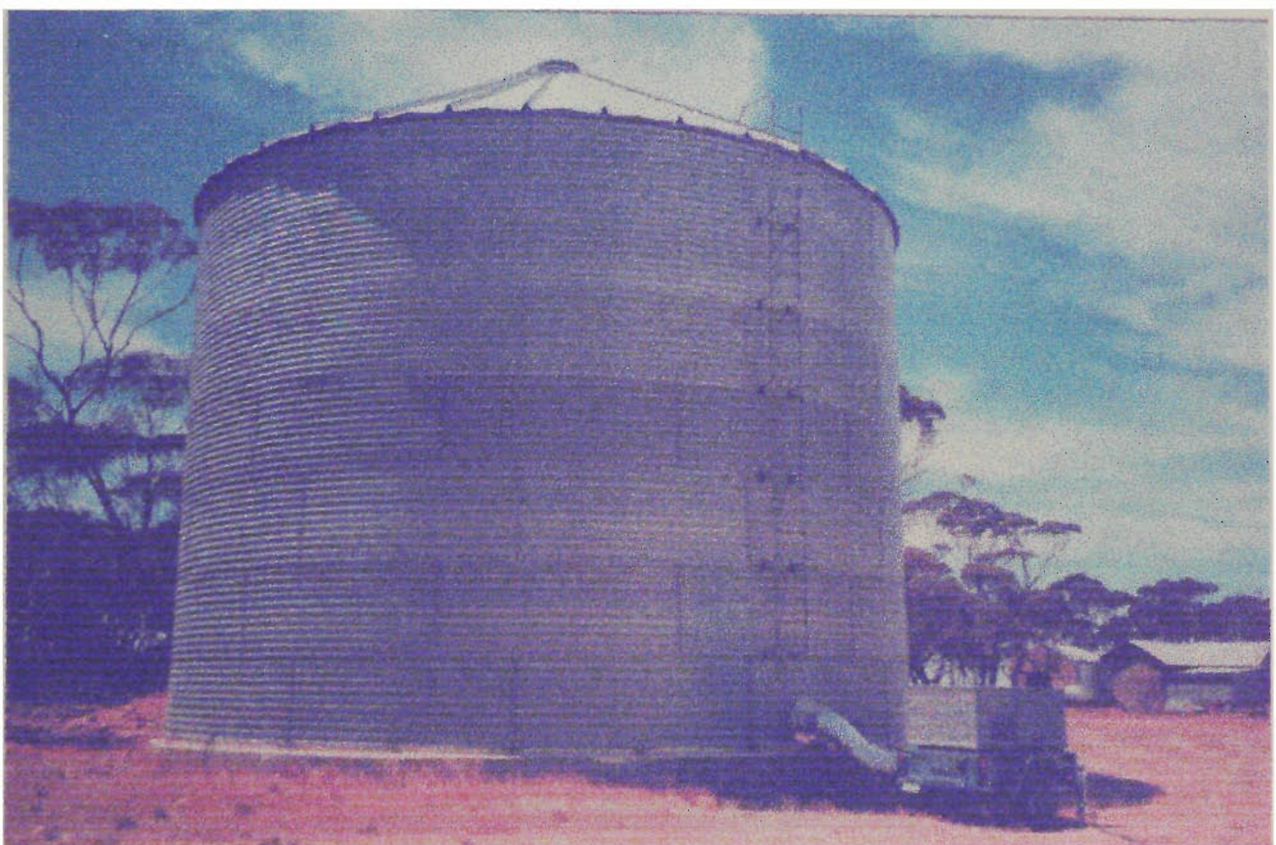


Fig. 4.7 - Cooling wheat in a 700 tonne steel silo where three-phase power is unavailable using a M^c^Bea-Stanley *COOLALL* single-phase grain cooler. Note the long distance from the power point at the shearing shed in the background.

Courtesy Moore Park Pastoral Company, Beulah, Victoria

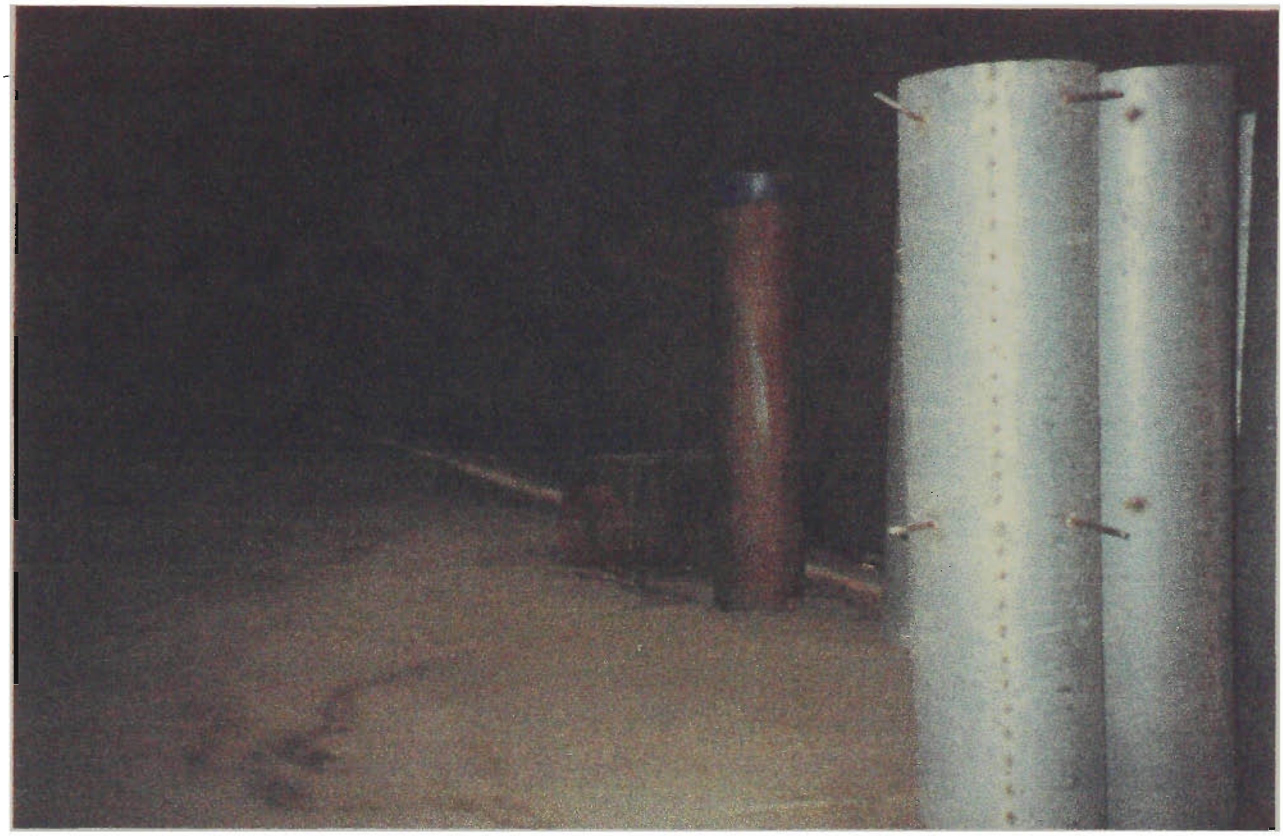


Fig. 4.8 - Perforated metal aeration ducting with strengthening cross bracing rods protruding to inhibit movement of the duct when placed horizontally on the floor.

Fig. 4.9 - Shed-type grain store in which measurements were made during chilling of barley using a McBea Mobile Grain Cooler

Courtesy G & C Cornell, Lockhart, New South Wales

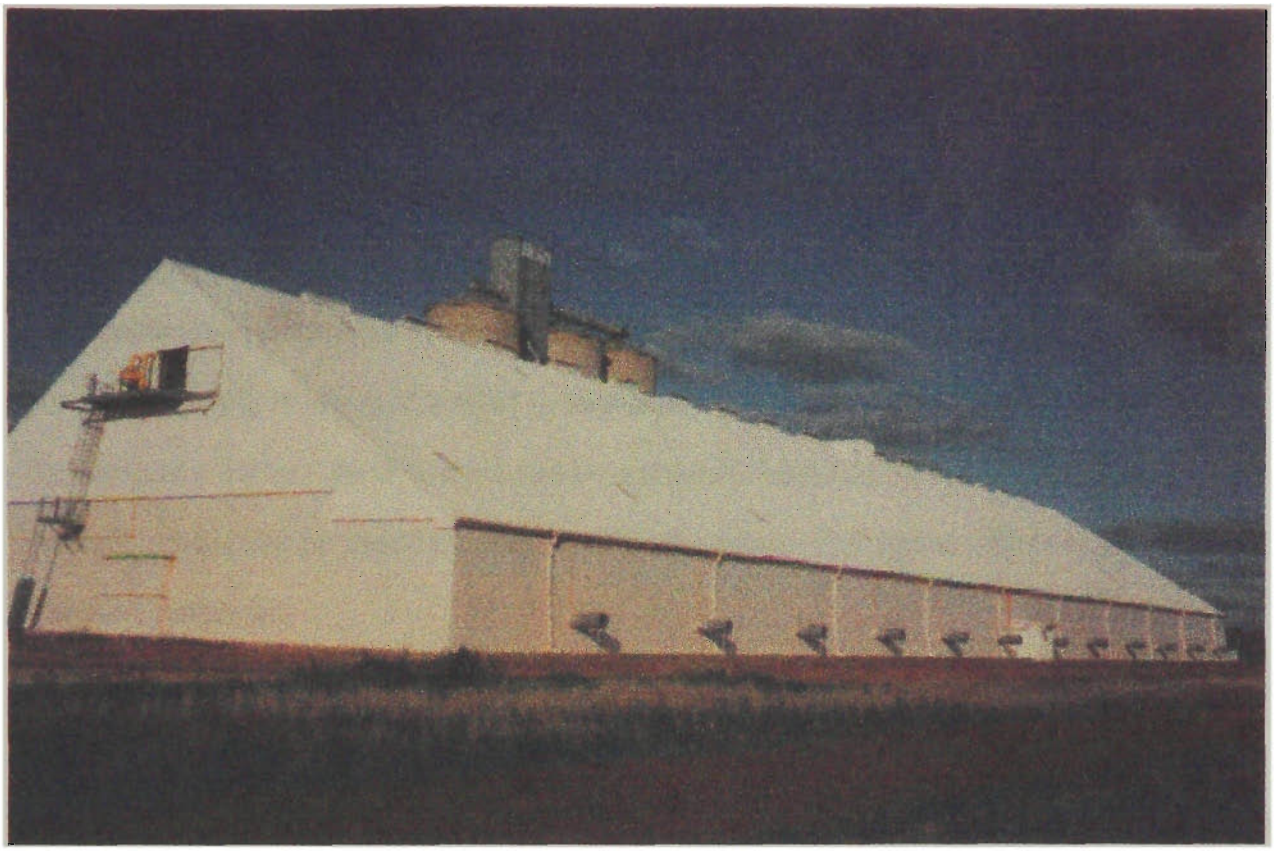


Fig. 4.10 - Large shed-type grain store showing aeration fans to which M^{c}Bea Mobile Grain Coolers can be attached during the summer following harvest for chilling the stored grain
Courtesy Graincorp Limited, New South Wales

monitoring equipment alludes to the wet-bulb temperature which uniquely identifies the rate of multiplication of each species, and enables operators to determine when the bulk has reached the threshold for development of any particular species known to be troublesome at the storage site.

The features of the instrumentation system used to probe various parts of a grain bulk are:-

- Wet-bulb temperature determines rate of insect population growth
- Dew-point temperature determines when the silo will start to sweat
- Water vapour pressure indicates the rate of diffusion of moisture towards the wall and floor
- Air moisture content is a measure of the rate of accumulation of moisture transferred by convection, and of the rate of change in grain moisture content during ventilation of the bulk
- Relative humidity indicates the potential for the development of moulds and is also a measure of the grain moisture content

- The probes comprising a 12mm nylon tube with fittings for insertion and aspiration of the sensor can be pushed many metres into the bulk in any convenient direction
- The sensor can be withdrawn from the probe tube if necessary to check its calibration and then re-inserted thus avoiding the need to remove and force back in the complete probe.
- Field calibration procedure is simple and automatic once the sensor has come to equilibrium
- No power supply is required except to recharge the special battery pack occasionally
- An automatic battery saver feature can be activated if desired
- A single sensor can be used in a number of probe tubes. One spare tube is supplied with the standard starter kit.
- The inserting rods can be withdrawn without dislodging the probe and the single set of rods can thus be used to insert numerous probes.
- The rods, probes and instrument can be carried easily up access ladders, along catwalks and over the grain surface
- All components including the instrument can survive a fall of at least 10 metres without serious damage
- The read-out gives an indication of the periods (from 10 to 80 seconds) for which both the temperature and the humidity have been stable, and the maximum and minimum values that have occurred over the measurement period
- A communications cable with appropriate software is available to connect the instrument to a computer, datalogger, printer or other output or control device

The initial temperature of the barley in the northern section of the shed type grain store studied was high and averaged 40.1°C. The moisture content assessed from measurements at intake of the grain was 11% (wet basis). The corresponding initial grain wet-bulb temperature was 30.4°C. The importance of the wet-bulb temperature of the intergranular air in determining the rate of growth of insect populations is explained in Section 2.5. The operator was particularly concerned to suppress lesser grain borer, and at this initial grain wet-bulb temperature, the population would double every week as indicated by extrapolation of the lower graph of the performance of M^c^Bea Grain Cooler

RM180GC shown in Fig. 2.3. Caution must be exercised in extrapolation since the ability of some species to multiply is limited by high temperatures as for the rice weevil as shown in Fig. 2.2. Comprehensive grain wet-bulb temperature measurements were made on the thirteenth day after the commencement of cooling to assess whether it was time to move the grain cooler to the western duct in the northern end of the shed to cool the grain furthest from where the refrigerated air had been entering the bulk. Comparisons between experimentally measured grain temperatures and those predicted by the mathematical model are made in Chapter 5. The value of the mathematical model in providing a scientific basis for the decision to move the grain cooler is highlighted in Section 5.3.

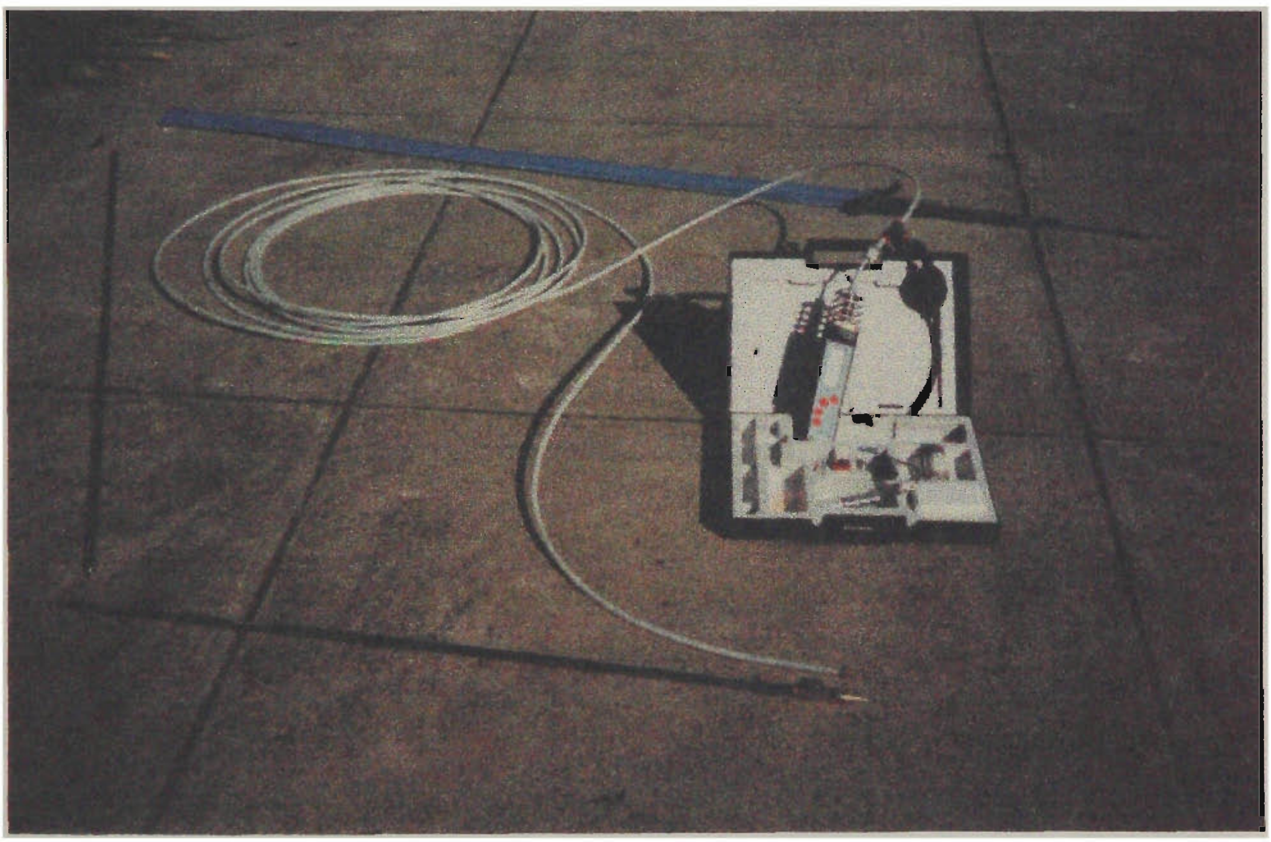


Fig. 4.11 - Components of M^cBea Services MS1 Deep Probe Wet-bulb Temperature Measuring System showing read-out instrument connected to 15m probe cable with associated inserting rods in carry bag and calibration cell in instrument carry case

Courtesy M^cBea Services, Melbourne, Victoria

CHAPTER 5

5. OPTIMISING POTENTIAL OF THE MODEL FOR DESIGN AND CONTROL

5.1 INTRODUCTION

In chapters 2 and 3 a detailed mathematical model of the stored grain ecosystem was developed. In this chapter, predictions by the model are compared with experimental measurements and used to optimise the operation of a commercial grain cooling unit developed by the candidate and described in Chapter 4. The potential of the model for not only optimising the strategic management of the mobile grain cooling plant, but also its performance is outlined. The opportunities for approaching grain cooling system design problems in a more fundamental way using the model are highlighted with particular reference to duct layout design which is currently dependent on predominantly empirical methods.

5.2 DUCT LAYOUT

The location of air distribution ducting on the floor of grain stores has been largely arbitrary with guidelines recommended by Holman (1966) based on air flow distribution considerations and practical experience. The model developed as a result of this research permits designers to examine the effects of different duct locations and layouts on insect populations or other indices of quality control, thereby identifying the layout which, under given climatic conditions, will minimise the quality loss parameter selected. This optimum will probably be largely independent of the air flow through the grain, and could well be also substantially independent of quality loss parameters most of which respond directly to the general thermodynamic performance of the cooling system. The model could therefore be used to maximise the rate of heat loss from the grain bulk as used by Hunter (1986a) for aeration systems using naturally occurring atmospheric air. The model's predictions will be an improvement on those of Hunter (1986a) because peripheral effects are taken into account, non-uniform initial temperatures and moisture contents throughout the bulk can be accommodated and the cyclical effects of outside ambient temperature are included. Importantly, the model is truly two-dimensional, and this represents a significant improvement on most models developed to date. Any other design parameter which interacts with quality control phenomena, the dimensions and construction of the grain store, local weather conditions or cost can be examined using the model to optimise the design.

5.3 AIR FLOW

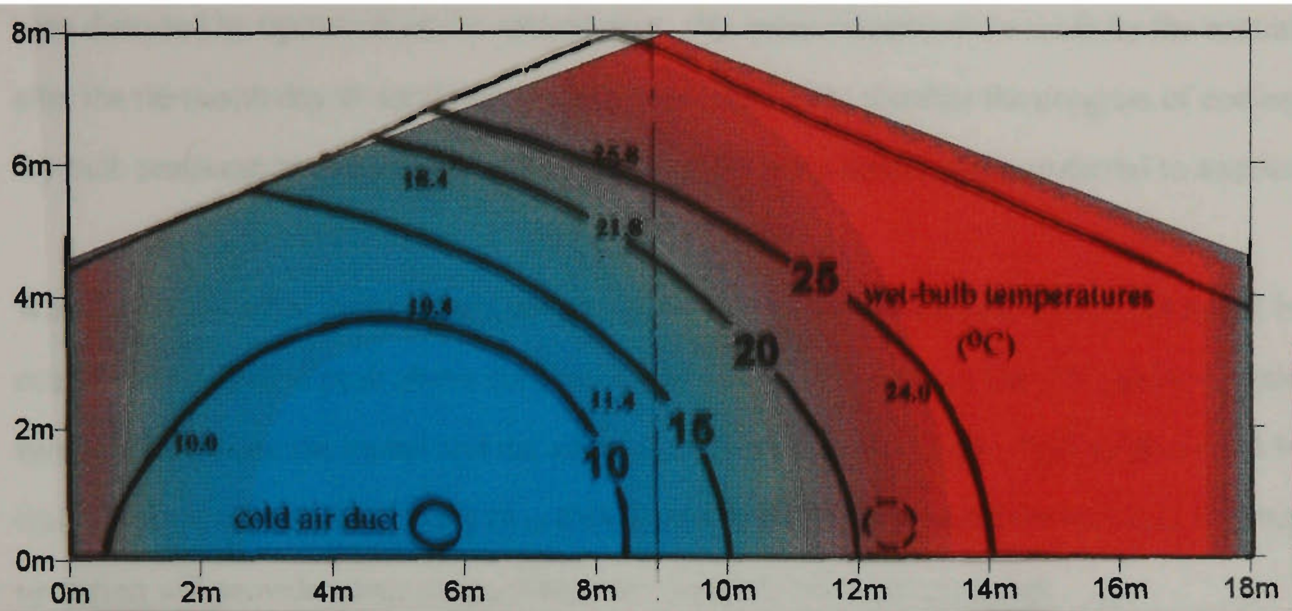
The selection of the specific air flow per unit mass of grain for aeration systems is also largely an arbitrary choice. For example it could be based on the time to cool so as to prevent emergence of adult insects from eggs in the grain at the start of cooling, limitations to the power available, cost considerations or climatic data. In Australia, rates have ranged from around 0.6 to 2 litres per second per tonne of silo capacity with the higher rates being preferred in recent times (Desmarchelier and Wilson, 1993). The lower rates were used in the 1960's to maintain germination of malt grade barley at moisture contents above the then acceptance limit of 12% (wet basis), and for experiments on wheat described by Sutherland (1966 and 1969) and Elder and Sutherland (1970). The model now permits designers to examine the effects of differing fixed air flows on the deterioration of viability or other index of quality, or on insect population growth over a given time under the influence of specific climatic conditions and fan control systems.

The optimum air flow may well change over the storage period and, for natural aeration systems under the control of an atmospheric air thermostat, the operating time for the fan may be varied to compensate for this by adjusting the thermostat set-point accordingly. When using "time-proportioning" control described by Griffiths and Elder (1971), the rates of adjustment of the thermostat set-point could be determined by an optimising model forming part of the control system. For grain refrigeration plant such as the commercial mobile grain cooler used on the grain store described in Chapter 4 of this thesis, a controller based on the model could be used to modulate the air flow through the cooler to achieve minimum loss of quality under the prevailing climatic conditions. Where climatic data for the site are available, the model could be loaded with this data for estimating the long term effects of various air flows within the capabilities of the plant and taking into account the resistance of the grain bulk and duct work to air flow. A new model of the commercial grain cooler which incorporates a flow control device has been developed recently by the candidate with private research and commercialisation funding and is shown on the right in Fig. 4.2.

5.4 OPERATION OF MOBILE COMMERCIAL GRAIN COOLERS

5.4.1 EXPERIMENT AND PREDICTION

The commercial grain store described in Chapter 4 of this thesis was cooled in December 1993 using the mobile commercial grain cooler also described in Chapter 4. The grain cooling contractor recommended using two coolers with one on each existing aeration duct. The operator, however, chose to hire only one cooler with the intention of moving it from one duct to the next after an appropriate period. The contractor estimated it would take one month to cool the 1500 tonnes of barley involved, and after 13 days revisited the site to assess the progress of cooling. The temperature profiles in Fig. 5.1 were estimated from readings taken at various positions deep in the bulk using commercially available wet-bulb temperature probes (Appendix 4) developed by the candidate specifically for quality and insect control in stored grain. It was then decided to relocate the cooler on to the second duct on the other side of the shed where cooling had been delayed. The model, which was not available at the time, could have been used to investigate the effects on insect population growth of moving the cooler on different dates to determine the optimum date to minimise insect numbers. The commercial grain store dimensions and duct size and locations, the physical properties of the barley and its initial temperature and moisture content, and the climatic data for a weather station in the region were installed in the model, and the operation of the cooler for 13 days simulated. The resulting cooling pattern is shown in Fig. 5.2 and is seen to be in reasonable agreement with the contractor's estimated wet-bulb temperature profiles. The final



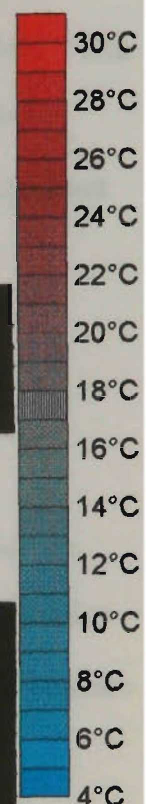


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Fig. 5.1 - Wet-bulb temperature contours after 13 days of cooling via the left side aeration duct estimated from measurements shown which were obtained using special commercially available stored grain monitoring equipment

Courtesy G & C Cornell, Lockhart, New South Wales

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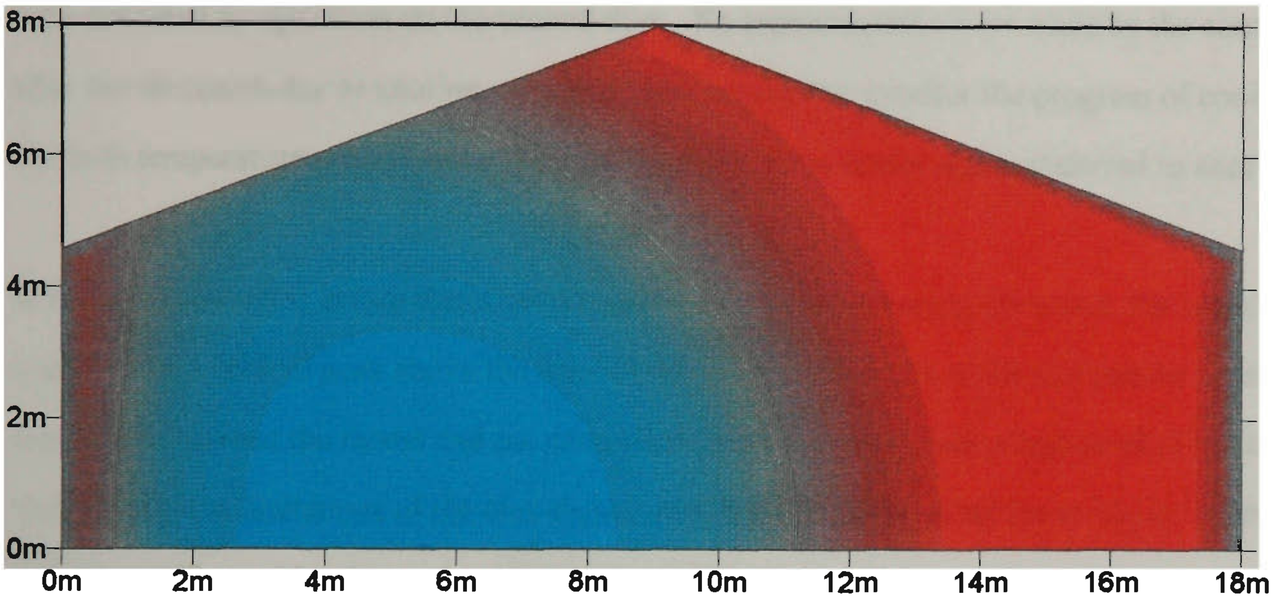


Fig. 5.2 - Predicted wet-bulb temperature pattern after 13 days simulated operation of the cooling plant used on the left side duct of the rural grain store studied

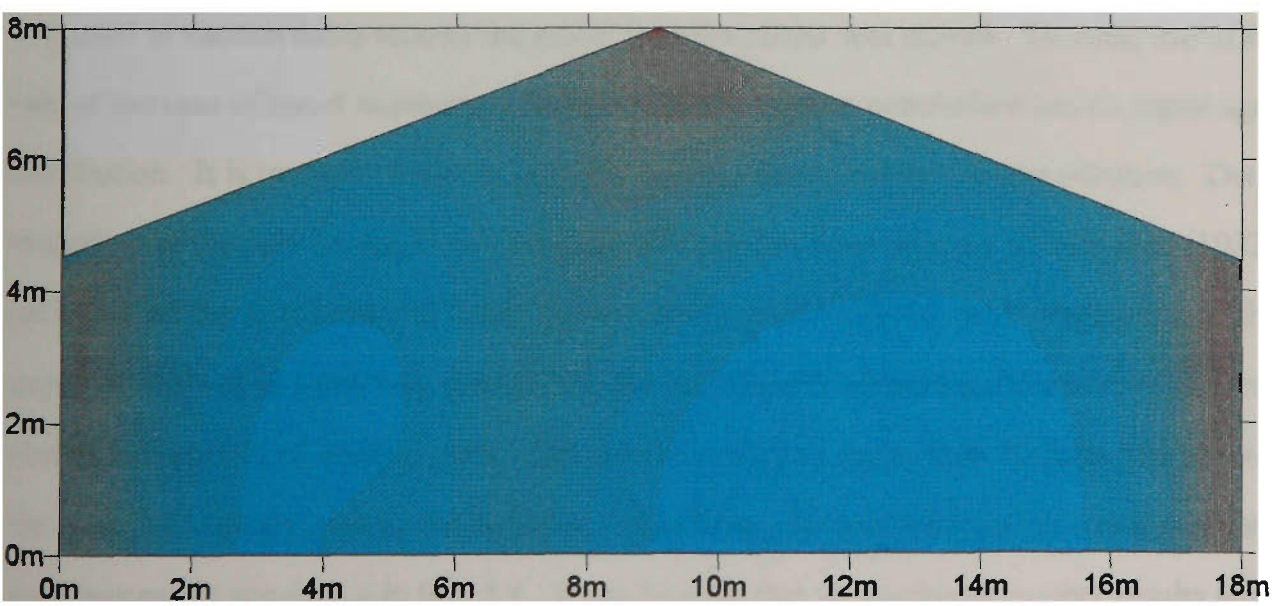


Fig. 5.3 - Predicted wet-bulb temperature pattern after 30 days simulated operation of the cooling plant used on the rural commercial grain store studied with last 17 days on right side duct

pattern of wet-bulb temperatures after an additional 17 days with the grain cooler connected to the other aeration duct is shown in Fig. 5.3. Note how the cold zone generated around the first duct has been distorted by operation on the second duct. No measurements were made by the contractor after the thirteenth day as another party had been engaged to monitor the progress of cooling using dry-bulb temperature probes only. After 30 days, the grain cooler was transferred to another store.

Whereas the model is in two dimensions representing a prone rectangular prism, the actual bulk consisted of a conical peak above the level of the grain at the walls of the rectangular container. The agreement between the model and the actual bulk measurements gives a high level of confidence that, despite the limitations of the two-dimensional configuration, using the model to optimise plant operation will provide adequate guidelines for practical industrial purposes.

5.4.2 MINIMISING INSECT NUMBERS

5.4.2.1 COMMERCIALLY CONSTRAINED OPERATION

The model simulating the above commercial grain cooling operation was then run to calculate the number of insects that would result from an initial infestation of one adult per tonne with the cooler relocated at various dates around the actual date the cooler was moved. To make use of the intrinsic rate of increase of insect numbers, it is implicit that the insect populations have a stable age distribution. It is recognised that in practice this may not represent the true situation. Detailed modelling of the various stages of the insect life cycle has been done by Thorpe *et al* (1982a); but until data on the distribution of insect populations in grain received into storage are available experimentally or in some way predictable, the intrinsic rate seems a good criterion for optimisation studies and control of cooling plant. The numbers of lesser grain borer *Rhyzopertha dominica* (F.), the insect of main concern to the operator, when the cooler was relocated at a range of days after commencement are shown in Fig. 5.4. It can be seen that the minimum number results when the cooler is relocated on day 7. This is a surprising result since most experienced operators would be more likely to conclude that moving the cooler about half way through the cooling process would be close to optimal. The contractor favoured moving it earlier being conscious of the exponential rate

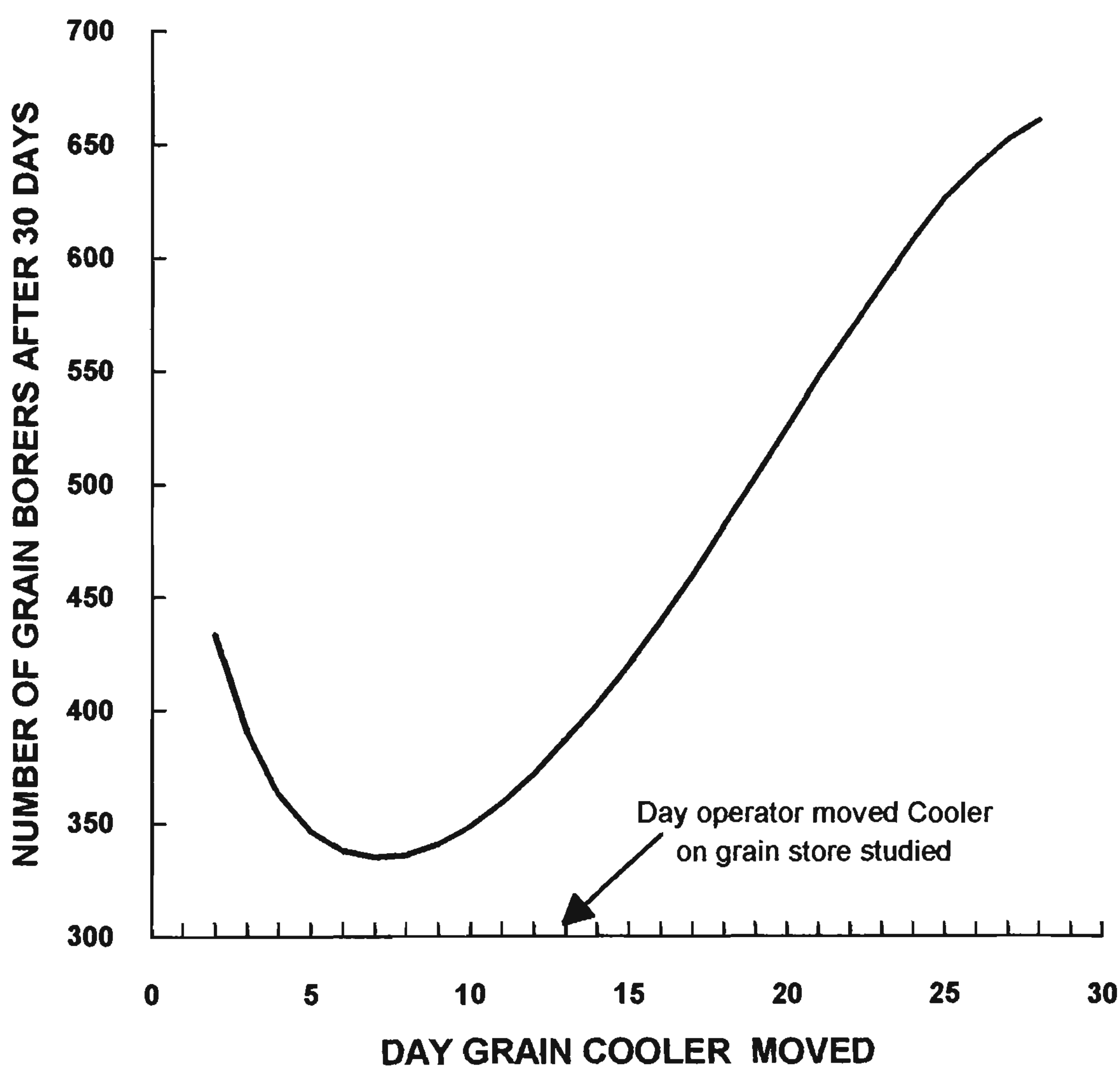
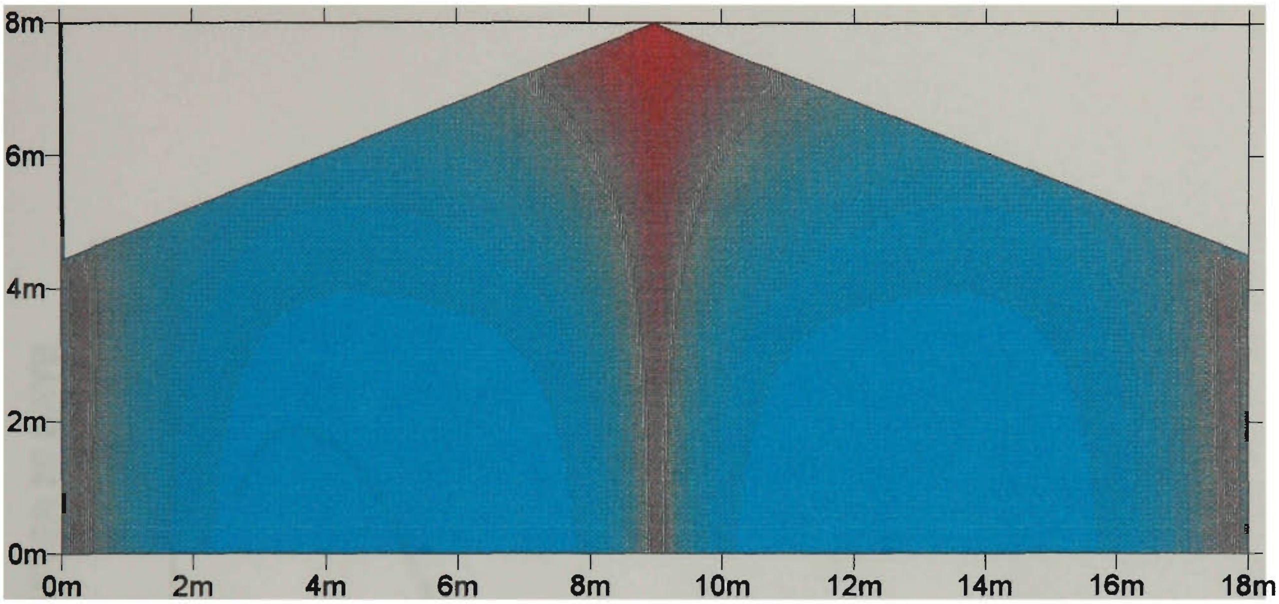


Fig. 5.4 - Effect of the time of relocation of a mobile grain cooler on the population of the lesser grain borer following a 30 day cooling period. Initial insect population was 87. Cooler was moved from the left side aeration duct to the right side of the shed-type grain store

Note: No cooling yields 2177 grain borers of growth of insect populations in the part of the bulk remote from where the cold air was entering; but was still considerably in error. This shows the importance of the model for minimising risk of serious insect infestation, in that it is able to determine optimum operating procedures where an operator has a limited number of grain coolers all required at about the same time of the year, or for budgetary or other extraneous reasons, an operator cannot use the required number of coolers to implement the most efficient cooling.

5.4.2.2 A MORE EFFICIENT COOLING OPERATION

If two grain coolers, one on each duct, were used for 15 days the cooling pattern in Fig. 5.5 results. At the end of the 30 day period, the effect of conduction of heat is seen in Fig. 5.6. There is also a hint of heat generated by respiration of the grain close to the aeration ducts. The number of lesser grain borers after 30 days is only about 10% less than when using one cooler moved on the optimum day. However, the seed viability dropped only 0.1% compared with 0.4% using a single cooler. Furthermore, instead of losing 33% of the pesticide methacrifos if applied, the two cooler operation for 15 days retarded the degradation to only 21% by the 30th day. Overall, using two coolers for half the time provides superior quality control for the same cost. The higher temperatures resulting in the central core when two coolers are used may be of concern if there is a significant amount of fine material present during filling as this may tend to accumulate in this region and provide opportunities for secondary insects to develop. However, the threshold wet-bulb temperatures are higher for these species than for the borers and weevils as shown in Table 2.4. Nevertheless, an operator may opt to use one cooler for longer than the other to skew the temperature distribution in the manner shown in Fig. 5.3 thereby avoiding the central warmer column of grain. There are implications in such considerations for design such as the provision of a near central duct for short term cooling in that region, particularly if this could be implemented while the store is being filled. A skewed duct layout may also have advantages where the western wall of the store is subject to serious solar heating effects compared with the other surfaces of the structure. All of these scenarios can be simulated by the model to determine the optimum design and operating procedures. Mortality was not included, but it may be expected that, although the actual numbers would be different, the optimum operating strategy may not be influenced to any significant extent. An initial non-uniform



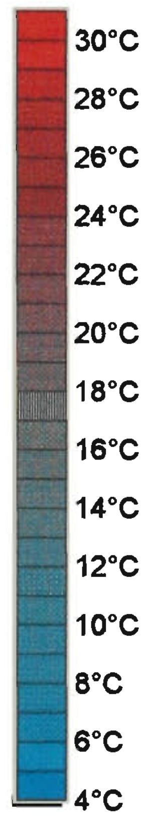


Fig. 5.5 - Predicted wet-bulb temperature pattern after 15 days simulated operation of two mobile grain coolers, one on each aeration duct of the rural commercial grain store studied.

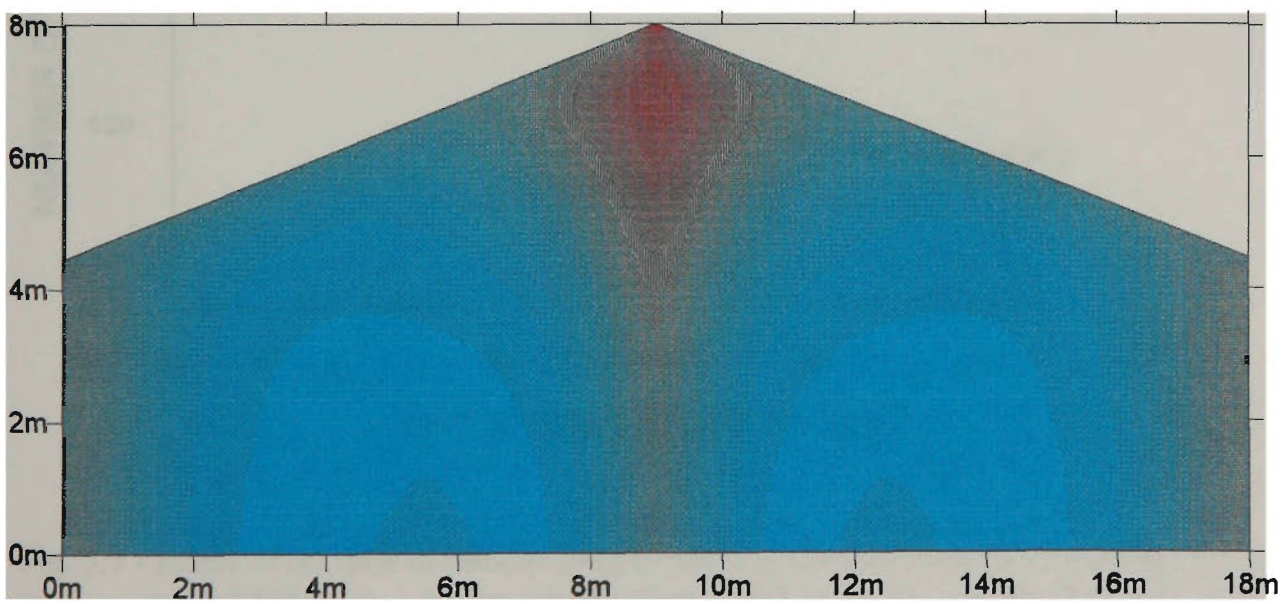


Fig. 5.6 - Predicted wet-bulb temperature pattern after an additional 15 days with no cooling showing the effects of conduction of heat near the walls and in the centre of the grain bulk in the rural commercial grain store studied.

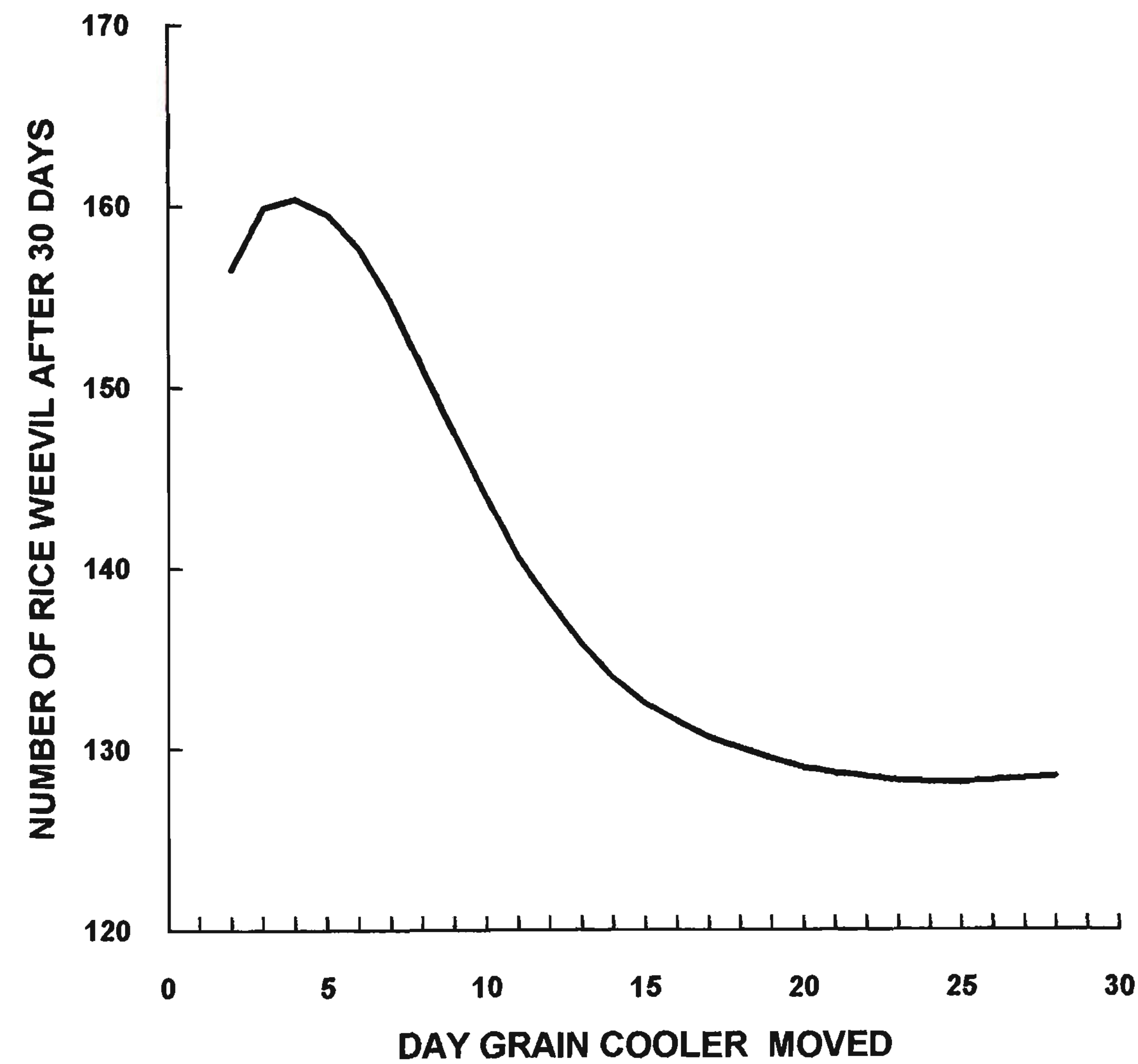


Fig. 5.7 - Effect of the time of relocation of a mobile grain cooler on the population of the rice weevil following a 30 day cooling period. Initial insect population was 87. Cooler was moved from the left side aeration duct to the right side of the shed-type grain store

Note: No cooling yields 119 rice weevils. The initial high temperature inhibits population growth, the increase in numbers occurring only at the periphery of the bulk subject to lower ambient temperatures

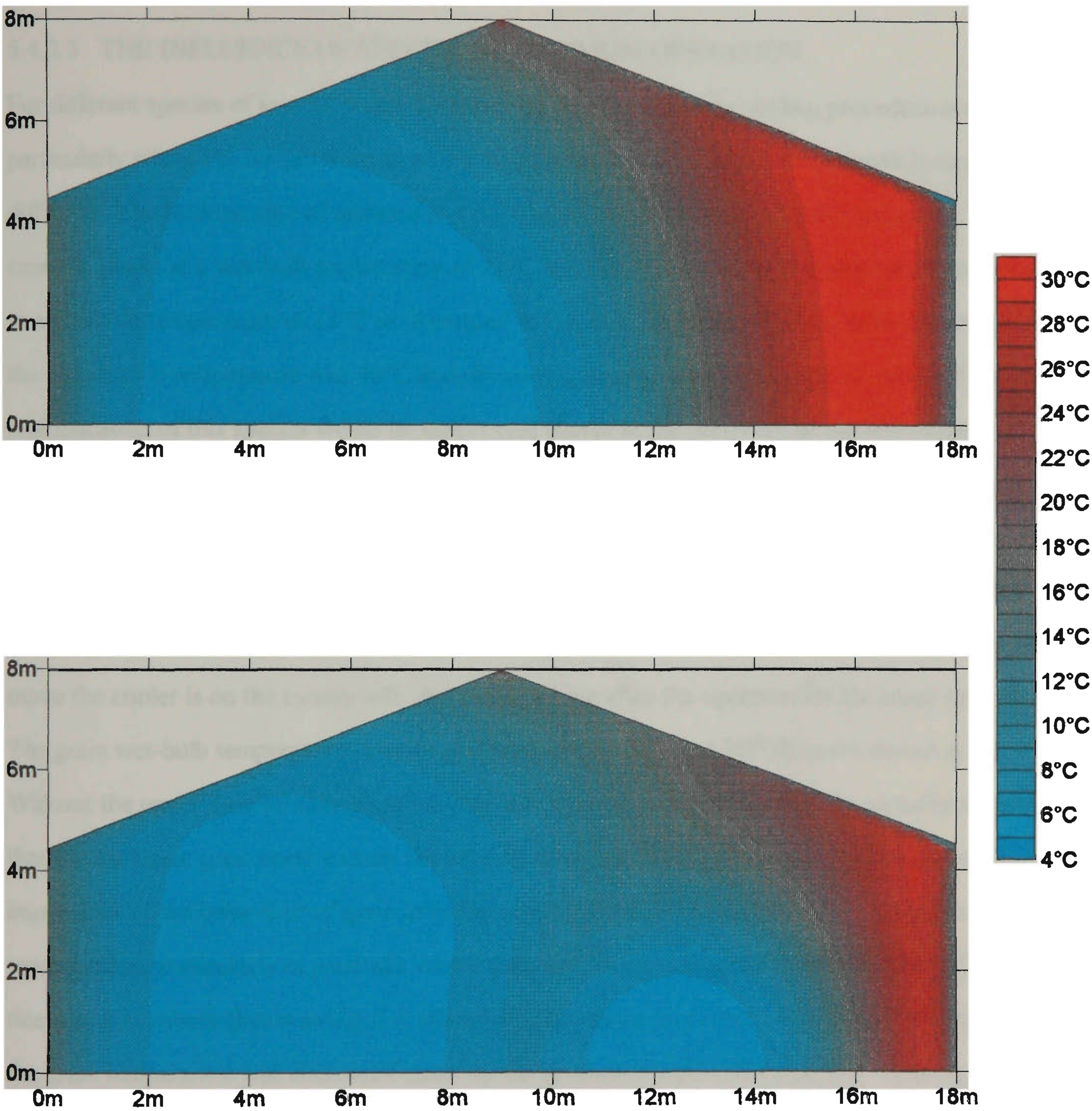


Fig. 5.8 - Predicted wet-bulb temperature patterns after 25 days of cooling via the left side aeration duct (top) and after an additional five days on the right side aeration duct (bottom) - optimum cooling strategy for minimising the number of rice weevils

distribution of insects also may not have any appreciable effect on the optimum. The model can be run for all these situations.

5.4.2.3 THE INFLUENCE OF SPECIES ON OPTIMUM OPERATION

For different species of insects, it may be expected that the optimum cooling procedure may vary particularly where the temperature at which the maximum rate of population growth is significantly different. The intrinsic rate of increase in a population of rice weevil *Sitophilus oryzae* (L.) for example peaks at a wet-bulb temperature of 23°C and declines at higher temperatures to no growth at a dry-bulb temperature of 33°C as illustrated in Fig. 2.1. In the 1500 tonne bulk of barley studied, the initial grain temperature was 40°C and the corresponding wet-bulb temperature was 31°C, thus multiplication of this species would be suppressed except at the periphery of the bulk subject to cooling to the outside temperature. As the bulk is cooled by through flow of chilled air, the rate of multiplication increases initially as the grain temperature falls to the lower threshold of 9.8°C wet-bulb (Desmarchelier, 1988). The number of rice weevils at the end of the 30 day cooling period resulting from relocating the grain cooler at different days is shown in Fig. 5.7. The optimum time to move the cooler is on the twenty fifth day which is long after the optimum for the lesser grain borer. The grain wet-bulb temperature patterns predicted on the 25th and 30th days are shown in Fig. 5.8. Without the upper limit of multiplication imposed, the optimum was found to be virtually the same as that for the lesser grain borer namely the seventh or eighth day. This demonstrates the critical importance of the behaviour of grain infesting insects above the temperature for maximum reproduction, particularly in Australia where such conditions are typical at harvest time. The peak in rice weevil numbers shown in Fig. 5.7 when the grain cooler is moved on the fourth day signifies that the grain temperature was decreased closer to the maximum rate of increase, and removing the cooler at this time permitted multiplication close to this rate in a considerable proportion of the grain over the left side air distribution duct.

Where it is desired to minimise the total population of all species likely to be present to reduce the risk of detection by a buyer's inspector, the numbers for each species simulated can be summed to determine the optimum day on which to move the grain cooler. The optimum day for the total of

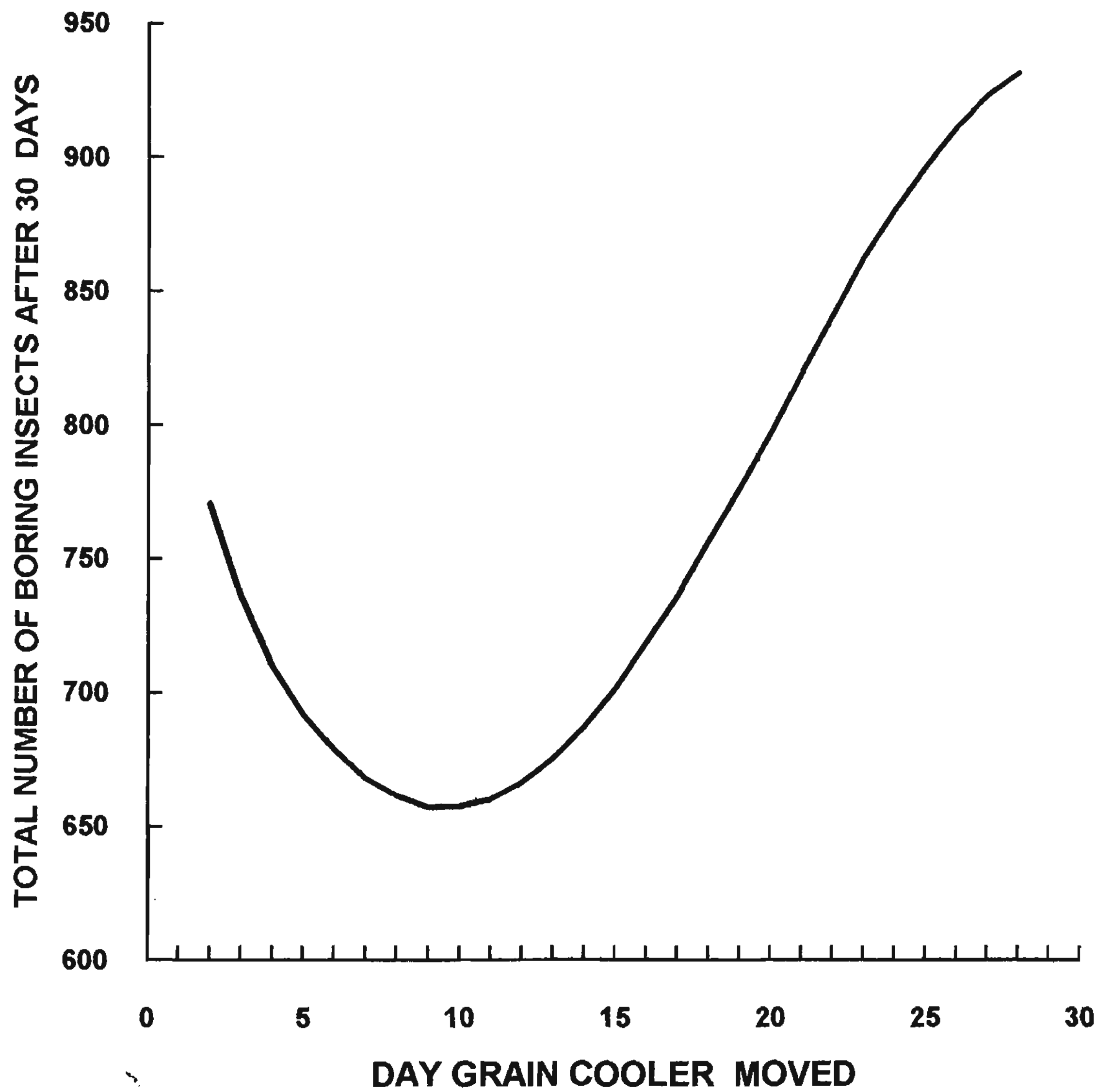


Fig. 5.9 - Effect of the time of relocation of a mobile grain cooler on the population of three species of grain boring insects following a 30 day cooling period. Initial insect population was 87 of each species. Cooler was moved from the left side aeration duct to the right side of the shed-type grain store

Note: No cooling yields 2427 grain boring insects lesser grain borers plus two strains of rice weevil is shown in Fig. 5.9.

5.4.3 LOCATING POTENTIAL PROBLEMS

The model can also be used to locate zones in the bulk where insect numbers will be the greatest thus providing direction to quality control personnel who generally examine the whole surface region on a regular basis. This then provides the opportunity to reduce inspection costs. It also shows where spot cooling using portable screw-in aerator tubes as shown in Fig. 5.10 could be used to complement the general cooling provided by mobile plant particularly if it is required urgently elsewhere before the bulk has been brought down to the target temperature. The pattern of multiplication ratios for populations of the lesser grain borer after cooling for 30 days moving the grain cooler on the optimum day for minimising borer numbers is shown in Fig. 5.11. The corresponding pattern for a population of the rice weevil is shown in Fig. 5.12, but it should be remembered that the grain cooler was not moved on the optimum day for minimising weevil numbers. The pattern of multiplication ratios for the rice weevil when the cooler is moved on the 25th day, the optimum for minimising weevil numbers, is shown in Fig. 5.13. This pattern shows that weevils may be present deep in a central region of the bulk inaccessible to inspectors, and it therefore may be preferable to move the grain cooler on a date which would enhance detection. The case shown in Fig. 5.12 is one example of this. The multiplication ratios show that the lesser grain borer becomes the dominant species.

5.4.4 MINIMISING OTHER QUALITY LOSSES

The model also incorporates equations and data for optimising loss of viability of seed, breakdown of applied insecticides, loss of dry matter in the case of aerating wet grain, and is capable of optimising any other parameter for which its relationship to temperature and moisture content are known. The model is to be used by the grain silo cooling contractor when encountering applications in which, for non-technical reasons, the operation of cooling plant will be less than ideal, or in other circumstances where manipulation of the model will assist in grain protection consulting work.

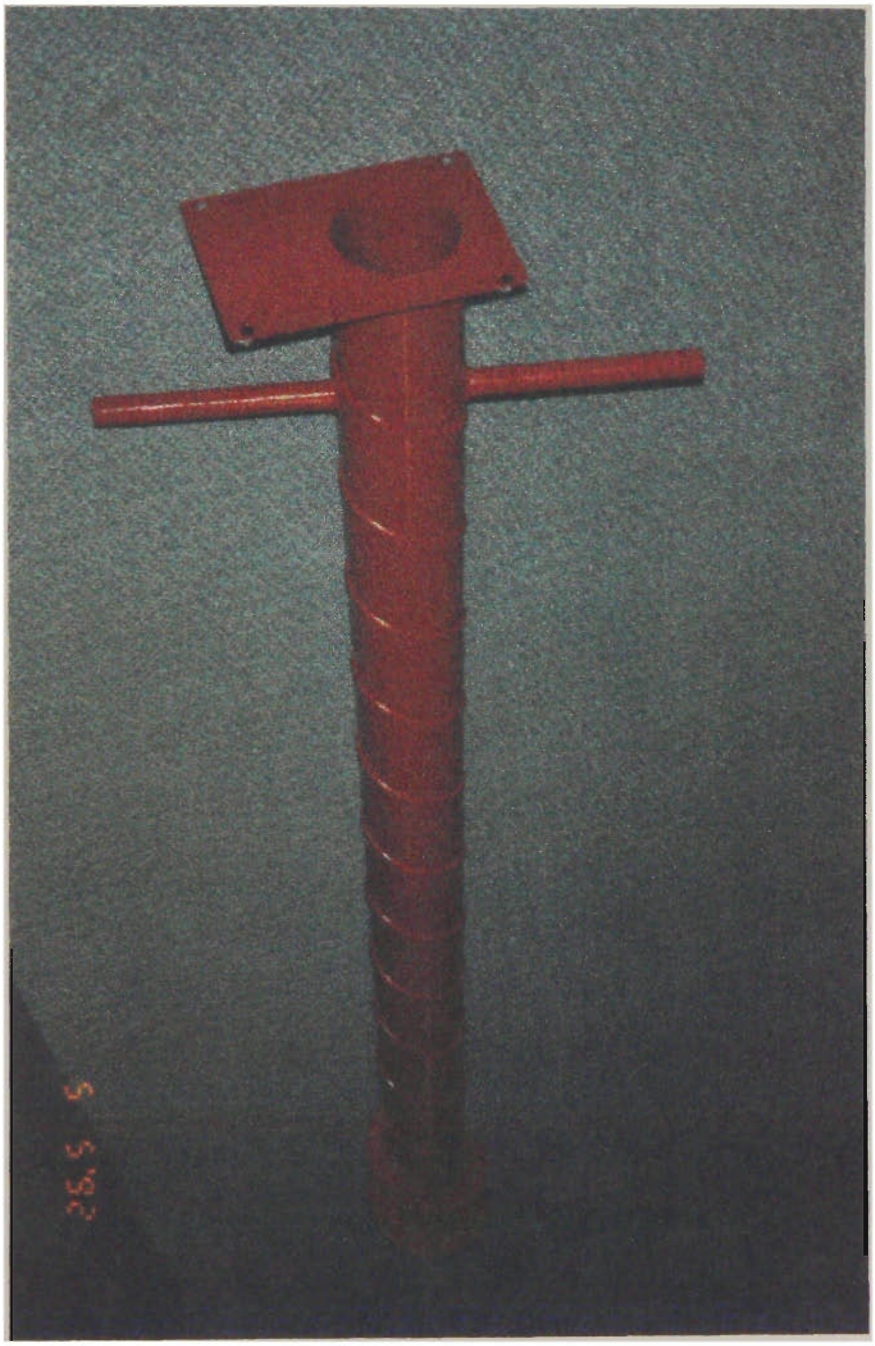


Fig. 5.10 - Portable screw-in aeration tube for spot cooling using a fan to either force air into or induce air from localised regions of a grain bulk

Courtesy Agridry Rimik Pty Ltd, Toowoomba, Queensland

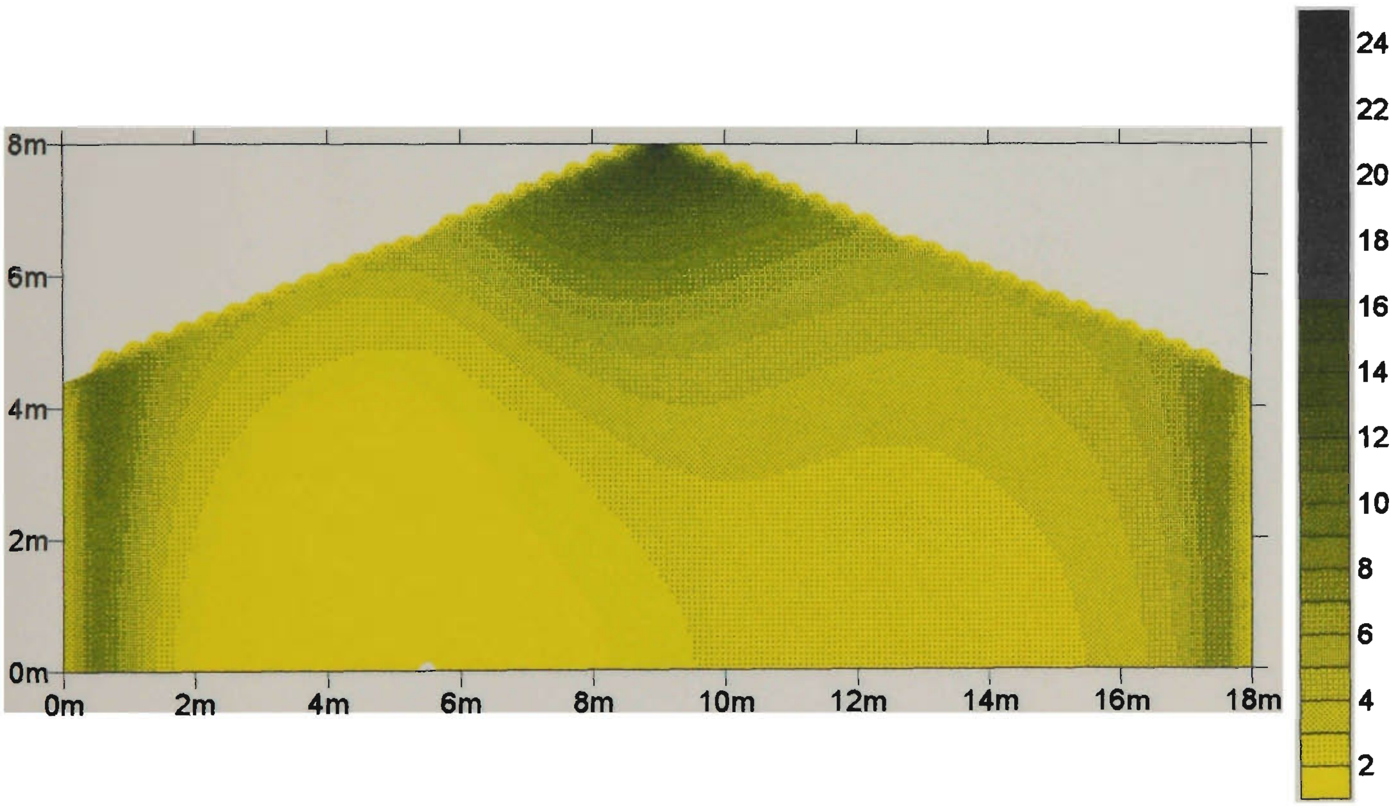


Fig 5.11 - Pattern of multiplication ratios for an initial uniformly distributed population of lesser grain borers after 30 days of cooling with the simulated mobile grain cooler relocated from the left to the right side aeration duct on the optimum (7th) day for minimising numbers.

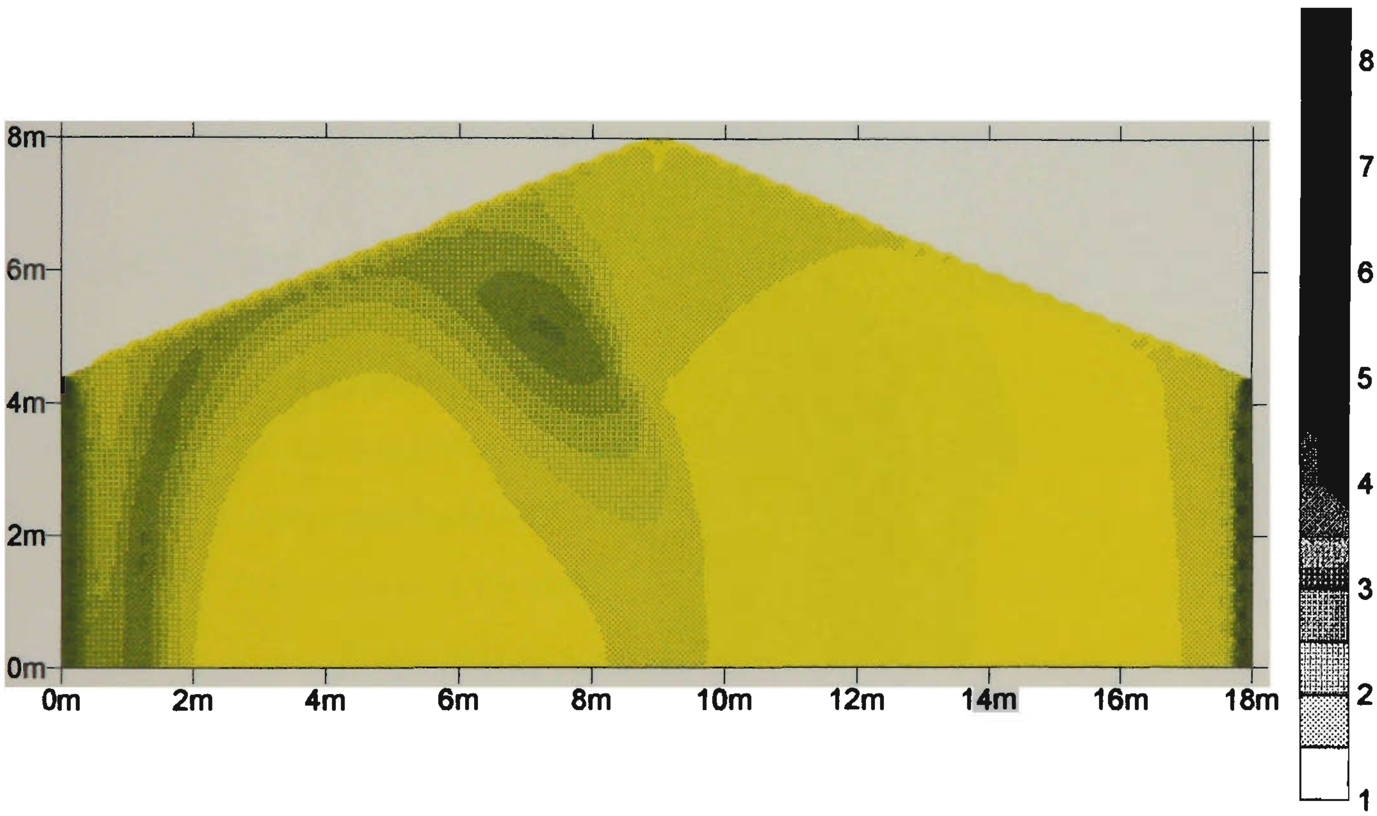


Fig 5.12 - Pattern of multiplication ratios for a initial uniformly distributed population of rice weevils after 30 days of cooling with the simulated mobile grain cooler relocated from the left to the right side aeration duct on the 7th day (not optimum for rice weevil control)

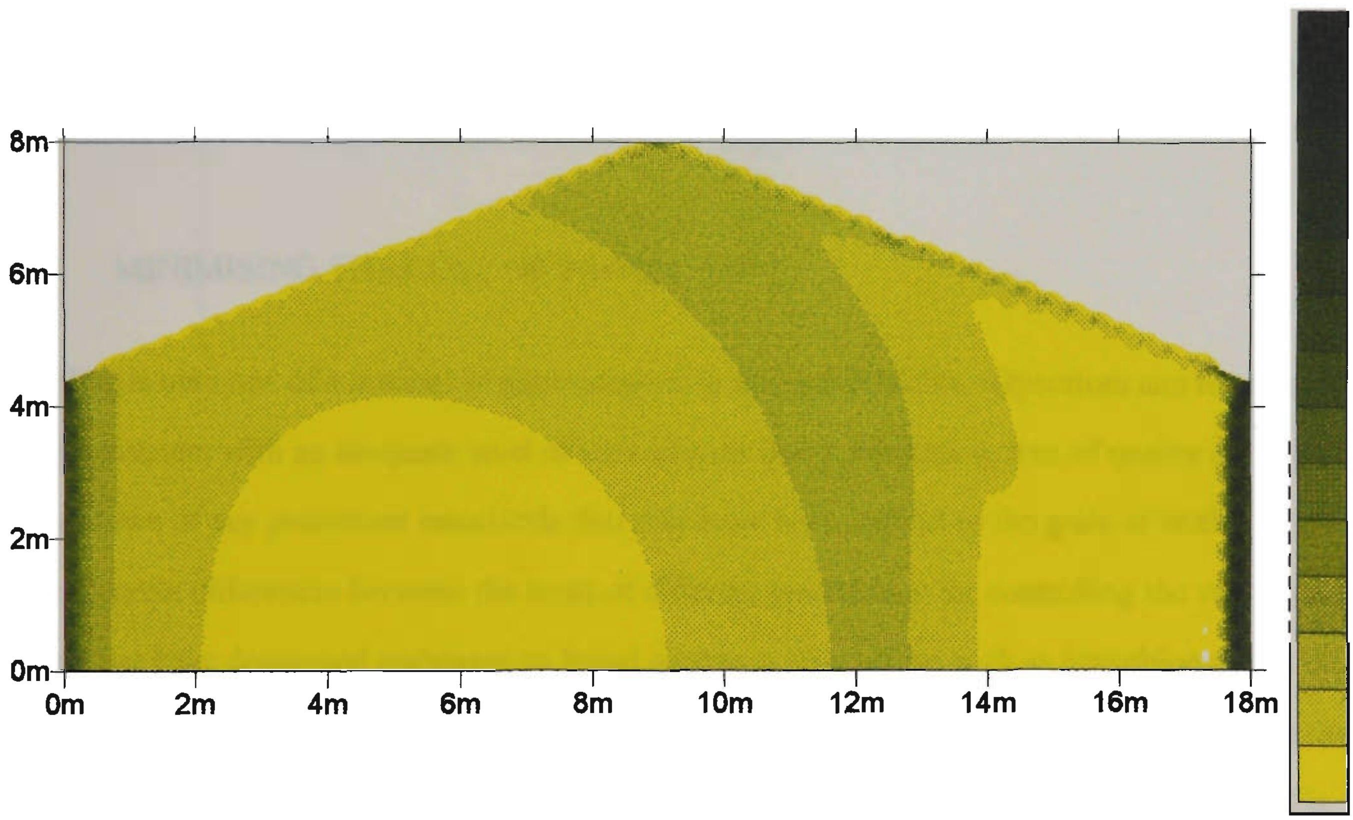


Fig 5.13 - Pattern of multiplication ratios for a initial uniformly distributed population of rice weevils after 30 days of cooling with the simulated mobile grain cooler relocated from the left to the right side aeration duct on the optimum (25th) day for minimising numbers.

5.4.5 LONG-TERM EFFECTS

In the optimisation procedure adopted in this Section, the numbers of insects at the end of the cooling contract has been the objective function; however, the model can be run beyond the date on which the grain cooling plant is removed to examine the long term effects of different cooling procedures on the various indices of quality simulated. A short-term example of this capability of the model is demonstrated in Figs 5.5 and 5.6 where the cooling ceased after 15 days and the model continued to calculate the heat and moisture exchanges with no air flow over a subsequent 15 days. Corresponding insect multiplication ratios, pesticide residues, germination etc for the total period are generated, and are indicated for the case above in Section 5.4.2.2.

5.5 MINIMISING THE COST OF PROTECTION

Cooling is only one of a number of grain protection options available. Operators aim to minimise cost consistent with an adequate level of control over insect infestation, loss of quality and the breakdown of any protectant insecticide that may have been applied to the grain at intake. There are considerable differences between the costs of different insecticides for controlling the various insect types that have developed resistance to broad spectrum insecticides such as Malathion which was introduced into the Australian grain industry in 1963. The optimum day on which to relocate the grain cooler from one duct to the other under the grain in the shed-type grain store simulated is shown by the maximum residue after 30 days of cooling for each of four pesticides in common use. Bioresmethrin to control lesser grain borer is a costly substance so an operator may decide to use cooling for this pest and rely on fenitrothion, a much cheaper pesticide, to control rice weevil and other insect pests not yet resistant to organophosphorus insecticides. It is seen from Fig. 5.14 that the optimum day for moving the grain cooler to minimise the loss of fenitrothion is the sixth day which is very close to the optimum for minimising the growth of populations of lesser grain borer using cooling as shown in Fig. 5.4. This strategy may prove to be the least cost combination for insect control. The total treatment cost could be optimised by the model given the ruling electricity tariff and pesticide purchase costs. M^cBea Grain Protection Services' clients are currently reporting electricity costs of between 72 cents and $1.60 per tonne of grain cooled, and combined protectant

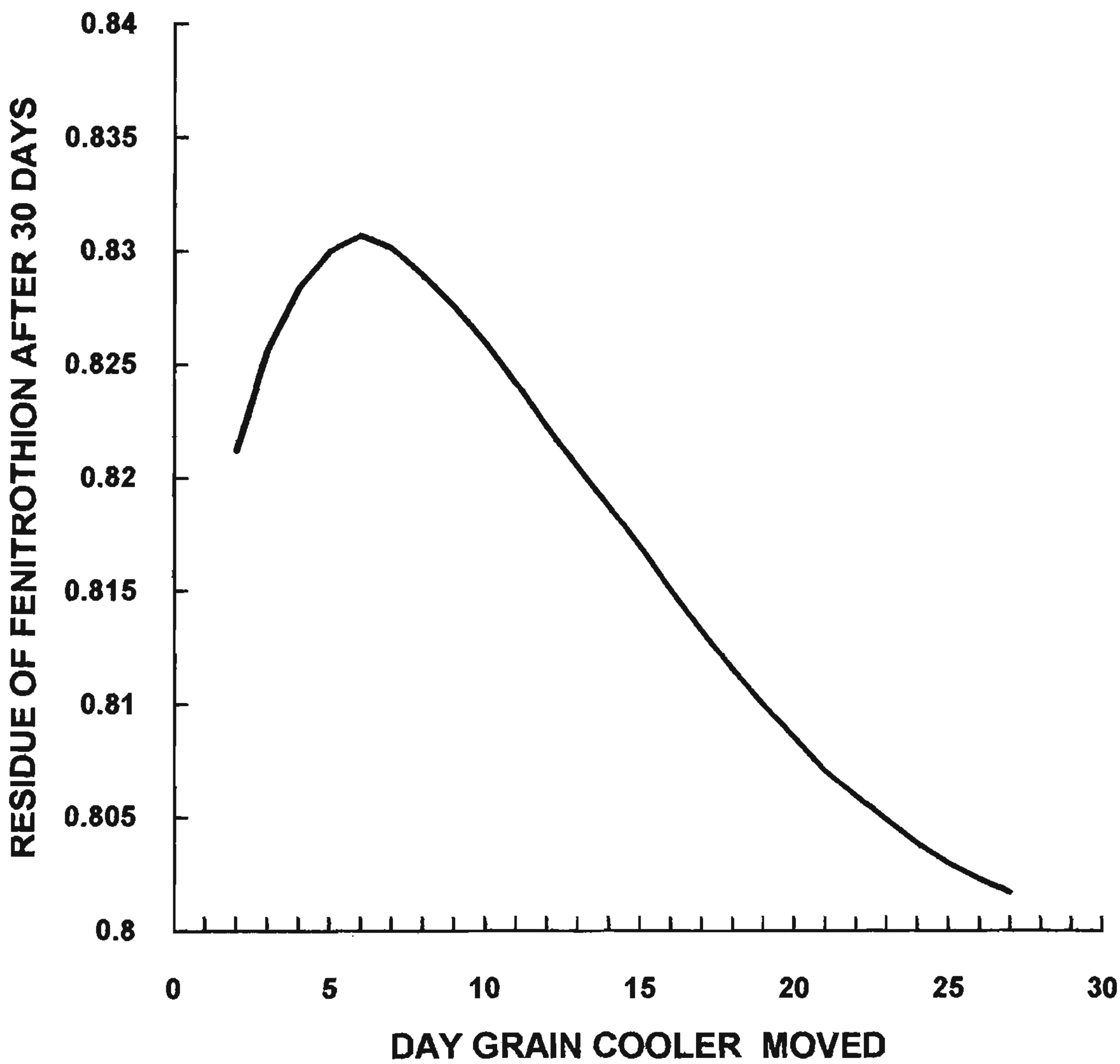


Fig. 5.14 - Effect of the time of relocation of a mobile grain cooler on the concentration of the pesticide fenitrothion following a 30 day cooling period. Initial concentration 1mg/kg. Cooler was moved from the left side aeration duct to the right side of the shed-type grain store

Note: No cooling yields 0.6263 mg/kg

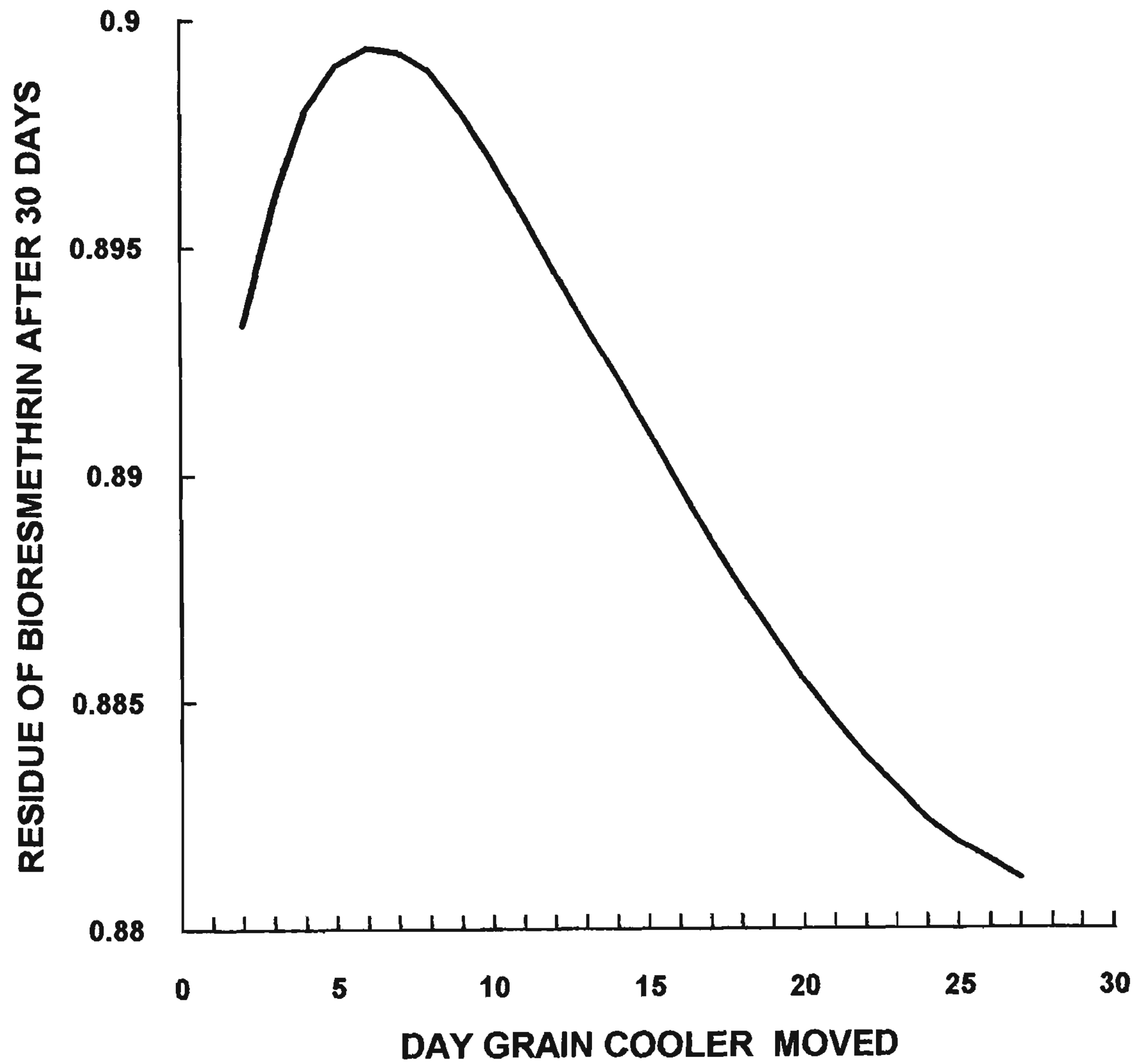


Fig. 5.15 - Effect of the time of relocation of a mobile grain cooler on the concentration of the pesticide bioresmethrin following a 30 day cooling period. Initial concentration 1mg/kg. Cooler was moved from the left side aeration duct to the right side of the shed-type grain store

Note: No cooling yields 0.7732 mg/kg

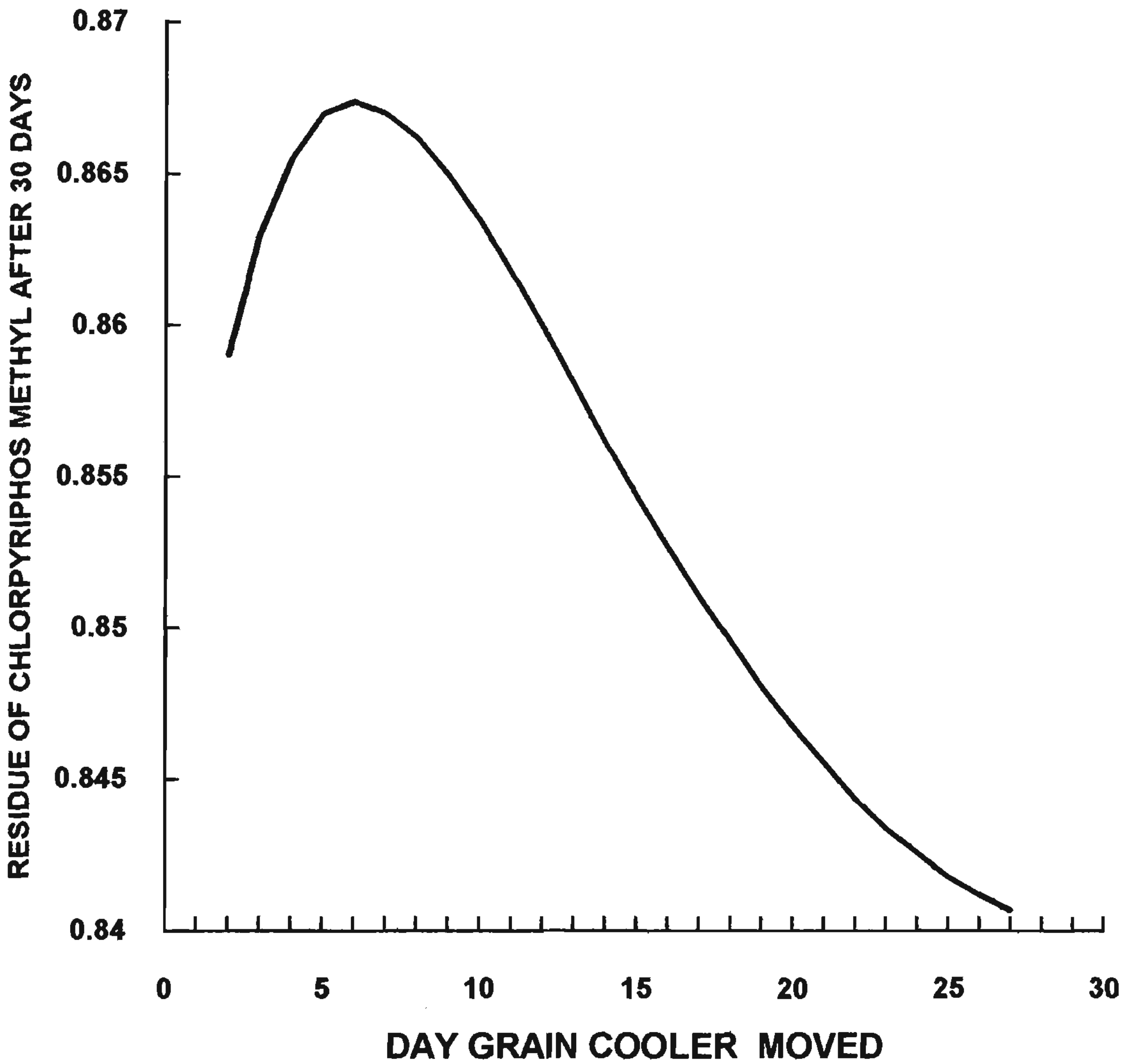


Fig. 5.16 - Effect of the time of relocation of a mobile grain cooler on the concentration of the pesticide chlorpyriphos methyl following a 30 day cooling period. Initial concentration 1mg/kg. Cooler was moved from the left side aeration duct to the right side of the shed-type grain store

Note: No cooling yields 0.6864 mg/kg

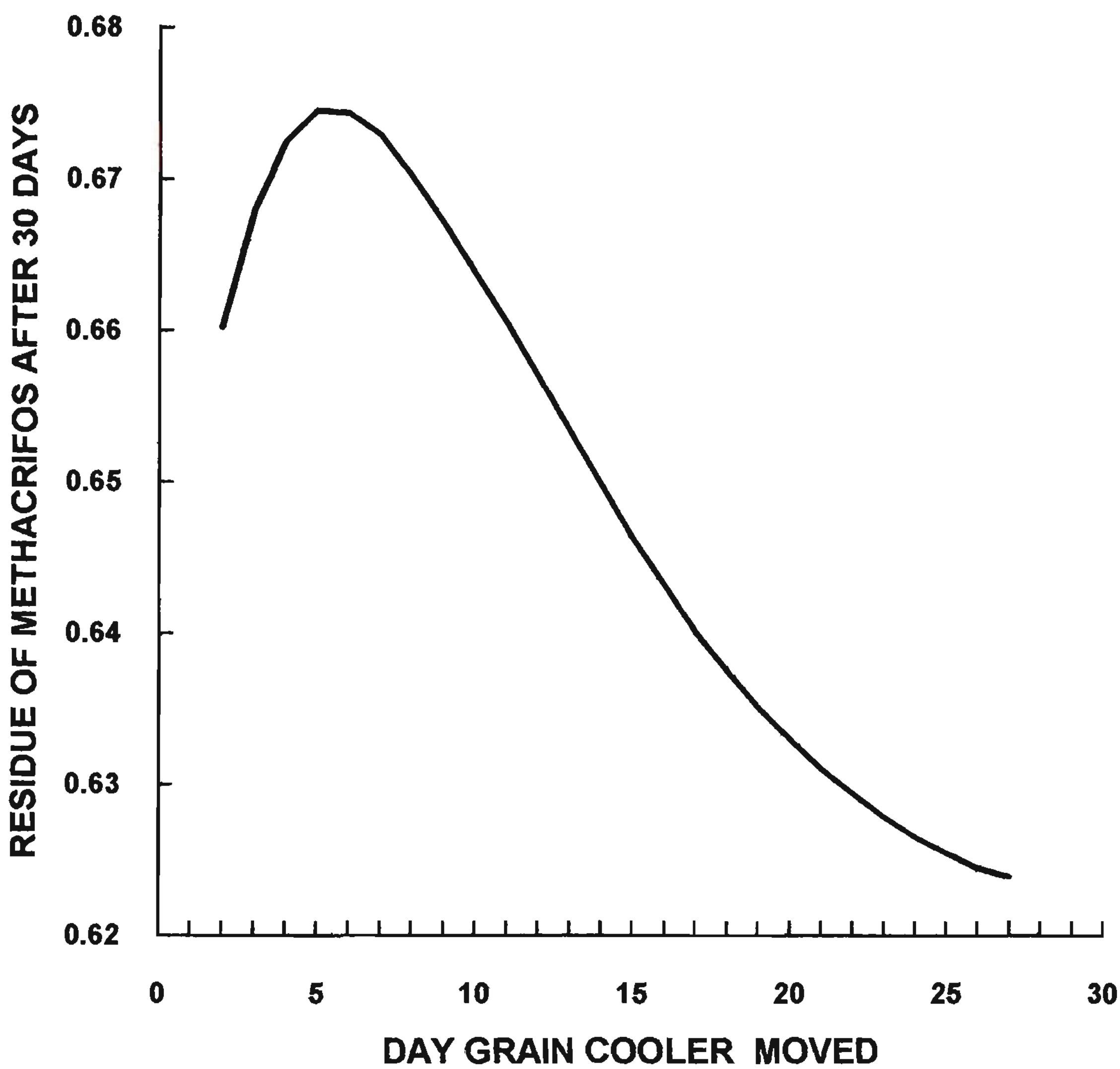


Fig. 5.17 - Effect of the time of relocation of a mobile grain cooler on the concentration of the pesticide methacrifos following a 30 day cooling period. Initial concentration 1mg/kg. Cooler was moved from the left side aeration duct to the right side of the shed-type grain store

Note: No cooling yields 0.3039 mg/kg

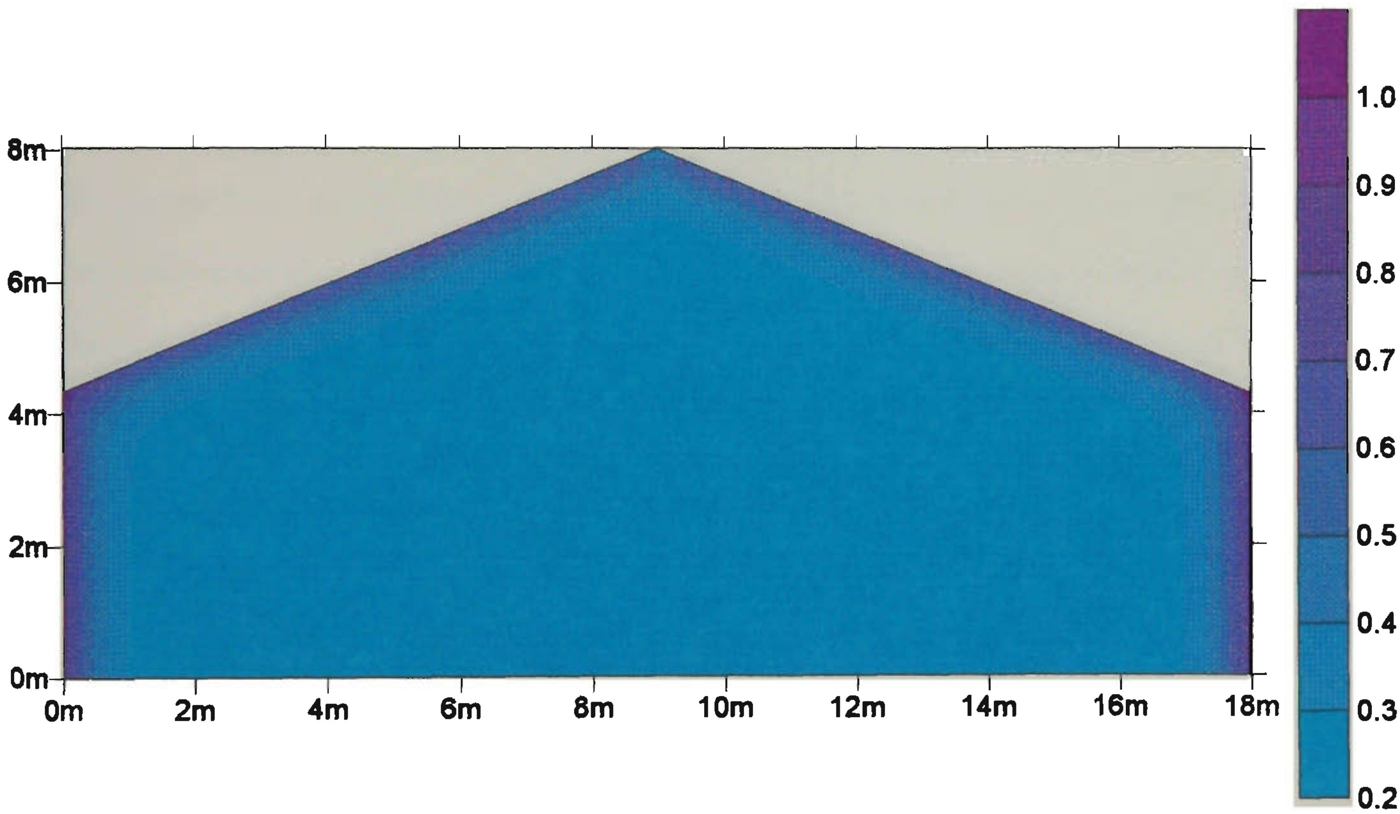


Fig. 5.18 - Pattern after 30 days of concentrations of the pesticide methacrifos applied initially at a rate of 1mg/kg in an uncooled bulk of barley in a shed-type grain store having the same characteristics as the grain store studied

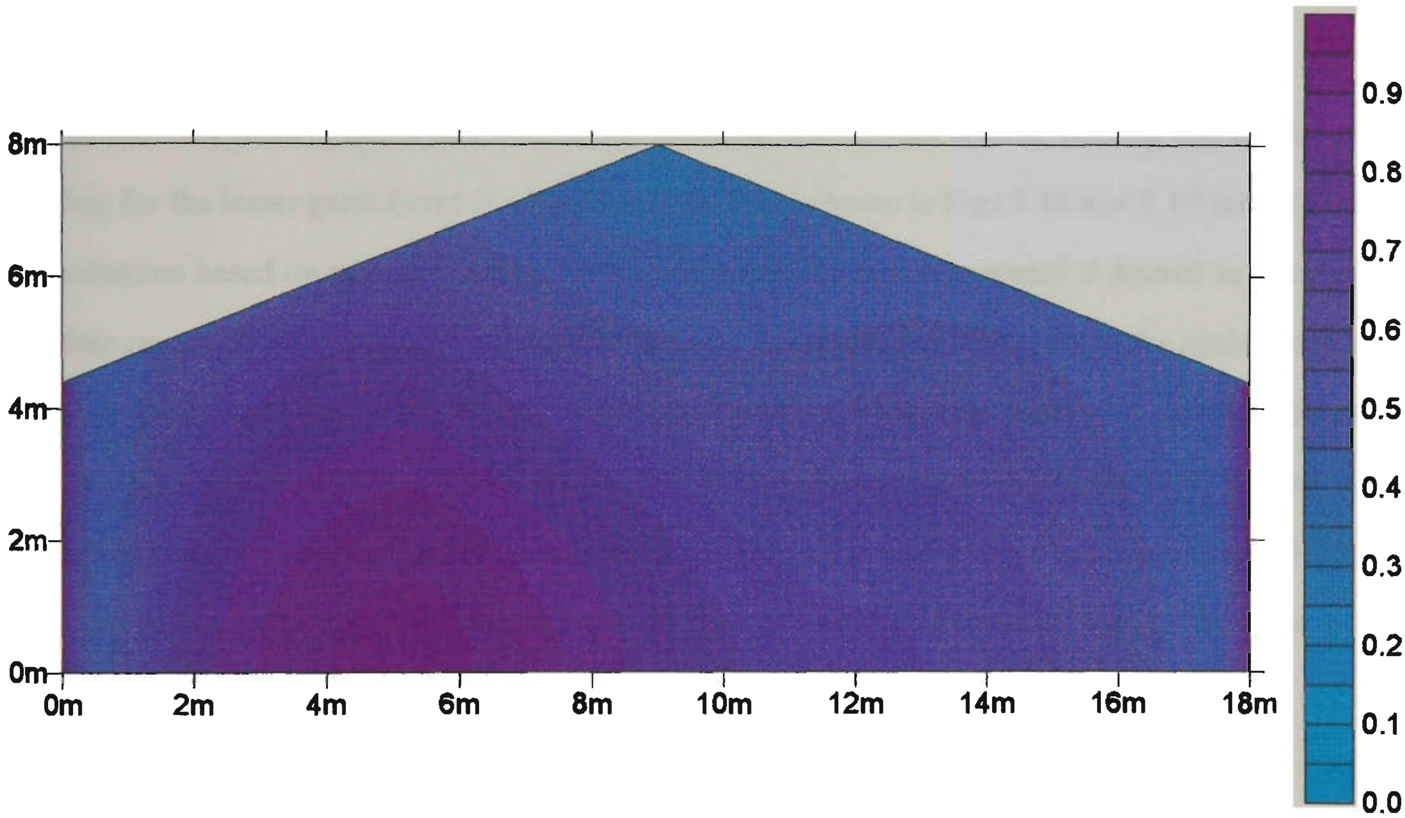


Fig. 5.19 - Pattern after 30 days of concentrations of the pesticide methacrifos applied initially at a rate of 1mg/kg when a bulk of barley in a shed-type grain store having the same characteristics as the grain store studied is cooled by a commercial mobile grain cooler connected initially for 7 days to the left side aeration duct and thereafter on the right side

costs of the order of $2 per tonne of grain treated once. If re treatment is necessary, the cost of turning the grain is added to the material cost for subsequent treatments and this is estimated by operators of shed-type grain stores to be between $4 and $6 per tonne. The residue of pesticide remaining after only 30 days if the grain was not cooled is indicated in the captions to Figs 5.14 - 5.17. This clearly foreshadows the need for re treatment within a few months, or the application initially of a heavier and therefore more costly dose of chemical, if the grain is to be held for a longer period.

The profiles for relative concentrations of the pesticide methacrifos with no cooling and the optimal cooling for the lesser grain borer *R. dominica* (day 7) are shown in Figs 5.18 and 5.19 respectively. Optimisation based on minimum breakdown of the pesticide can be executed if desired to determine the date on which the grain cooler should be moved. In the case of methacrifos, the optimum is the fifth day as shown in Fig. 5.17. The operator may decide to move the cooler on a compromise date to minimise loss of protectant insecticide but at the same time minimise the opportunity for any insects that may be resistant to the chemicals to multiply. It is interesting to note in Figs 5.14 - 5.17, that the optimum day to move the cooler for the four pesticides simulated is close to the same as the optimum day for suppression of the lesser grain borer using cooling (Fig. 5.4).

The relative humidity of the intergranular air at various regions of the bulk after 30 days of cooling is shown in Fig. 5.20. In only an extremely small region around the right side aeration duct does the relative humidity exceed 75%, and the temperature here remains very low for a considerable distance around this zone as indicated in Fig. 5.21. Toxin production is reported by Kozakiewicz and Smith (1994) when water activity is 0.82 (82% rh) or above but not at temperatures below 25°C. The risk of mould development is therefore very low and the likelihood of toxins being produced, particularly at such low temperatures, is therefore extremely remote.

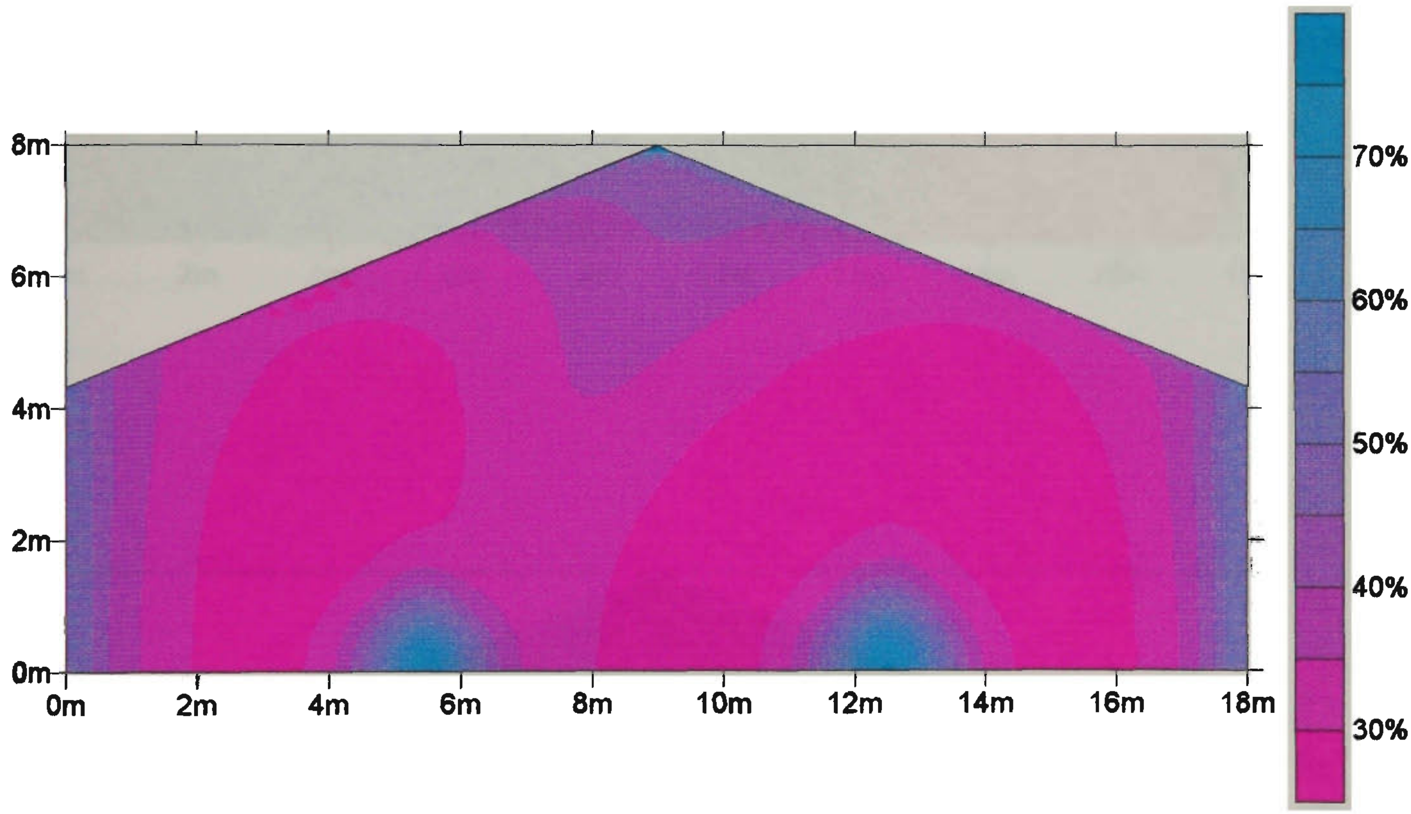


Fig. 5.20 - Pattern of equilibrium relative humidities (water activity) of the intergranular air in the bulk of barley simulated after 30 days of cooling by a commercial mobile grain cooler supplying chilled air for 13 days to the left side aeration duct, then 17 days to the right

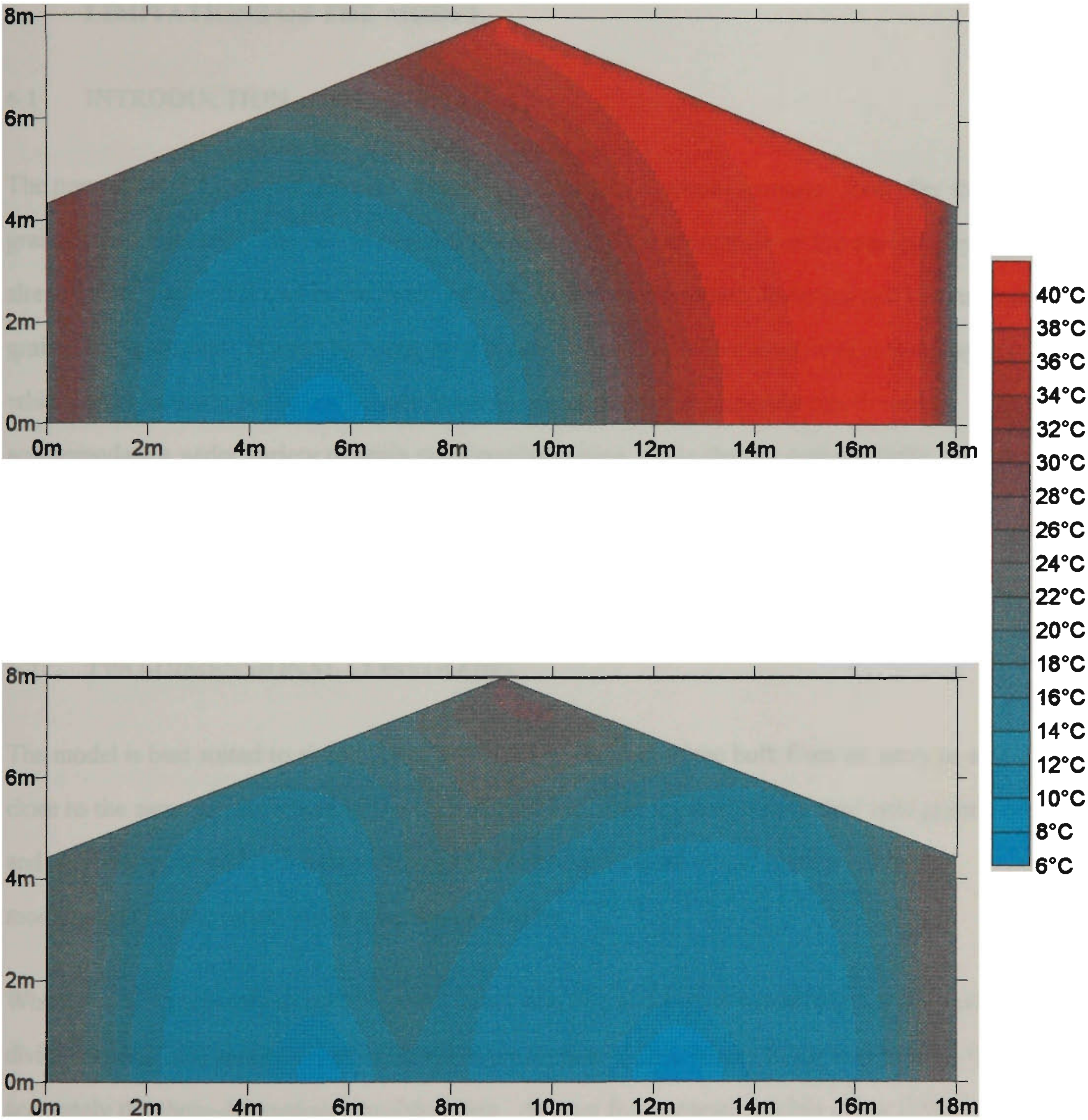


Fig. 5.21 - Grain temperature patterns after 13 days (top) of cooling by a commercial mobile grain cooler supplying chilled air via the left side aeration duct to the bulk of barley simulated, and after an additional 17 days (bottom) via the right side duct

CHAPTER 6

6. LIMITATIONS OF THE MODEL

6.1 INTRODUCTION

The present work forms the basis for designing a commercial micro-computer controller for bulk grain cooling systems. The results presented in Chapter 5 demonstrate that the computer program is already a very powerful tool in the hands of both grain cooling system designers and commercial grain store operators. It must be recognised however that there are a number of improvements which could be made to the mathematical model to generate more accurate results and to accommodate a wider variety of grain store configurations. This chapter outlines three enhancements of the versatility of the model, followed by a number of refinements to increase accuracy.

6.2 TWO-DIMENSIONAL CONSTRAINT

The model is best suited to situations where the cross-section of the bulk from air entry to exit is close to the same for the length of the third dimension. This applies to long shed type grain stores and silos equipped with cross-flow aeration. The present model would require substantial modification for the latter; but is ideal for the former.

Where it is felt necessary to take the third dimension into account, it would seem quite feasible to divide the bulk into sections with air flows in proportion to their length to approximate fairly accurately the three-dimensional configuration. At least five separate models of the different sections would be needed for a typical shed, and this would therefore result in a proportionate increase in the computational time to determine the optimum control strategy.

Ideally a three-dimensional model is required which could be developed from the existing two-dimensional model. The mathematical treatment of the three-dimensional case is a fairly straight forward extension of the two-dimensional procedure; however, many of the subroutines are not readily amenable to modification making this aspect of the change quite tedious and time consuming.

6.3 FLOOR DUCT

The air distribution duct in the model is assumed to be of the trench type with perforated metal flush with the floor on top of a supporting mesh grid. For half-round ducts on the floor, the equivalent floor duct would have a width equal to the perforated periphery of the half-round duct. In the case of round ducts, the equivalent floor duct width can be taken as 80% of the perforated periphery (Holman, 1966). During the formative stages of this research project, a subroutine for the various shapes of duct at differing heights above the floor was developed for an earlier program written in QBASIC but this has not yet been translated into Fortran. The effect of duct shape is expected to have little influence on the outcome of optimising calculations and is therefore not regarded as a serious limitation of the model.

6.4 HORIZONTAL FLOOR

Some shed-type grain stores are self emptying in that the floor slopes at an angle greater than the angle of repose of the material. The present model is set up only for stores with a horizontal floor. The sloping floor case might be best handled using a transformation method (Singh and Thorpe, 1993); but it is envisaged that, when a three-dimensional model is developed, the sloping floor will become a standard configuration with the flat floor being a special case in much the same way that a sloping top surface is in the present model with a levelled surface being a special case. The three-dimensional model proposed would also provide for conical-based cylindrical silos with the boundaries of the bulk specified by the node positions closest to the cylindrical or conical surfaces defined by the structure's specifications. This type of three-dimensional model is sufficiently versatile to incorporate special features such as a garner bin occupying part of the ventilated storage space, a large sloping tube for receiving an emptying auger, an elevator pit into which the grain flows during filling or any other peculiarity of a particular grain store.

6.5 HEAT CONDUCTION THROUGH THE FLOOR IGNORED

When a grain bulk on the ground has been cooled, heat flows from the soil beneath the bulk decreasing the soil temperature and giving rise to heat in-flow from the surrounding ambient. The effect of heat conducted through the soil from the floor of buildings is described by Delsante (1990) and this work could form a basis for modelling such conduction to a cold bulk of grain in contact with the building floor. At present, the model assumes that the grain-floor interface is adiabatic; but specified temperatures could be imposed if desired. Initially, heat will flow from the hot grain to the soil and later the flow will reverse as the bulk cools. Over all therefore, it is anticipated that this effect may have little influence on the optimal plant operating procedure.

During the initial cooling of a bulk of barley described in Chapter 4, the grain temperature measured is not as low as that predicted by the model. It is possible that the conduction of heat from the ground could have elevated both the temperature of the air flowing along the aeration duct on the floor and the temperature of the cooled grain close to the duct. Furthermore, the very hot grain loaded onto the floor of the shed would have had some days to transfer heat to the concrete floor and soil before the section was filled and cooling commenced.

If thought necessary to account for this effect, the bulk could be extended below the floor, having a thermal conductivity corresponding to that of the soil, and protruding some distance each side of the bulk where it is subject to atmospheric conditions. Such an extension to the present model could form the basis of studies investigating the feasibility of long term storage as a buffer against drought and as an accumulator for bumper harvests.

6.6 HEAT LIBERATED BY INSECTS

Where insect population densities are very high, the heat generated by the respiration of the animals will have some influence on the temperature in the region of the infestation. From the work of Howe and Oxley (1952) and Evans (1981) an indication of the order of heat production can be assessed from the quantity of carbon dioxide produced by the insects studied. In a stable population, for one adult with associated nine larvae of the rice weevil *Sitophilus oryzae* (L.), the heat output is about 0.5mW at 30°C which corresponds to a specific rate of temperature increase of 0.03 kelvin/day per unit insect density (one adult per kg of grain). This effect has not been included because cooling is normally applied as a preventive treatment against insect infestation well before insect numbers have built up to one per kg, and even at this level the heat output is more than an order of magnitude smaller than the heat being removed from the bulk by a cooling system. In the optimisation study in Chapter 5, the insect density in the barley at the walls and other vulnerable regions of the grain store long after the cooling plant has been removed is indicated by extrapolation of the end of the relevant plots shown in Fig. 6.1. This does not account for the fact that, over the ensuing months, the

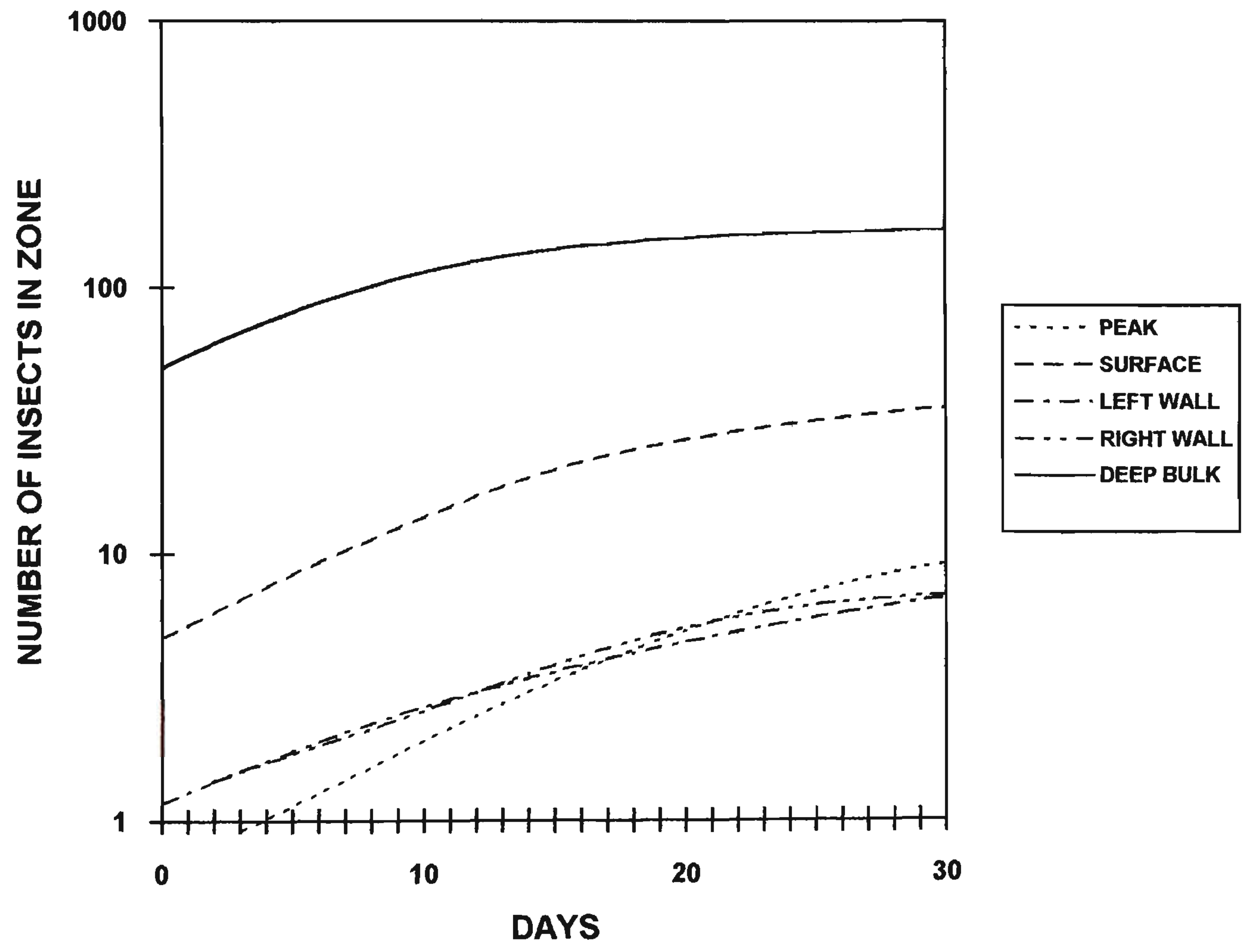


Fig. 6.1 - Increase in the number of lesser grain borers in selected 0.5m thick zones and within 1m of the peak during cooling of the grain store simulated using the optimum day to move a commercially available mobile grain cooler from the left to the right side aeration duct (see Fig. 5.4). Initial numbers represent an insect density of one adult per tonne

weather is likely to be cooling down thereby decreasing the potential for insect activity in peripheral regions of the bulk. A similar extrapolation using the initial gradient of each plot gives a measure of the population explosion if the bulk was not cooled. The model is set up to simulate the effect of up to five cycles of changed operating and weather conditions. Two cycles were used to account for relocation of a single mobile grain cooler as in Section 5.4.2.1, and for the simultaneous removal of the two coolers as in Section 5.4.2.2. This facilitates the study of intermittent cooling to remove heat which accumulates as a result of conduction and respiration when the plant is not connected.

6.7 BUOYANCY EFFECTS NOT INCLUDED

6.7.1 EFFECTS WITHIN THE GRAIN BULK

When air is not flowing through the bulk, differences in air density will give rise to natural convective air flows which in turn will transfer heat and moisture to a degree dependent on the period between cooling plant operation.

For natural aeration systems under the control of an atmospheric thermostat adjusted using the time-proportioning principle (Aust Patent 438732), fan operation occurs on a regular basis each week; but only during the coldest periods. The influence of natural convection is therefore expected to be minimal.

When mobile refrigeration plant is hired to cool the bulk quickly and then removed, air density differences will be the dominant potential for natural convection over a considerable period of time. Because moisture tends to be transferred away from hot regions towards cold regions where the relative humidity increases progressively, the accumulation of moisture and consequent spoilage is extremely unlikely since the cold regions of the bulk are those where there are no boundaries. This is in contrast to the behaviour of a hot bulk in a cold environment where it is shown by Griffiths (1964) that moisture accumulation at the cold surfaces of the bulk is serious.

For cold grain therefore it is probable that the impact of natural convection will be quite small compared with the effect of the forced convection imposed by the grain cooling plant.

6.7.2 EFFECTS ABOVE THE GRAIN SURFACE

The model assumes that the temperature of the air in the head space is the mean of the air temperature leaving the top surface of the bulk. The peak of the bulk is the most difficult to cool, and initially hot air leaving the top surface will tend to flow up along the sloping surface to the peak region thereby reducing the potential for the peak to lose heat to the cooler environment. As cooler air starts to emerge from the surface, it will tend to flow down the slope away from the peak which further mitigates against the cooling of the peak. Furthermore, the natural convective forces in the space above the grain and below the hot roof will move the hottest air to the region of the peak.

Although the air in the head space has no influence on the cooling within the majority of the bulk, it may well be important in determining the growth of insect populations in the peak which in the longer term is most likely to contain the highest level of infestation. In the short term, it is not likely to influence the optimum operating schedule for the cooling plant. It is more likely to determine more precisely the moment to bring mobile cooling plant back to provide additional cooling. This raises the interesting question whether the optimising controller should be associated with the particular grain store or part of the mobile refrigeration plant.

6.8 STORE SURFACE COATING NOT INCLUDED

The temperature of the walls of the grain store are assumed equal to the ambient temperature. This will be quite accurate for silos painted white; but for old galvanised iron or the company's identifying colour some correction is needed. Because this affects only a relatively small amount of grain, it is considered to have little impact on the determination of optimum operating conditions. As a first approximation, the model could be run with a wall temperature 15 kelvin above ambient to obtain some perception of the importance of the surface coating.

6.9 AIR SUPPLY DUCT RESISTANCE NOT INCLUDED

The resistance of the ducting leading from the cooling plant to the perforated metal air distribution ducts on the floor of the grain store will decrease the flow of air delivered by the cold air fan. There are many variations in supply duct configuration from direct through the wall to the air distribution duct to tortuous pathways through manifolds and flexible connections. Some operators who hire mobile grain cooling plant connect the flexible duct from the cooler to the inlet of the existing aeration fan allowing it to idle around as the refrigerated air flow passes through it. Some extreme examples are known where a mobile grain cooler was connected to an emptying auger tube! A commercial controller on board the grain cooler is expected to have a means of sensing the air flow through the system and using this to predict performance. The difference between this value and the predicted resistance of the bulk to air flow accounts for the losses in the supply duct and any vents in the roof of the grain store. Changes in this difference may indicate that the air filter on the mobile grain cooler needs cleaning.

6.10 LINEAR RESISTANCE CHARACTERISTIC

The assumption that, when air flows through bulk grain, the pressure gradient is proportional to the speed of the air is valid for the very low air velocities normally encountered in grain aeration systems. The speed of the air at the surface of perforated metal air distribution ducts can, however, be in the range where this assumption becomes dubious. Although this effect may not alter the shape of the pressure profile, the duct pressure predicted by the model will be somewhat less than the actual pressure and therefore the flow through the grain will not be as high as that modelled. In a practical system in which the cooling system controller is monitoring the air flow through the plant, the effect of non-linearity is taken into account in the same way that supply duct resistance and other influences on the pressure at the outlet of the cooling plant are allowed for in Section 6.7 above.

6.11 ISOTROPIC RESISTANCE TO AIR FLOW

It is assumed that the resistance of the bulk to air flow is the same in all directions. However, it has been shown by Hood and Thorpe (1992) that the resistance in the vertical direction can be much greater than that in the horizontal direction. They report that linseed exhibits the greatest degree of anisotropy, with the resistance to air flow being double in the vertical direction compared with that in the horizontal direction. Despite this, Hood and Thorpe (1992) have shown that the effect of anisotropy on the pressure distribution is insignificant. The virtually unchanged pressure gradients will however generate increased air flow in the horizontal direction when the lower resistance is taken into account, thus the speed of cooling along the floor and up the wall of the grain store will be improved at the expense of the speed vertically above the duct. Furthermore, at the floor and wall there is an increase in the void fraction resulting from the spherical particles meeting a flat surface, and this could also increase the speed of cooling along boundaries. These factors could be important considerations when optimising aeration duct layout as discussed in Section 5.2.

6.12 CRUDENESS OF CLIMATIC MODEL

The model incorporates a sinusoidal swing in atmospheric air temperature based on climatic data and assumes that the corresponding air moisture content remains constant. This is probably quite adequate for mobile refrigeration plant, but for natural aeration systems which detect only the coldest periods, the swinging diurnal temperature needs to have imposed on it a variation determined by the percentile statistics of the climate. A useful climatic model is described by Hunter (1981).

CHAPTER 7

7. CONCLUSIONS

Cooling bulk stored grain has the potential for eliminating many of the characteristic storage problems which are still being experienced despite rigorous attempts to ensure the grain is initially dry and free from insect infestation. Pesticides have been applied to prevent the likelihood of infestation or deal with any obvious problem. Strains of insects have become resistant to a succession of chemicals that have been introduced in Australia over the past three decades. The rapid emergence of resistant insects is facilitated by the normal high temperature of the grain, as well as by the relaxation of procedural discipline in the correct pesticide application technology. Sealing silos improves the effectiveness of pesticides and provides a barrier to reinfestation as well as excluding rodents, birds and other pests; but does not address the moisture problems commonly experienced (particularly by those entering the now deregulated grain market) that arise from convection and diffusion characteristic of a warm bulk of grain, or quality loss which results from the food being stored at a high temperature. It has been shown that cooling removes the cause of these mechanisms that lead to premature deterioration as well as arresting serious insect infestation and rapid loss of effectiveness of pesticide applied.

The salient accomplishments of the modelling work are as follows:-

- The two-dimensional matrix with non-uniform spacing of calculation nodes is capable of representing any shed-type grain store in common use in Australia in sufficient detail to position the air distribution ducting in any precise location and accurately determine the air pressure, temperature and humidity fields resulting from through air flow, and the interacting effects of heat flow through the walls and over the grain surface.
- The influence of diurnal ambient conditions on both the storage structure and the cooling plant is taken into account.
- The mathematical model is shown to provide a very powerful facility for optimising the design and operation of grain cooling systems.

- The inclusion of the kinetics of chemical pesticide decay offers the opportunity of minimising the cost of protecting grain by seeking an optimum combination of cooling and chemical control consistent with quality criteria.
- The ability of the model to identify the location in the bulk of potential trouble spots compared with regions where cooling has been very effective enables grain store operators to minimise the cost of regular inspection procedures.
- Where grain is stored at a high moisture content, the model is equipped to determine the outcome of interactions between the heat of respiration and the effects of cooling and of peripheral heat exchange.
- The loss of viability of seed grain has been shown to be predicted readily and, where this property of the commodity being stored is of critical importance, the mathematical model is able to optimise cooling plant operation to minimise germination loss.

The distinguishing features of the computer program are:-

- The automatic determination of the appropriate node matrix given the store dimensions, the height of the bulk and the size and location of air distribution ducts.
- Inclusion of a mathematical model of the performance of a commercially available mobile grain cooler developed by the candidate.
- Data on the properties of several grains, pesticides and infesting insects as relevant to their response to heat and moisture.
- A comprehensive data input file for nominating the values of the variables involved and the cooling plant operating in a particular grain storage situation.
- An option to automatically select an appropriate time step for calculations to speed up processing consistent with the measure of accuracy required.
- Output of the psychrometric properties of the bulk to determine the potential response of the mechanisms and organisms that give rise to deterioration of the grain.

The mathematical model therefore adequately represents the important physical, chemical and biological processes occurring in bulk grain stored in sheds or in other rectangular configurations.

Given climatic data for any storage site, the application of cooling by means of aeration with naturally occurring atmospheric air or conditioned air can be optimised to yield the minimum deterioration of any quality index, be it loss of seed viability, breakdown of applied pesticide, growth of insect infestations etc. Given cost data, a quality control strategy giving the minimum treatment cost could be established.

The benefits to the industry of the model include:-

- Optimisation of the layout of air distribution ducts to minimise the response of any selected agent of quality loss
- Optimised strategic management of a limited number of mobile grain coolers not immediately available when a grain store is filled
- Integration of the model's program in controllers for grain cooling systems
- The model can be run using currently available personal computers
- Immediate adoption by a commercial grain cooling contractor managing a fleet of mobile grain coolers
- A basis for the development of a three-dimensional model for more complex grain store configurations

For the Australian commercial mobile grain chilling unit simulated, the speed of the mathematical processing is only a little more than an order of magnitude faster than the actual cooling process. The cost of the micro-computer controller is a significant component of the total plant cost and therefore it is more probable that such a controller would be justified only on larger plant which will inevitably speed up the real cooling process and render the mathematical model of little use for establishing plant operation parameters within a reasonable time frame. The commercial application of this controller will become viable when the speed of industrial microprocessors exceeds 100MHz. This is quite possible in the near future and is likely to coincide with the completion of the further development of the model if the research and commercialisation work is continued.

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APPENDIX 1

SUPPORTING PAPERS

1. Elder, W B (1992) - Protectant decay during aeration of bulk grain. Proc. Conference on Engineering in Agriculture, Albury, October 1992. The Institution of Engineers Australia, Preprints of Papers pp 97-101

2. Elder, W B and Thorpe, G R (1994) - The control of mobile grain cooling units. Conference on Engineering in Agriculture, Christchurch, New Zealand, 21-24 August 1994. Paper No. SEAg 94/031, The Institution of Engineers Australia

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Protectant Decay During Aeration of Bulk Grain

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SUMMARY An equation is given for predicting the final concentration of a chemical protectant applied to grain in an aerated silo. The worked example shows that for a specific location where climatic data is known there is an optimum operating schedule for the aeration fan which yields the least decay of the chemical. Using a compromise schedule of fixed running hours per week. the final concentration under aeration is shown to be more than three times the value obtainable with no cooling. Thus cooling by aeration allows much lower doses or significantly longer protection.

1. INTRODUCTION

Aeration of bulk stored grain has many advantages. By cooling grain, the rate of decay of any protectant insecticides applied is decreased. This means that lower doses can be used without loss of effect. Alternatively longer storage periods are made possible before re-treatment becomes necessary.

2. THE AERATION PROCESS

A high pressure fan is used to force atmospheric air through grain in a silo via suitable air distribution ducting. Normally a controller is used to switch the fans on or off automatically when the atmospheric air temperature is respectively below or above a thermostat set point. The result is that a cooling wave commences where the air enters the bulk and gradually progresses through the mass of grain during fan operation. The temperature achieved by aeration depends on the proportion of time for which the fan is operating. Continuous operation will cause a cooling wave to traverse the bulk quite quickly but the temperature achieved will not be as low as it would be if fan operation was intermittent during the cooler periods of each day. Of course, the cooling wave will not progress as rapidly under intermittent operation.

3. THEORY

The decay of a protectant has been shown by Desmarchelier (1) to be a function of the wet-bulb temperature of the interstitial air in a grain bulk. The relationship may be expressed as follows:-

$$\log_e k = \alpha + \beta t_{w_g} \tag{1}$$

where k is the decay rate (s^{-1}) and
α, β are characteristic coefficients for the protectant
t_{w_g} is the wet-bulb temperature of the air between the seeds in the grain bulk ("grain wet-bulb")

The concentration of the protectant at any time θ has been expressed by Thorpe and Elder (2) as:-

$$C = C_o e^{-k\theta} \tag{2}$$

where C_o is the initial concentration.

A typical cooling regime is depicted in Fig.1 in which the decay rate changes progressively during the cooling period and then remains constant until the end of the month. Climatic data is usually obtainable as mean monthly records as in "Climatic Averages Australia" (3) therefore, in this analysis, no further cooling can occur after the aeration system has produced the lowest achievable temperature until the commencement of the subsequent month.

The lowest achievable temperature has been calculated by Hunter (4) on the basis of the fraction of time F an aeration system operates below the fan thermostat setting and is given by:-

$$t_{w_{MIN}} = \bar{t}_{14} + \frac{F}{2}(\bar{t}_{w_{86}} - \bar{t}_{14}) \tag{3}$$

where $\bar{t}_{14}$ is the 14 percentile of the daily minimum temperature
$\bar{t}_{w_{86}}$ is the 86 percentile of the daily maximum wet-bulb temperature and is calculated from Hunter (4) as follows:-

$$\bar{t}_{w_{86}} = \bar{t}_{14} + \frac{(\bar{t}_{86} - \bar{t}_{14})(\bar{t}_{w_{3PM}} - \bar{t}_{14})}{\bar{t}_{3PM} - \bar{t}_{14}} \tag{4}$$

where $\bar{t}_{86}$ is the 86 percentile of the daily maximum temperature
$\bar{t}_{3PM}$ is the monthly mean of the temperature at 3PM

The values for $t_{w_{MIN}}$ (t_{w_1} etc) for each month are shown in Fig.1

The time for a cooling wave or front at this temperature to traverse the bulk is obtained from Sutherland et al (5) and expressed as follows:-

$$\theta_c = \frac{\epsilon}{A_1 d_s q} \tag{5}$$

where ϵ is the void fraction of the bulk
A_1 is the ratio of the front to the interstitial air velocity (Fig.2)
d_s is the bulk density
q is the specific air flow per unit mass of grain

If the aeration system is operating for only a fraction F of the time, the period required to reach the minimum achievable temperature is

$$\frac{\theta_c}{F}$$

These values for each month are shown in Fig.1. The grain wet-bulb temperature at the end of each month is t_{w_i} where i denotes the month number from the start of the storage period. Usually this temperature will be the lowest achievable value unless the air flow is very low or the fraction of time for which the fan operates is very small.

At any time θ, the average grain wet-bulb temperature can be calculated from similar triangles in Fig.1 as follows:-

$$t_{w_g} = t_{w_{i-1}} - \frac{t_{w_{i-1}} - t_{w_i}}{\frac{\theta_{c_i}}{F_i}} [\theta - (i-1)\theta_M] \tag{6}$$

From Equation (1)

$$\log_e k = \alpha + \beta(t_{w_{i-1}} - \frac{t_{w_{i-1}} - t_{w_i}}{\frac{\theta_{c_i}}{F_i}} [\theta - (i-1)\theta_M]) \tag{7}$$

$$k = e^{\alpha + \beta(t_{w_{i-1}} - \frac{t_{w_{i-1}} - t_{w_i}}{\theta_{c_i}/F_i} [\theta - (i-1)\theta_M])} \tag{8}$$

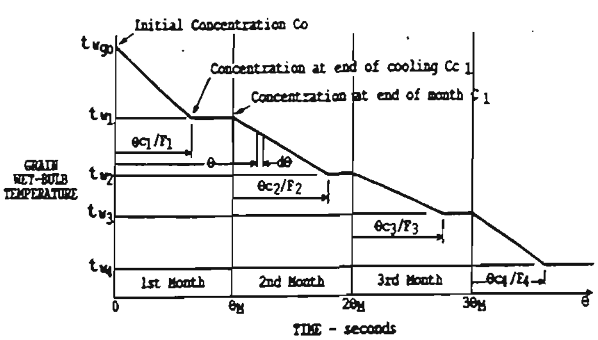

Fig.1 - Idealized cooling performance of an aeration system under the influence of a specific climate

Over a small time interval dθ, the change in concentration of the protectant is expressed by differentiating Equation (2)

$$\frac{dC}{d\theta} = -kC_o e^{-k\theta} = -kC$$

$$\text{Thus } \frac{dC}{C} = -kd\theta \tag{9}$$

Substituting (8) in (9) and integrating over the cooling period in the ith month

$$\int_{C_{i-1}}^{C_{c_i}} \frac{dC}{C} = -\int_{\theta_M(i-1)}^{\theta_M(i-1)+\frac{\theta_{c_i}}{F_i}} e^{\alpha+\beta(t_{w_{i-1}} - \frac{t_{w_{i-1}} - t_{w_i}}{\theta_{c_i}/F_i} [\theta-(i-1)\theta_M])} d\theta$$

Evaluation leads to the following:-

$$\log_e C_{c_i} - \log_e C_{i-1} = \frac{\theta_{c_i} e^{\alpha+\beta t_{w_{i-1}}}}{F_i \beta (t_{w_{i-1}} - t_{w_i})} (e^{-\beta(t_{w_{i-1}} - t_{w_i})} - 1) \tag{10}$$

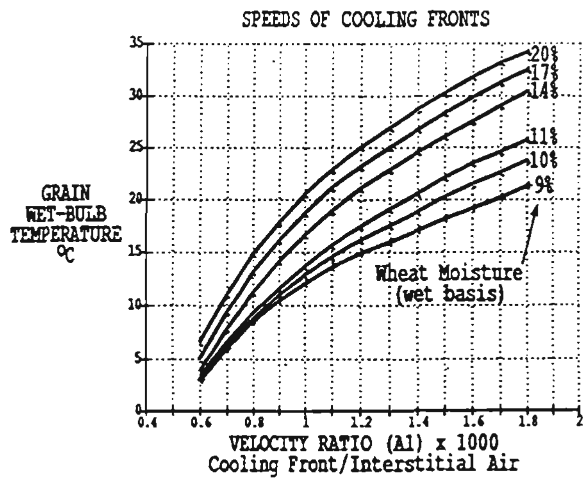

Fig.2 - Speeds of cooling fronts in aerated wheat for given interstitial air wet-bulb temperatures

After cooling to the lowest achievable temperature in a particular month, the protectant continues to decay at a rate determined by this temperature substituted in Equation (1)

$$\log_e k = \alpha + \beta t_{w_i}$$

$$k = e^{\alpha + \beta t_{w_i}} \tag{11}$$

Substituting Equation (11) in Equation (9) and integrating

$$\int_{C_{c_i}}^{C_i} \frac{dC}{C} = -e^{\alpha+\beta t_{w_i}} \int_{(i-1)\theta_M + \frac{\theta_{c_i}}{F_i}}^{i\theta_M} d\theta$$

Integrating to the end of the month leads to

$$\log_e C_i - \log_e C_{c_i} = -e^{\alpha+\beta t_{w_i}} . (\theta_M - \frac{\theta_{c_i}}{F_i}) \tag{12}$$

The total decay over the ith month is obtained by adding Equations (10) and (12) and rearranging to obtain the ratio

$$\log_e \frac{C_i}{C_{i-1}} = \left(\frac{\theta_{c_i}}{F_i}\left(\frac{1}{\beta(t_{w_{i-1}}-t_{w_i})}+1\right)-\theta_M\right)e^{\alpha+\beta t_{w_i}} - \frac{\theta_{c_i} e^{\alpha+\beta t_{w_{i-1}}}}{F_i \beta(t_{w_{i-1}}-t_{w_i})} \quad (13)$$

Let the initial concentration be C_o at the beginning of the first month, then the concentration of the protectant C_m at the end of "m" months is related to C_o as follows:-

$$\frac{C_m}{C_o} = \frac{C_1}{C_o} \cdot \frac{C_2}{C_1} \cdot \frac{C_3}{C_2} \cdots\cdots \frac{C_m}{C_{m-1}}$$

$$\log_e \frac{C_m}{C_o} = \log_e \frac{C_1}{C_o} + \log_e \frac{C_2}{C_1} \cdots\cdots \log_e \frac{C_m}{C_{m-1}}$$

$$\log_e \frac{C_m}{C_o} = \sum_{i=1}^{i=m} \left(\frac{\theta_{c_i}}{F_i}\left(\frac{1}{\beta(t_{w_{i-1}}-t_{w_i})}+1\right)-\theta_M\right)e^{\alpha+\beta t_{w_i}} - \frac{\theta_{c_i} e^{\alpha+\beta t_{w_{i-1}}}}{F_i \beta(t_{w_{i-1}}-t_{w_i})} \quad (14)$$

The above equation gives the overall breakdown of a protectant of known characteristics α and β resulting from aeration at a specific air flow "q" and fractions of time run each month "F" under the influence of defined climatic conditions. θ_c is obtained from Equation (5) after t_{wMIN} for each month (t_{w_i}) has been determined using climatic data in Equation (3) and the corresponding value of A_1 for the moisture content of the grain has been read from Fig.2. The initial grain wet-bulb temperature is to be substituted for $t_{w_{i-1}}$ when i=1. The values for the parameters in Equation (14) are to be expressed in fundamental S.I.Units as shown in Table I.

Desmarchelier (1) gives values for the protectant decay coefficients in logarithms to base 10 and time units in weeks for fenitrothion. Converting to base e logs we obtain the coefficient α = -4.72 and the coefficient β = 0.081. In the corresponding time units θ_M = 4.33 weeks.

To obtain the cooling time θ_{c_i}, we need to nominate a fraction of time F_i used for aeration. The lowest achievable temperature t_{w_i} is determined using Equation (3) and the corresponding velocity of the cooling front can be obtained from Fig.2.

Let us select F_i = 0.5 during January, thus t_{w_i} = 14.6°C
From Fig.2 we obtain $A_1 = 1.04\times10^{-3}$

From Equation (5), θ_{c_i} = 505x103 seconds (0.836 weeks)

From Equation (13), $\frac{C_1}{C_o}$ = 0.805

If we had selected F_1 = 0.15, a lower temperature would have been achieved; but the longer time taken to reach it could permit greater protectant decay than if cooled more rapidly to the higher temperature under 50% operation.

In this example, for F=0.15, t_{w_i} = 13.1°C thus $A_1 = 0.97\times10^{-3}$ and θ_{c_i} = 0.896 weeks

From Equation (13) we now have $\frac{C_1}{C_o}$ = 0.773

TABLE I

Parameter	Description	Units	Equations
α	Protectant decay coefficient	-	(1)
β	Protectant decay rate coefficient	$°C^{-1}$	(1)
t_{w_i}	Lowest achievable grain wet-bulb temperature under aeration for the coldest Fi of the time	°C	(3)(4)
θ_M	Average time in one month	s	(6)(7)(8)
θ_{c_i}	Cooling time at temperature t_{w_i}	s	(5)
F_i	Coldest fraction of time during which aeration is occurring	-	(3)

4. EXAMPLE

Consider the storage of wheat at 11% moisture content (wet basis) treated with fenitrothion at a concentration of 12mg/kg and aerated at a rate of 1L/s per tonne of grain. Assume that the initial grain wet-bulb temperature is typically 20°C. The location of the silo is Narrandera in New South Wales, Australia. Take the first month of storage to be January.

For January (i=1) $t_{w_{i-1}}$ = 20°C (t_{w_o})

t_{w_i} is a function of F_i and values for F_i=0.5 and 0.15 which represent the settings provided on commercial time-proportioning aeration controllers are shown in Table II.

With continuous operation (F_1=1) the grain will acquire the mean atmospheric wet-bulb temperature namely 16.9°C, $A_1 = 1.16\times10^{-3}$ and θ_{c_i} = 0.749 weeks.

This results in a value for $\frac{C_1}{C_o}$ of 0.784.

Clearly there is an optimum value of F_i which gives the least breakdown of the protectant and in this example F_1 = 0.5 appears the best. Other values close to this could be tested to determine the optimum more precisely.

In subsequent months lower optimum values of F_i may be expected. Examination of the data for February shows that for F_i = 0.15, the lowest achievable temperature is higher than that obtained in January with F_i at 0.5. As F_i goes to zero (no operation), the lowest achievable temperature goes to $\bar{t}_{14}$ i.e. 14.4°C compared with 14.6°C under 50% aeration operation in January so very little improvement in the situation can be expected by aerating in February.

grain temperature and moisture content i.e. initial grain wet-bulb temperature. High capacity systems would be able to achieve the lowest temperature operating for say 50% of the time quite quickly.

TABLE II

Climatic Data for Narrandera, New South Wales

Parameter	JAN	FEB	MAR	APR	MAY	JUN	JUL
$\bar{t}_{3PM}$	29.1	29.0	26.4	22.7	16.8	14.0	13.3
$\bar{t}_{w3PM}$	18.4	18.6	16.9	15.0	11.8	10.2	9.3
$\bar{t}_{86}$	37.2	34.3	32.2	28.3	22.2	17.8	16.7
$\bar{t}_{14}$	12.4	14.4	9.2	6.1	2.8	0.0	-1.8
From Equation (4)							
$\bar{t}_{w86}$	21.3	20.1	19.5	18.0	15.3	13.0	11.8
From Equation (3)							
t_{w_i} (F=0.5)	14.6	15.8	11.8	9.1	5.9	3.2	4.0
t_{w_i} (F=0.15)	13.1	14.8	10.0	7.0	3.7	1.0	0.0

For brevity let us assume that F_i = 0.15 for the remaining six months of storage. The overall protectant decay ratio can then be determined from Equation (14). Table III below shows the ratios for each month as well as the final value.

We may compare the loss of protectant with that which would have occurred over the same period without cooling i.e. $t_{w_{i-1}}$ = 20°C throughout the whole of the storage period. Substituting this value in Equation (1), we find that k = 0.071 weeks^{-1}. Using this in Equation (2) we can obtain the final concentration of the protectant if no cooling occurred over the seven months of storage viz. 0.116 of its initial value.

Therefore during the same month a smaller fraction of time could be selected to advantage after the period of time required to pass the first cooling front through the bulk at the 50% operation conditions has elapsed. The optimum fraction of time for this second stage can be determined by substituting the time remaining in the month for θ_M and other parameters in Equation (13) as if the month commenced at the end of the 50% operation stage. Iteration using lower values of F_i will soon identify the highest protectant concentration ratio that can be achieved by the end of the month. Some systems may be able to take advantage of three or more stages each month.

TABLE III

Protectant concentration ratios

Month	JAN	FEB	MAR	APR	MAY	JUN	JUL	$\frac{C_m}{C_o}$
$\frac{C_i}{C_{i-1}}$	0.805	0.820	0.831	0.875	0.898	0.919	0.935	0.370

With the initial dose of 12mg/kg, the residues after seven months storage are as follows:-

Aerated 4.4mg/kg
Not cooled 1.4mg/kg

This shows that the initial application rate could be reduced by a factor of three in an aerated storage to yield the same residue as on uncooled grain by the end of the storage period in this example.

5. DISCUSSION

The effect of different specific air flows on protectant breakdown can be examined for a particular protectant in a given climate and assuming an initial

The optimum fraction of time for aeration operation could be calculated by differentiating Equation (13) with respect to F_i. Note that t_{w_i} is a function of F_i and can be obtained from Equation (3). It is this influence which creates the potential optimum for F_i. Clearly an analytical solution will be cumbersome. In the example above, only three computations were necessary to identify the order of the optimum and it is envisaged that little additional effort would be required to quickly converge on a value of F_i close enough for practical purposes. Given adequate computer power, a program for numerical differentiation would be a preferable procedure for obtaining the exact values for each month of storage. The development of such a program would be

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advantageous for microprocessor-based aeration controllers.

It should be noted that the minimum achievable temperatures used in this work do not take into account the rise in wet-bulb temperature as the air passes through the fan in blowing aeration systems. Information about the storage and system duct-work etc is necessary if this factor is to be taken into account. This is however unlikely to affect the optimum fraction of time: but the breakdown rate will be a little higher than if this effect is ignored.

6. CONCLUSIONS

This analysis provides an easily used formula for determining the breakdown of a protectant applied to bulk-stored grain aerated at a specific air flow in a given climatic zone.

Consideration should be given to more detailed analysis of the first month of storage where more than one fraction of time under aeration during the month could be advantageous as the initial grain temperature is reduced. For example, continuous aeration for a short period initially may be close to optimum.

The optimum fraction of time for operating the aeration system to give the minimum breakdown of the protectant applied to the grain can be determined from a small number of calculations using the formula developed.

7. ACKNOWLEDGEMENTS

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APPENDIX

Nomenclature

A_1 ratio of cooling front speed to intergranular air speed
C protectant concentration (mg/kg)
d density (kg/m^3)
F fraction of time the aeration fan runs
k protectant decay rate (s^{-1})
m number of months of storage
q specific air flow (m^3.s^{-1}.kg^{-1} of grain)
t air temperature (°C)
$\bar{t}$ mean air temperature (°C)
t_w air wet-bulb temperature (°C)

α protectant decay coefficient
β protectant decay rate coefficient °C^{-1}
ϵ void fraction of grain bulk
θ time (s)

Subscripts

c during cooling
e base of natural logarithms
g of grain
i month number
M in the month
o initial
s of seed
w wet-bulb
3PM at 3PM
14 14 percentile probability of temperature below value
86 86 percentile probability of temperature below value

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The Control of Mobile Grain Cooling Units

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SUMMARY A numerical mathematical model of heat and moisture transfer in aerated bulk grain is used to simulate the performance of a commercial mobile grain cooler applied to barley in two types of grain store. The temperature measurements recorded by the operator of the shed-type store showed reasonable agreement with the simulation. The tall cylindrical silo simulation was associated with a design for a storage facility. The potential for population growth of two grain infesting insect species was also simulated for both stores. Variation of air flow through the refrigeration evaporator under the prevailing climatic conditions identifies an optimum flow which will result in the minimum number of insects at the end of the cooling period. The model includes other quality parameters such as viability, dry matter loss, damp grain heating, the breakdown of applied pesticides and moisture accumulation. The desirability of a three-dimensional model for more accurate results is recognised.

1. INTRODUCTION

Cooling bulk grain maintains quality and suppresses insect infestation and other agents of loss. Controllers for systems which pass natural air through the bulk take various forms from time-switches to sophisticated feed-back devices. Mobile refrigeration plant is becoming more popular for decreasing the grain temperature more quickly than can be achieved with natural air. A typical arrangement is shown in Fig.1. The installation of a feed-back loop from a silo to mobile plant presents many practical problems especially for hiring where the various silos in which the sensing equipment is fitted and the mobile plant is owned by different parties. Sufficient is now known about heat and moisture transfer processes in bulk grain for a realistic mathematical model of the bulk to be formulated. The initial condition of the grain can be input from records of consignments received or from commercially available deep probe temperature and moisture monitoring equipment. Changed conditions are dictated by the known performance of the cooling plant and ambient conditions, and this calculated data can then be used for system control.

The mathematical model is in two dimensions typifying shed-type grain stores in common use. A three-dimensional model has been considered to more closely represent the upper region of the bulk where the natural angle of repose of the grain forms conical surfaces at the ends of the bulk. However, the length of shed-type grain stores is generally four or five times the width rendering the majority of the bulk a two-dimensional body. It is intended that, in addition to refining the modelling of the end grain, a future 3-D model will also account for cylindrical silos.

The model shows the gradual progress of cooling fronts (or waves) resulting from through air flow, and the continuous conduction of heat through the exposed surfaces of the bulk. Initially, much of the bulk remains at its initial high temperature until the cold zone starting at the duct has enlarged significantly. It applies to bulks cooled intermittently using selected natural atmospheric air as well as to bulks cooled continuously using conditioned air.

2. MATHEMATICAL ANALYSIS

2.1 Resistance to air flow

The present model assumes that the resistance to air flow is proportional to the local velocity of the air, and that the resistance coefficient is isotropic. This may be expressed as

$$\nabla p = -Rv$$

in which v is the velocity of the air, and R is a resistance coefficient. Hunter (1983) presents values of R for 28 different grains and seeds.

2.2 Heat and moisture exchange

Much of the past work on heat and mass transfer during ventilation of bulk grain assumes that the seeds are inert hygroscopic particles. This model however includes the effect of respiration of the seeds involving the liberation of heat and additional gases (carbon dioxide and water vapour) that mix with the ventilating air altering its speed, and the removal of oxygen from the ventilating air. To simplify the equations governing this reactive process, Thorpe (1994) has made order of magnitude assumptions to derive a thermal energy equation as follows:-

$$\varepsilon_\sigma \rho_\sigma \left\{ (c_2)_\sigma + (c_1)_\sigma W + \frac{\partial H_W}{\partial T} \right\} \frac{\partial T}{\partial t} - h_s \varepsilon_\sigma \rho_\sigma \frac{\partial W}{\partial t} - \rho_a \frac{\partial \varepsilon_\sigma}{\partial t} \int_0^W h_s dW$$
$$+ \rho_a \left(c_a + w \left((c_1)_\gamma + c_{2v} \right) \right) v . \nabla T$$
$$= K_{eff} \nabla^2 T + \varepsilon_o \rho_o Q_r \frac{dm}{dt} - 0.6 \varepsilon_o \rho_o h_v \frac{dm}{dt}$$

Moisture balance

The moisture balance on the grain bulk is expressed as

$$\varepsilon_o \rho_a \frac{\partial W}{\partial t} + \rho_a v . \nabla w = \varepsilon_\sigma \rho_\sigma \frac{dm}{dt} (1 + 1.66W)$$

The terms represent coupled heat and moisture transfer, the integral heat of wetting and temperature wave propagation equalling a diffusivity term and the effects of the loss of dry matter. The integral heat of wetting for a given moisture content has been expressed by Thorpe et al (1990) as follows:-

$$\int_0^W \left(1 - \frac{h_s}{h_v} \right) dW = c_{i1} + c_{i2} W + c_{i3} W^2 + c_{i4} W^3 + c_{i5} W^4$$

where the coefficients for a number of grains are shown in Table 1, and h_S is the heat of sorption and h_v is latent heat of vaporisation of free water.

TABLE 1

Grain	c_{i1}	c_{i2}	c_{i3}	c_{i4}	c_{i5}
Barley	-0.26249	4.6097	-0.00910	1.2485	8.4783
Canola	-0.22976	10.5894	-0.01706	2.4416	7.3356
Peanuts	-0.30395	7.4899	-0.07120	3.9970	11.2951
Sorghum	-0.17662	5.1872	-0.06118	4.2819	56.3811
Sunflower	-0.27797	12.6731	-0.04931	4.4794	6.0718
Wheat	-0.21133	4.7403	-0.03483	2.6210	17.6706

2.3 Dry matter loss and respiration heat

The dry matter loss calculated in the model is based on the respiration of maize reported by Thompson (1972). From this work, the rate of loss of dry matter has been derived by Thorpe (1994) as follows:-

$$\frac{dm}{dt} = \left\{4.72 \times 10^{-10} \exp\left(1.667 \times 10^{-6} t_{eq}\right) + 2.833 \times 10^{-9}\right\} / \left(M_M M_T\right)$$

where the temperature modifier M_T is calculated over three moisture ranges above and below 15.5°C namely below 19% (dry basis), from 19 to 28%, and above 28%. The moisture modifier M_M applies over the full range studied.

TABLE 2

Seed	Moisture content (% wet basis)	Maize equivalent moisture content (dry basis)
Wheat	14	17
	18	19
	22	28
Sorghum	14	17
	16	24
	18	28
Sunflower	10	18
	13	22
	16	27
Canola	10	19
	13	22
	16	26
Peanuts	10	15
	13	22
	16	26

It is assumed for the time being that this model of dry matter loss will be adequate for other grains. The respiration of moist bulks is likely to be dominated by the respiration of micro flora attacking the seeds. It appears from the work of Pitt and Hocking (1991) and Steele (1992) that their response is governed more by the relative humidity of the air at the surface of the seeds than by the overall water content of the bulk much of which may be inaccessible to moulds. It is therefore possible that the model of dry matter loss would be more accurate for other seeds if the equivalent maize moisture content was used, i.e. the maize moisture which will generate the same equilibrium relative humidity as the other seed at its moisture content. Some approximate equivalent values are given in Table 2. For the model, it may be preferable to later derive an expression for dry matter loss in terms of intergranular relative humidity which may be calculated from the grain type, moisture content and temperature.

2.4 Germination loss

Although the loss of germination of different seeds will be a complicated function of temperature and moisture, a general rule-of-thumb is emerging which claims that for every 4 kelvin decrease in temperature, the life of the seed over the range of common moisture contents is doubled (Banks 1993). The work reported by Banks also indicated that a 1% decrease in moisture content of the malting barley studied increased seed life by a factor of three. The general relationship may be expressed as follows:-

$$\frac{V}{V_0} = e^{-kt}$$

where V is the germination after time t, and V_0 is the initial germination. Given a known value of the time constant k at a certain temperature, its value at other temperatures can be evaluated given the above relationship. It can also be modified for changes in moisture content.

Temperature modification:-

k is a function of temperature T (and moisture content). From the above rule of thumb, as t is doubled, k must halve for a given V/V_0. t doubles for every 4K drop in temperature, thus k must halve for every 4K drop. Thus, if the value of k (k_0) is known at one temperature T_0, its value at a new temperature$_1$ will be as follows:-

$$k = k_0 \times 2^{\left(\frac{T_1 - T_0}{4}\right)}$$

Moisture modification:-

$$k = k_0 \times 3^{100(M_1 - M_0)}$$

The total change in viability is obtained by treating each effect in turn.

2.5 Grain insect population growth

Desmarchelier (1988) has shown that the intrinsic rates, r_m of population growth of eight species of stored-product Coleoptera are linearly related to the intergranular wet-bulb temperature, T_w. This may be expressed mathematically as

$$r_m = a + b(T_w - c)$$

where a, b and c are species specific constants. The number, N, of insects after a time, t, is thus given by

$$N = N_O \exp(r_m t)$$

where N_O is the number of insects initially in the grain.

2.6 Grain protectant breakdown

The loss of pesticide concentration has been related by Desmarchelier and Bengston (1979) to the temperature T and the relative humidity r of the intergranular air and is expressed as

$$\frac{C}{C_0} = \exp\left[\frac{-1.386rt * 10^{B(T-30)}}{t_{\frac{1}{2}}}\right]$$

in which the coefficient B and $t_{1/2}$ (the half-life) are specific to each compound. The model includes these coefficients for five grain protectants currently in use commercially as shown in Table 3. It should be noted that the half-life is expressed in weeks.

TABLE 3

Decay coefficients for chemical pesticides applied to stored grain

Pesticide	Half-life (weeks)	B (per degree C)
Bioresmethrin	24	0.033
Bioresmethrin + pip.but.	38	0.031
Chlorpyrifos-methyl	19	0.04
Fenitrothion	14	0.036
Methacrifos	8	0.055

2.7 Climatic data

The mean daily temperature and humidity for each month under consideration is used with a sinusoid superimposed with an amplitude representing the mean diurnal swing. This is the condition of the air entering the grain cooler.

$$T_{amb} = T_{mean} + T_{amp} \sin\left[\frac{2\pi t}{3600 * 24}\right]$$

where time t is in seconds

2.8 Grain cooler characteristics

The thermal performance of the McBea Mobile Grain Cooler has been modelled as follows:-

$$T_{w_{out}} = 167Q^3 - 262Q^2 + 148Q - 43.3 + 1.2T_{w_{amb}} - \frac{0.045(35 - T_{amb})}{Q}$$

This performance depends on the air flow Q through the Cooler which is dependent on the resistance offered by the grain bulk and ducting system, plus any controls varying the air flow to meet certain criteria. The Cooler's fan/coil/filter characteristic is represented by the following polynomial:-

$$P = 1000(3.33Q^3 - 9Q^2 + 1.97Q + 1.54)$$

where P is the static pressure at the Cooler's outlet.

Separate allowances need to be made for supply duct losses and, as these will be different in almost every case, this effect has not been included in the modelling. These losses are usually very small by comparison with the loss through the grain and will therefore have very little effect on the Cooler's performance.

3. NUMERICAL SOLUTION OF EQUATIONS

The thermal energy and mass conservation equations are solved by expressing them in finite difference form. The domain of interest is divided into a non-uniform mesh as shown in Fig. 2. Instabilities in the numerical solution are avoided by expressing derivatives involving upwind differences, i.e.

$$\frac{\partial T}{\partial x} = \frac{T_{i+1,j} - T_{i,j}}{hx(i)} \qquad \text{if } u \geq 0$$

and

$$\frac{\partial T}{\partial x} = \frac{T_{i,j} - T_{i-1,j}}{hx(i-1)} \qquad \text{if } u \langle 0$$

This can be expressed as

$$\frac{\partial T}{\partial x} = cx1(i)\, T_{i-1,j} + cx2(i)\, T_{i,j} + cx3(i)\, T_{i+1,j}$$

where $cx1(i)$, $cx2(i)$ and $cx3(i)$assume values appropriate to the direction of the local flow. Second derivatives with respect to x, say, may be expressed as

$$\frac{\partial^2 T}{\partial x^2} = cx4(i)\, T_{i-1,j} + cx5(i)\, T_{i,j} + cx6(i)\, T_{i+1,j}$$

as described by Graham et al (1994). A forward differencing scheme is used for the temperature derivative, i.e.

$$\frac{\partial T}{\partial t} = \frac{T_{i,j}^{p+1} - T_{i,j}^{p}}{\Delta t}$$

Using these finite difference approximations, the thermal energy conservation equation may be written in the form

$$\phi_1 \frac{T^{p-1}_{i,j} - T^{p}_{i,j}}{\Delta t} + \phi_2 = \phi_3$$

where $\phi_1 = \rho_o \varepsilon_o \left\{ (c_2)_o + (c_1)_o W + \frac{\partial H_w}{\partial T} \right\}$

$$\phi_2 = -h_s \rho_o \varepsilon_o \frac{\partial W}{\partial t} - \rho_o \frac{\partial \varepsilon_o}{\partial t} \int_0^W h_s dW$$

$$+ \left\{ \rho_a \left[c_a + w\left((c_1)_v + (c_2)_v \right) \right] \right\} \left\{ u\left(cx1T_{i-1} + cx2T + cx3T_{i+1} \right) + v\left(cy1T_{j-1} + cy2T + cy3T_{j+1} \right) \right\}$$

$$\phi_3 = K_{eff} \left\{ cx4T_{i-1} + cx5T + cx6T_{i+1} + cy4T_{j-1} + cy5 + cy6T_{j+1} \right\}$$

$$+ \rho_o \varepsilon_o Qr \frac{dm}{dt} - 0.6 \rho_o \varepsilon_o h_v \frac{dm}{dt}$$

in which the absence of a subscript or superscript implies we are considering the $(i,j)^{th}$ node at the p^{th} time step

$$\text{i.e.} \quad T^{p}_{i,j} \equiv T$$
$$T^{p}_{i+1,j} \equiv T_{i+1}$$
$$\text{and} \quad T^{p+1}_{i,j} \equiv T^{p+1}$$

The updated temperature of the $(i,j)^{th}$ node is thus calculated from

$$T^{p+1} = T + \Delta t \left(\phi_3 - \phi_2 \right) / \phi_1$$

The discretized form of the moisture conservation equation is

$$\phi_4 \frac{W^{p+1}}{\Delta t} + \phi_5 = \phi_6$$

where $\phi_4 = \rho_o \varepsilon_o$

$$\phi_5 = \rho_a \left\{ u\left(cx1w_{i-1} + cx2w + cx3w_{i+1} \right) + v\left(cy1w_{j-1} + cy2w + cy3w_{j+1} \right) \right\}$$

$$\phi_6 = \rho_o \varepsilon_o \frac{dm}{dt}$$

hence $W^{p+1} = W + \Delta t \left(\phi_6 - \phi_5 \right) / \phi_4$

4. COMMERCIAL APPLICATION

The ability to predict the conditions in a bulk of grain removes the need for expensive permanent probe systems for taking periodic measurements to determine management action. It will also assist in the design of storage facilities for examining the benefits of insulation or the justification for ventilating cylindrical bin inter-space cells in a concrete silo complex as well as optimising the design of grain cooling systems.

Cooling bulk grain is becoming more widespread in Australia through access to mobile refrigeration plant available for hire. Occasions arise where it is obvious that two grain coolers should be used in tandem such as for cooling a shed-type grain store having two parallel longitudinal aeration ducts, and yet only one cooler is available or requested by the operator. The cooler is first connected to the duct serving the side of the shed most exposed to external heat and, at an appropriate time, relocated onto the other duct to complete the cooling. The measurements shown in Fig.3 were made using portable grain wet-bulb temperature monitoring probes in a shed in southern NSW (Riverina) containing 1500 tonnes of malt grade barley. The mean climatic condition for the period of operation is shown in Fig.4. The temperature contours after 13 days of cooling on the first duct were estimated by the hiring contractor from the point measurements and some knowledge of the way air flows through bulk grain, and given to the operator with a recommendation to relocate the cooler in a day or two. Subsequently, a two-dimensional mathematical model of the bulk was produced from the above equations. The resulting cooling pattern is shown in Fig.5. There is reasonable agreement between the results. The departure in the region of the peak results from the actual peak not being a two-dimensional prism as assumed by the model but more of a conical shape. Although this shed was long compared with its width, a partition had been installed leaving the bulk being cooled on an almost square floor. The escape of air at the lower periphery of the conical surface above the duct would have resulted in less air flowing across the bulk.

The model can be used to determine the optimum time to relocate the cooler to the second or subsequent aeration duct based on temperature, quality loss, breakdown of applied insecticide or insect population growth potential. The multiplication ratios for populations of two grain infesting insect species are shown in Figs 7 and 8. For a given level of quality control, the model could also be used to assess the merit of using two coolers simultaneously instead of one relocated so as to evaluate the cost benefits. In the case above, the hire fee was a fixed monthly charge but is some cases an establishment charge will be made which may tend to bias the cost benefit towards keeping one cooler for a longer period. There may also be some expectation by operators that one cooler may be able to decrease the temperature satisfactorily on both sides of the bulk without the need for moving it and in a shorter time. In the commercial arena, there will always be various and mostly non-technical reasons why grain traders opt for one cooler only even if they are well aware that the physical process is not as efficient as using two coolers simultaneously.

The air flow through the cooler is determined by the resistance of the grain bulk to air flow. Some silos offer very little resistance and thus the air flow can be above the rated flow. During extended periods of very hot weather, the temperature of the air leaving the cooler will be higher than the rated value and may not be low enough to ensure adequate grain quality control. A manually-operated damper is supplied for users wishing to restrict the air flow to ensure lower temperatures. Some users have been prepared to accept the higher than normal temperature because they are concerned only about the insects they have observed previously which are those that can be inhibited by the temperature produced. There is however a risk that low temperature species will become evident in due course for example when competition from the high temperature insects is removed. One operator has already observed insects which they claim to have never experienced before. The models of insect multiplication ratio could be enhanced to calculate actual numbers of insects given an initial level of infestation of each species. This will then demonstrate the transition of dominance from species to species as cooling progresses; but the present equations do not have provision for the effect of competition between species. It is assumed that the infestation levels will generally be low enough that competition and over crowding will not be relevant.

As part of a design study for cooling barley in tall concrete silos in southern China, the effect of different air flows through the grain cooler was analysed using the model. The results are shown for 250 and 500 hours of operation in Figs 8 to 13. The mean climatic condition is shown in Fig.2.

5. CONTROLLER CRITERIA

Ideally, the air flow through the grain cooler should be controlled to ensure that the temperatures produced will provide the degree of quality control desired by the operator. It would seem prudent to target the low temperature insects; however, this may result in much slower cooling of the bulk which in turn will provide high temperature insects in the grain last to be cooled greater opportunity for population increase. A higher air flow and resultant more rapid cooling will more quickly suppress the high temperature insects but at the expense of allowing the low temperature insects to increase until either the weather cools down or the air flow is reduced at some stage during the cooling process to generate lower air temperatures out of the grain cooler. The magnitude of the different effects is calculated by the model and can be seen for insect population growth by comparing Figs 9, 11 and 13. The optimisation of the air flow to yield the minimum total number of live insects of all species requires analysis similar to that used by Elder (1992) to determine the optimum operating time for running aeration fans to minimise the breakdown of grain protectant insecticides applied to bulk-stored grain. Some operators may well be more interested in maintaining the effectiveness of applied insecticides than in insect infestation. Others may have a need to prevent loss of viability of the seeds in storage and this will also require careful optimisation of the temperature-time spectrum to minimise the loss. Where grain is stored at a high moisture content, the minimisation of dry matter loss or heat damage may be the appropriate criterion.

An important improvement that the mathematical model presented here has over analytical optimisation solutions is that the effects of peripheral heating can be taken into account. This peripheral heating is shown in Fig.14 in which a cooling wave at a high air flow has already passed through the bulk. It is interesting to note that there is a corresponding drying effect at the wall. The orientation of the store, its construction materials, the wall and roof surface finish and shading could be included in a commercial controller. The studies so far have assumed that the bulk surfaces against walls are at the outside ambient temperature, that the top surface is at the exit air temperature and that the floor is perfectly insulated.

A controller for the refrigeration plant is required which will accept a number of control targets such as those described above which can be selected by the operator. Initial values such as grain temperature and moisture, protectant dose, estimated insect densities and germination will need to be loaded into the controller including some climatic data for the site. The mathematical model of the grain store will require input of store width, length, wall height and properties of the grain including angle of repose and the total mass. Default values for thermal and physical properties of a number of typical grains can be included so that the operator need only specify the grain type. Likewise, the relevant characteristics of a number of insect, protectant and seed types can be stored in the controller's memory for the operator to select. The operator will however be required to enter the dimensions of the aeration ducting or other air distribution system and its location.

At this stage it is not intended to allow for partial emptying of the grain store which will alter the air flow patterns through the grain. This scenario generally results in the bulk no longer representing a two-dimensional prism. This possibility is to be kept in mind when developing a three-dimensional mathematical model of a grain bulk. The 3-D model is also more appropriate for including the properties of wall and roof surface finish, and for conduction of heat via the soil through the floor. The effect of natural convection in the space between the grain and the roof will not be included. This will however be important for models of uncooled bulks as it will demonstrate the progressive accumulation of moisture in the top layer of grain as outside air temperatures decrease. Despite decades of stringent moisture content limits on grain being accepted for storage, this phenomenon and the corresponding sweating of the silo roof is often observed by many who store grain in temperate climates for a considerable period.

6. CONCLUSIONS

The potential for control of grain storage cooling plant using a two-dimensional mathematical model of a shed-type grain store has been illustrated using two species of grain infesting insects. The optimisation of the air flow for the minimum number of insects after the cooling is completed can be applied to other grain quality loss properties. The model has shown the effects of heat flow through the walls of a tall silo on grain temperature, moisture and insect population growth potential.

The model can also be used as a guide to management of cooling plant, and this has been illustrated by the optimal timing of the relocation of the grain cooler from one aeration duct under a bulk to the next.

The model is limited in its application being in only two dimensions. The results for the tall circular silo obtained assuming a square cross-section give a good indication of the effect of conduction of heat through the wall, particularly near the top of the bulk where the thickness of the heated zone appears significant. A three-dimensional model would give more accurate values. It would also be more accurate for shed-type stores having multiple ducts in being able to allow for the increased loss of air at each end of the bulk, thereby improving the timing of relocating the cooler from duct to duct.

There is also potential for optimising the cost of cooling to meet a given quality control criterion by comparing the performance of one grain cooler moved from duct to duct with multiple coolers operating simultaneously over a shorter period.

7. ACKNOWLEDGMENTS

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W B Elder
19 Aug 94

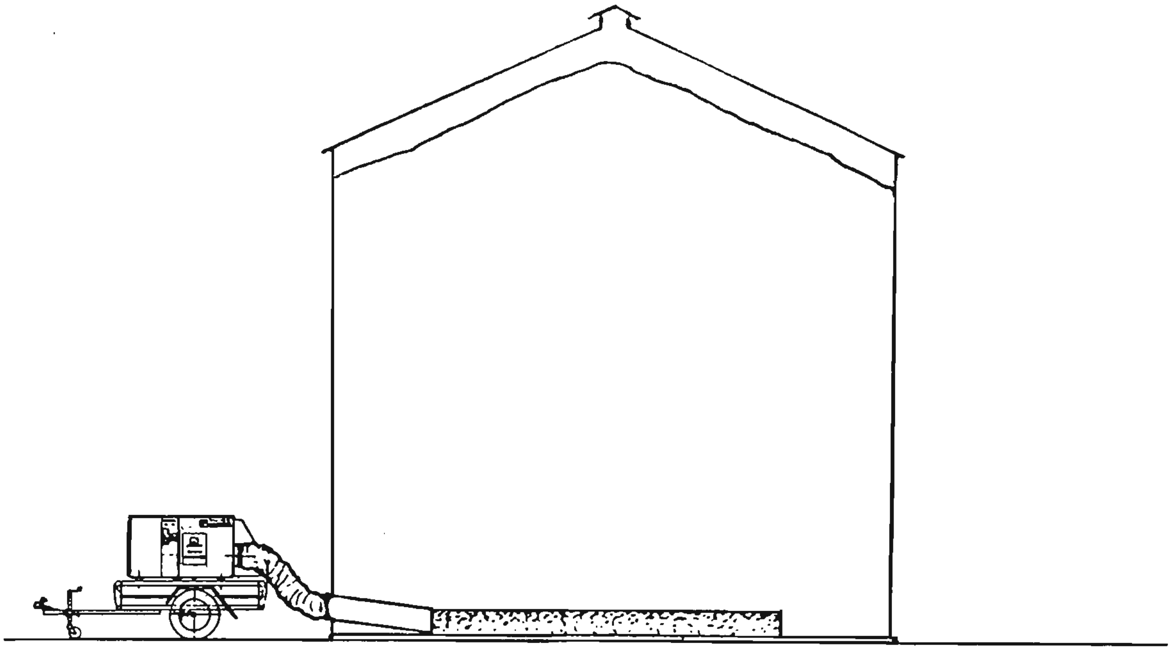


Fig.1 - Typical arrangement for chilling grain using a McBea Mobile Grain Cooler

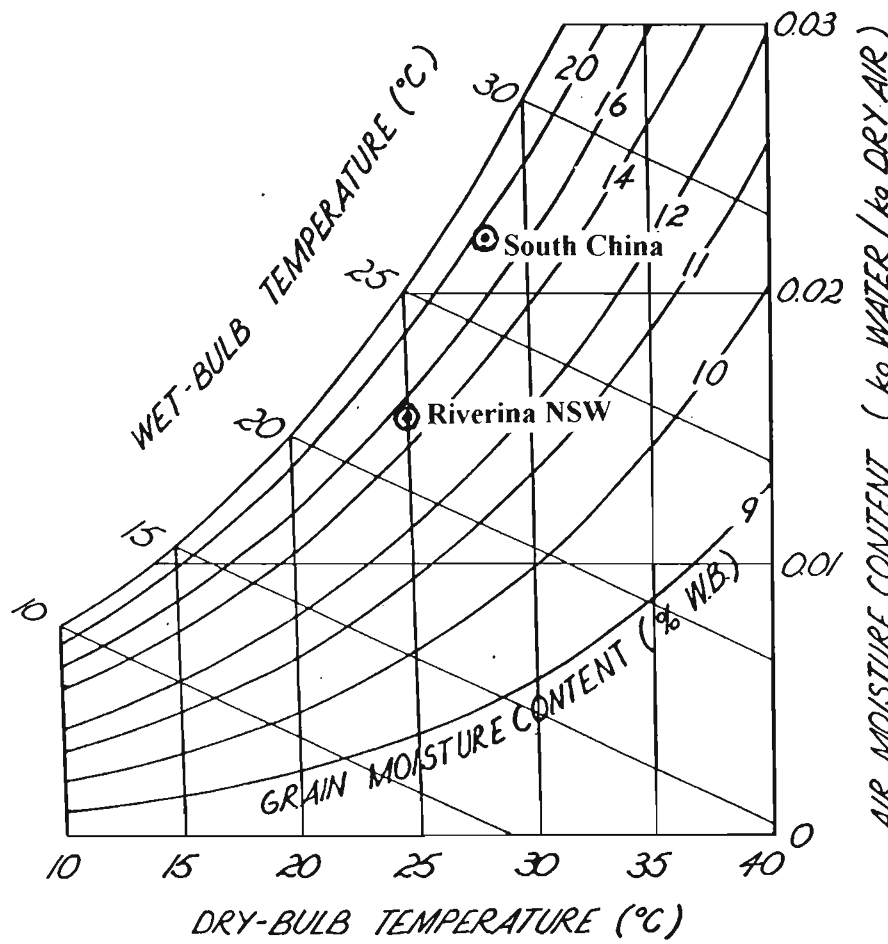


Fig.2 - Mean climatic conditions at the sites of the two grain stores simulated using the mathematical model of heat and moisture transfer and grain quality factors

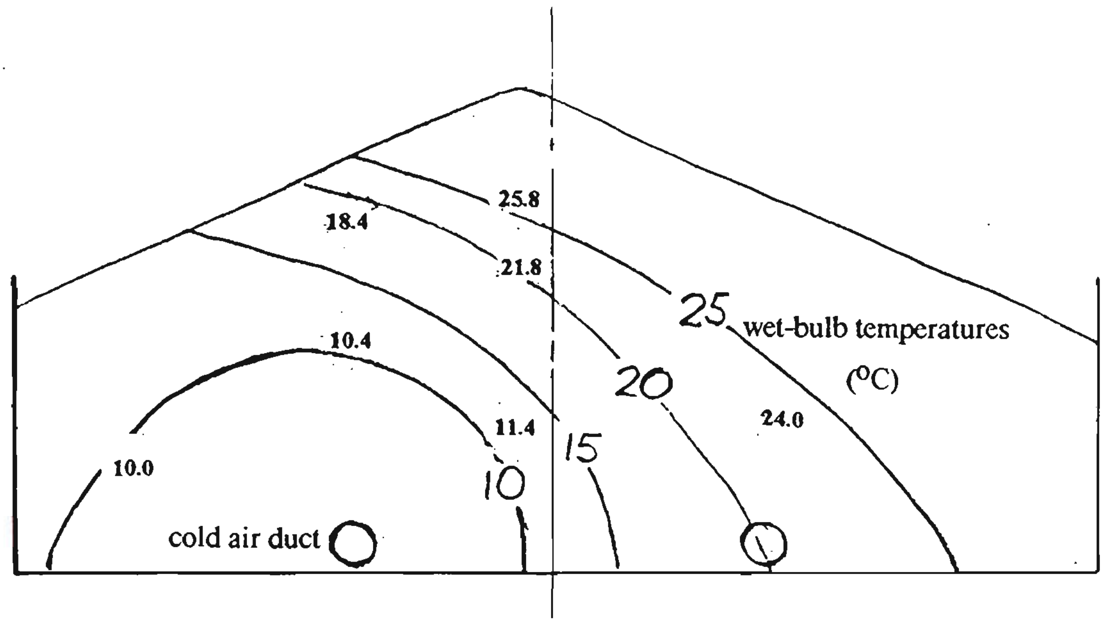


Fig.3 - Wet-bulb temperature profiles estimated from the readings shown taken by the grain merchant after 13 days of cooling barley in a shed-type grain store

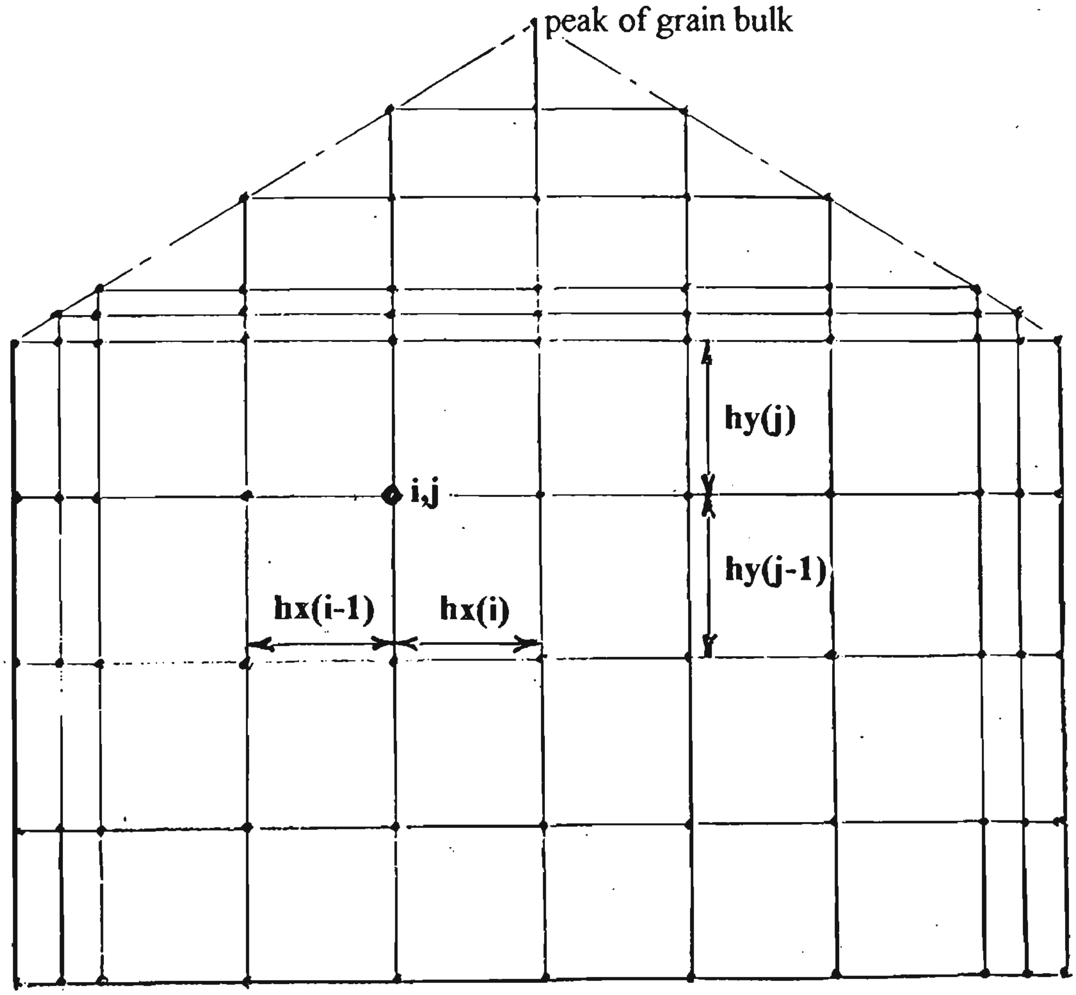


Fig. 4 -The non-uniform finite difference mesh for the two-dimensional model showing closer node spacing at the wall for more accurate calculation of peripheral effects

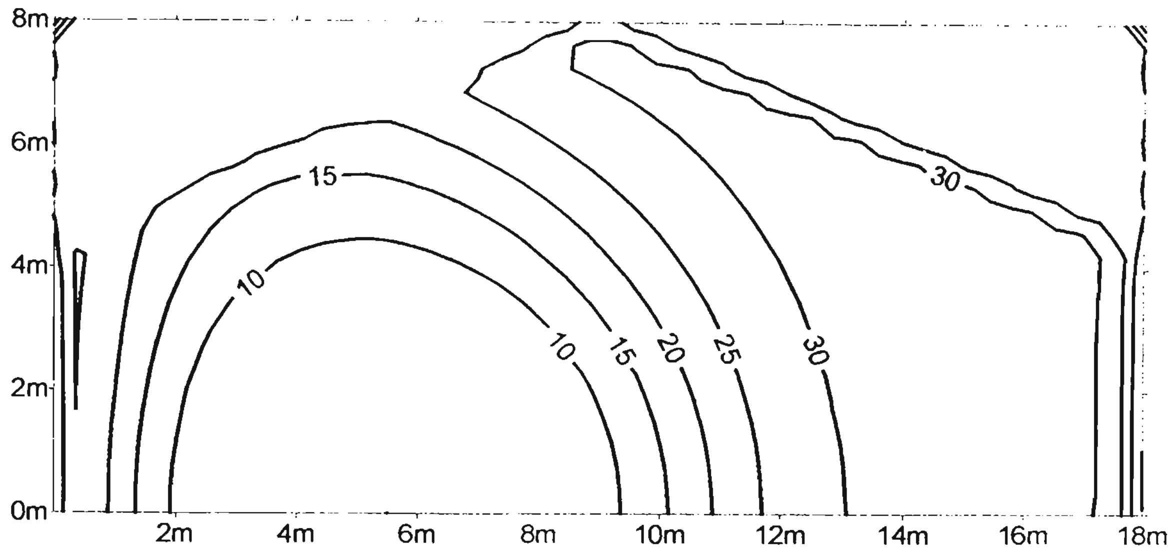


Fig.5 - Wet-bulb temperature profiles after 250 hours at the rated air flow of the cooler on an offset duct as predicted by the numerical mathematical model of the grain bulk. The lack of smoothness in the curves results from the node spacing being 0.85m. Doubling the number of nodes makes program execution time impractically long.

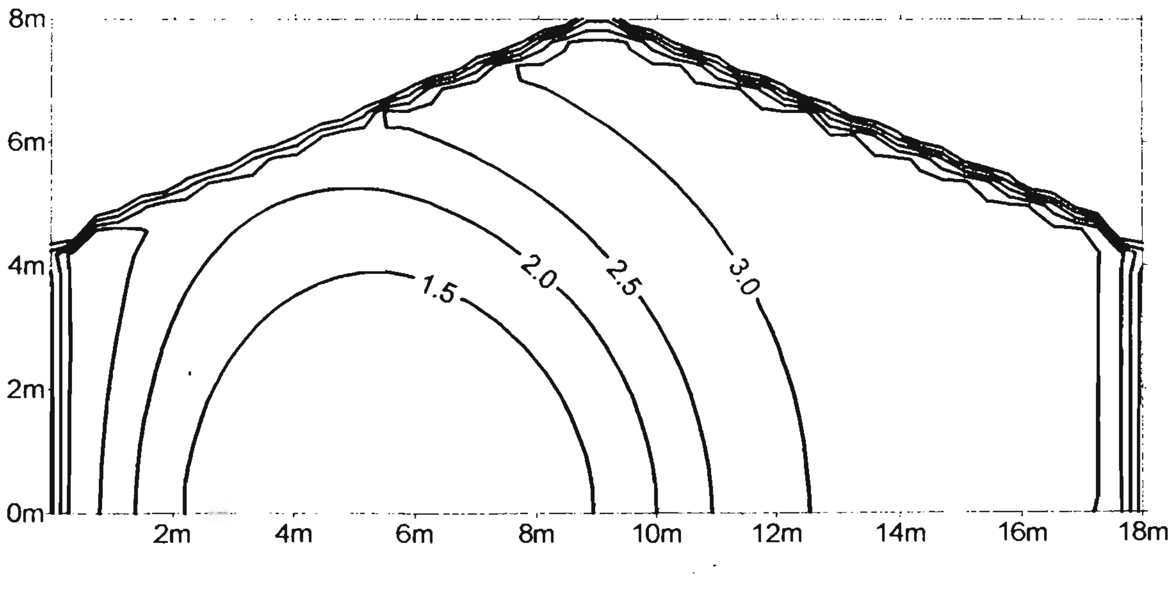


Fig.6 - Calculated multiplication of population of lesser grain borer during cooling via an offset duct after 250 hours of grain cooler operation

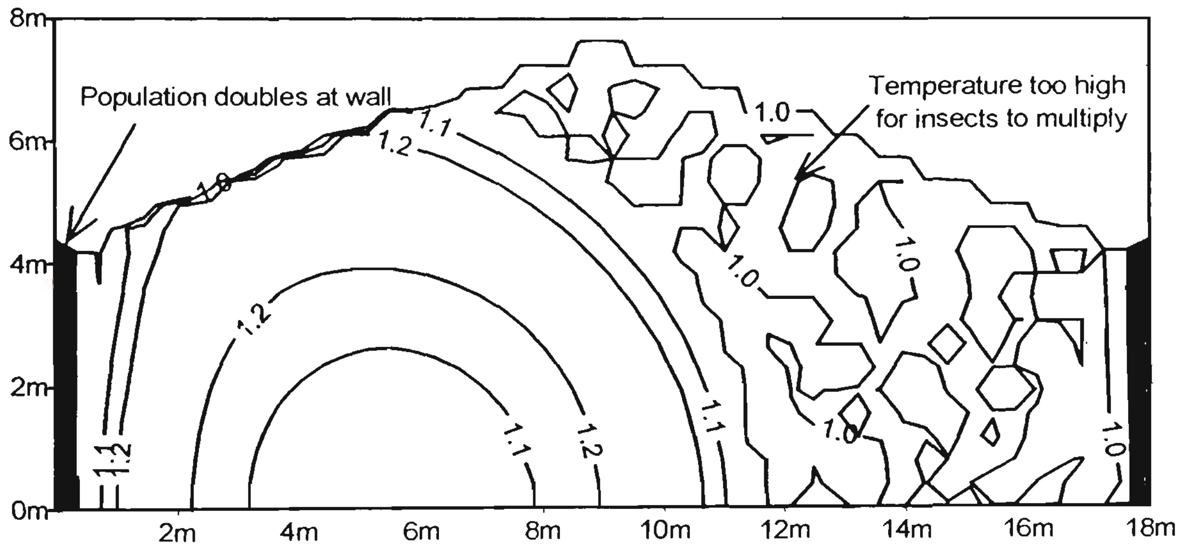


Fig.7 - Calculated multiplication of population of rice weevil during cooling of barley via an offset duct after 250 hours of grain cooler operation

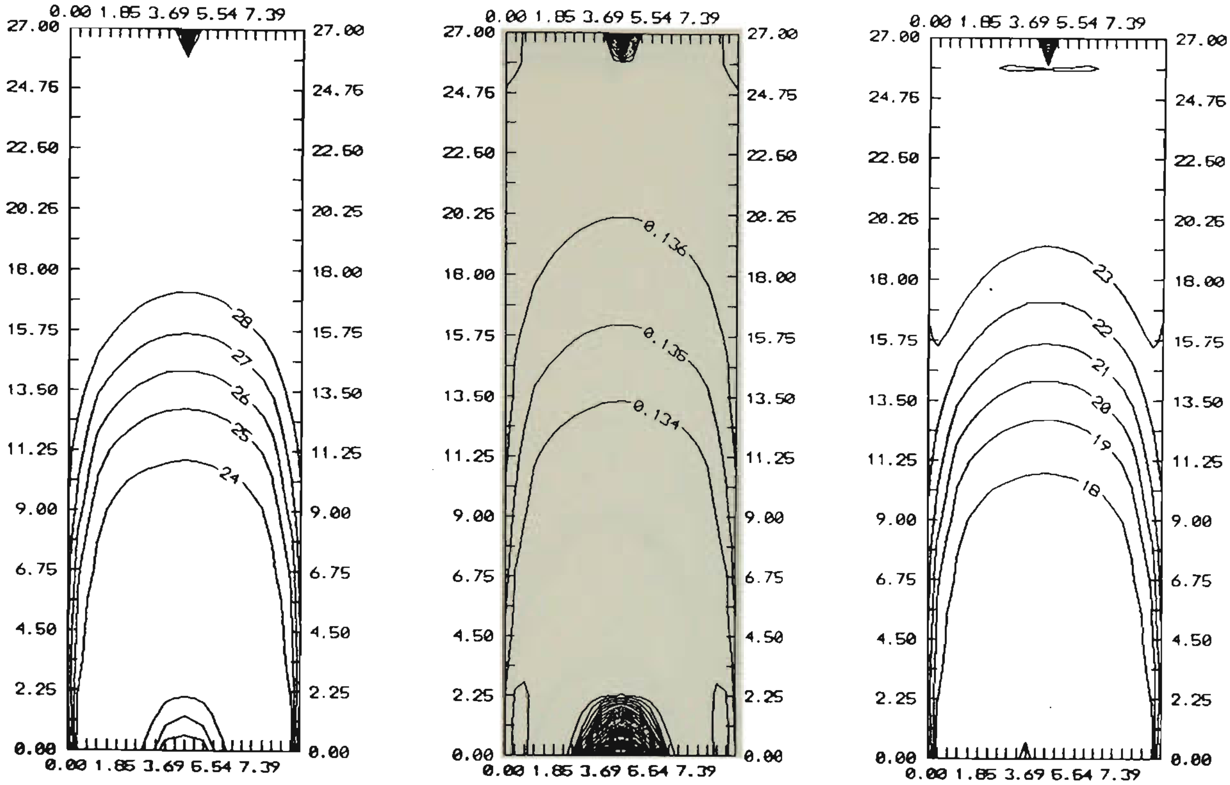


Fig.8 - Temperature, moisture (dry basis) and wet-bulb temperature profiles in a tall silo of barley after 250 hours of grain cooler operation at rated air flow

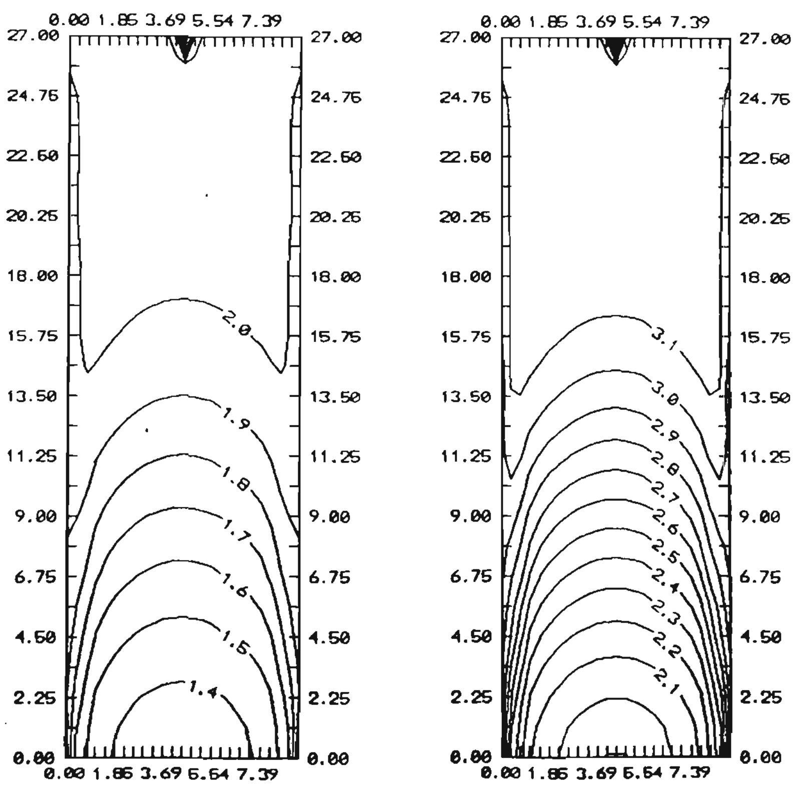


Fig.9 - Calculated multiplication of populations of lesser grain borer and rice weevil in a tall silo of barley after 250 hours of grain cooler operation at rated air flow

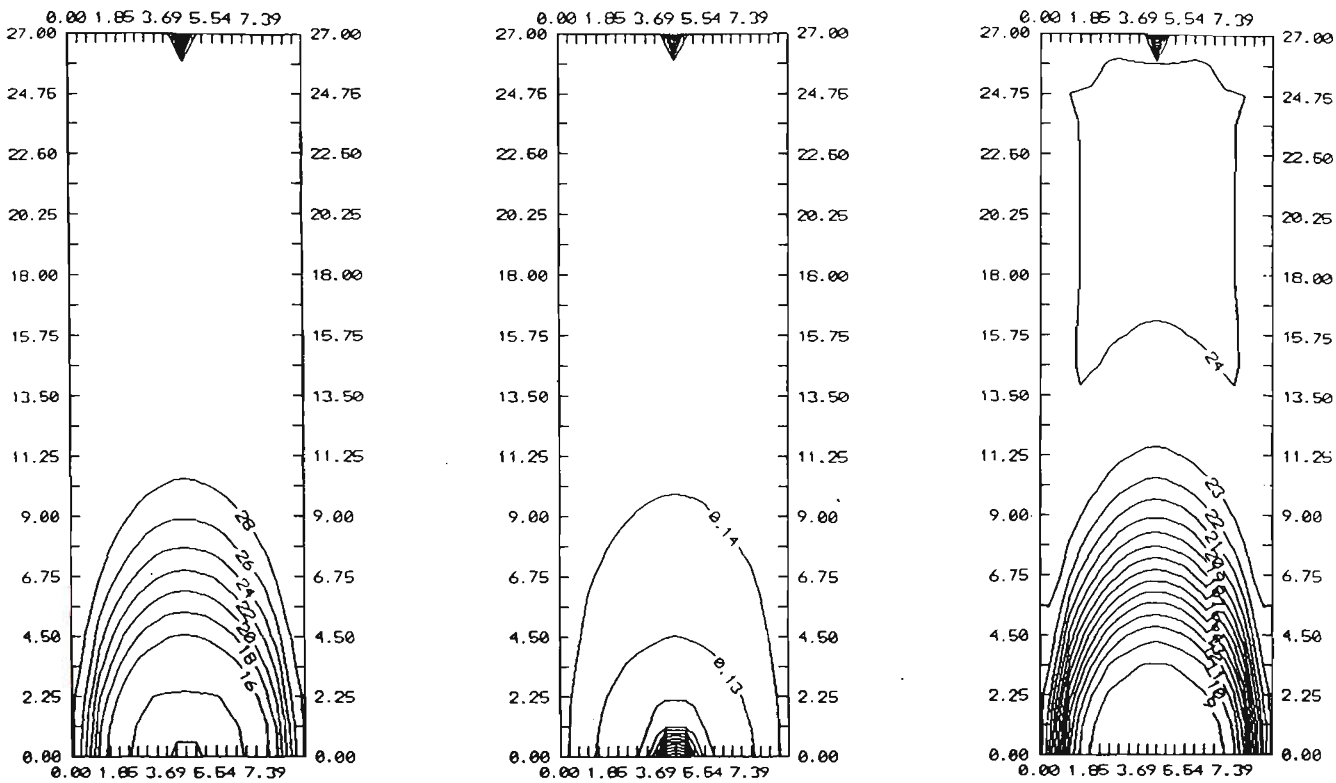


Fig. 10 - Temperature, moisture (dry basis) and wet-bulb temperature profiles in a tall silo of barley after 250 hours of grain cooler operation with air flow throttled

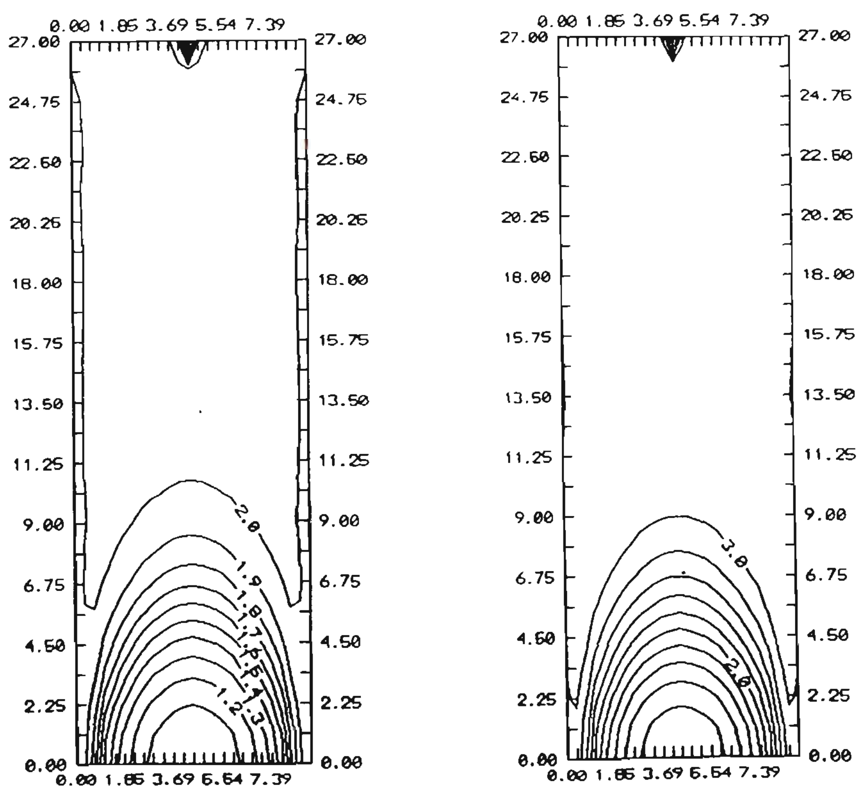


Fig. 11 - Calculated multiplication of populations of lesser grain borer and rice weevil in a tall silo of barley after 250 hours of grain cooler operation with air flow throttled

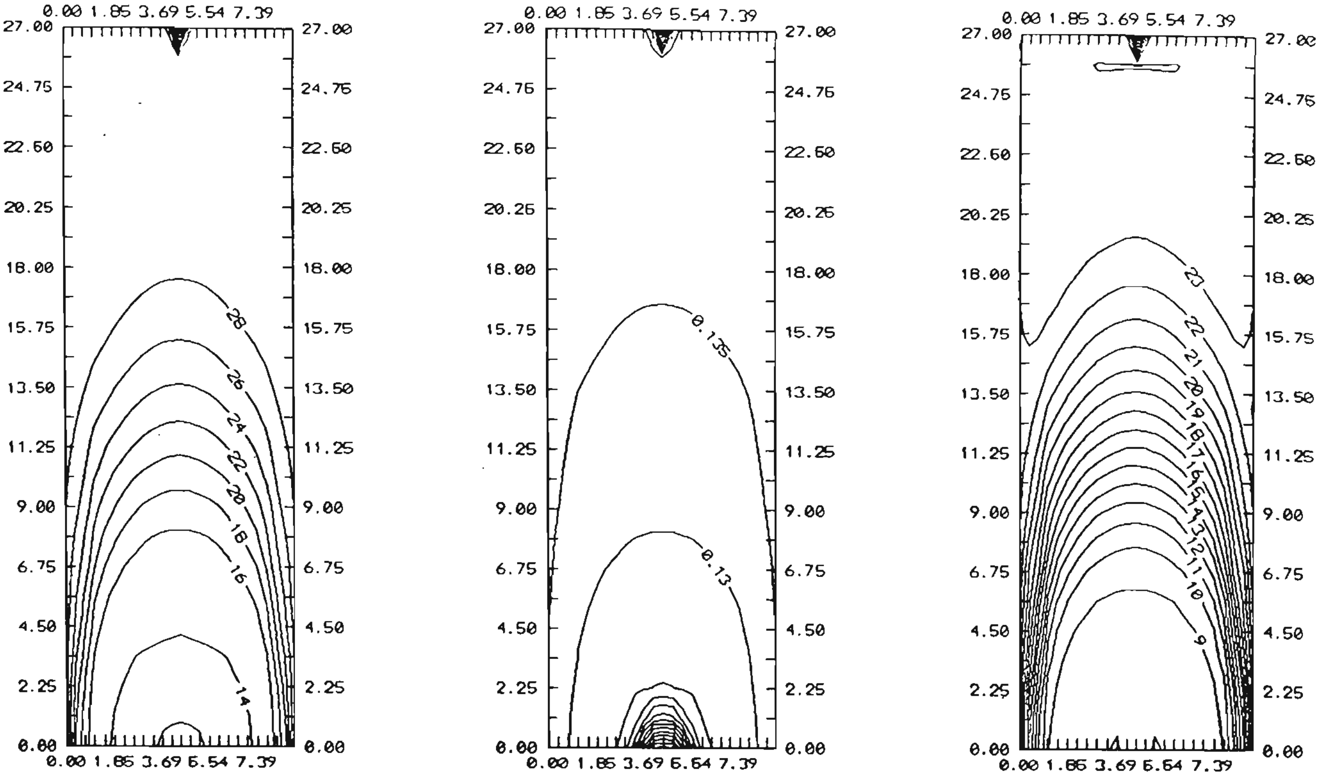


Fig.12 - Temperature, moisture (dry basis) and wet-bulb temperature profiles in a tall silo of barley after 500 hours of grain cooler operation with air flow throttled

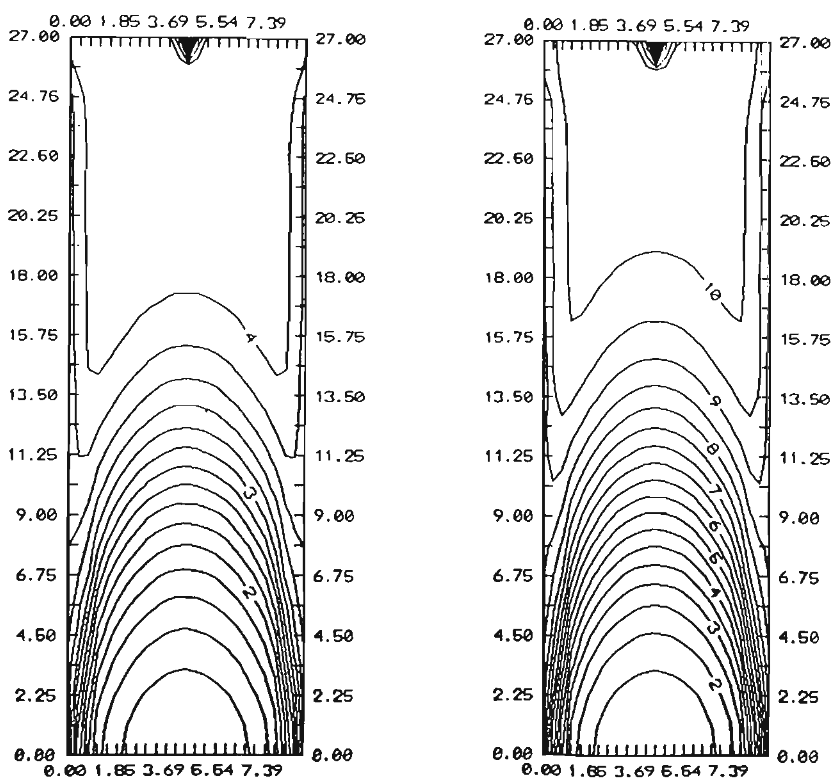
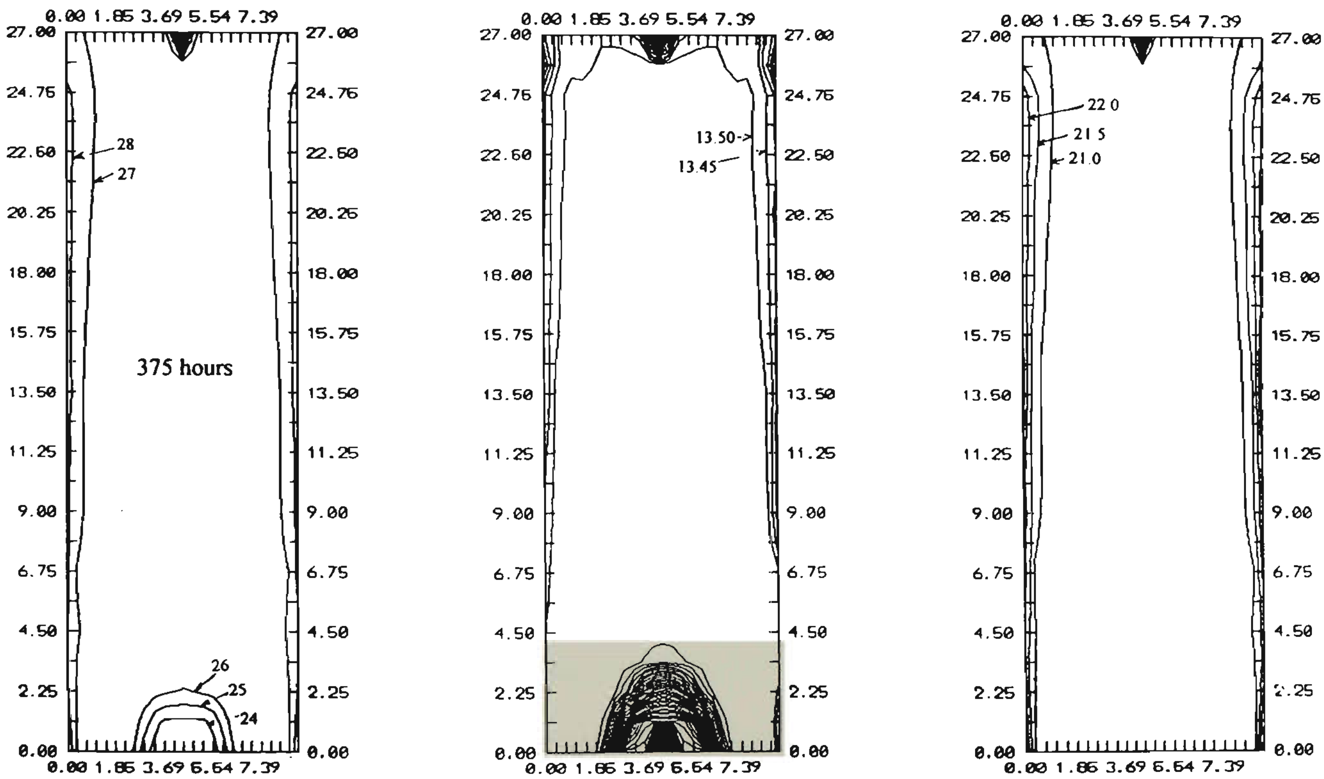


Fig.13 - Calculated multiplication of populations of lesser grain borer and rice weevil in a tall silo of barley after 500 hours of grain cooler operation with air flow throttled



TEMPERATURE MOISTURE CONTENT (dry basis) WET-BULB TEMPERATURE

Fig.14 - Temperature, moisture (dry basis) and wet-bulb temperature profiles in a tall silo of barley after cooling at a high rate of unrestricted air flow through grain cooler.

APPENDIX 2

A paper printed with permission which includes the effects of respiration on the performance of ventilated bulks of grain

More complete mathematical descriptions of heat and moisture transfer in ventilated bulks of respiring grains.

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SUMMARY When cereal and other foodgrains are stored sufficiently moist for the relative humidity of the intergranular air to exceed about 70% there is a danger that fungi will become active. This results in spoilage of the grains, and may lead to the production of toxins that are harmful in concentrations of parts per billion to humans. In this paper the heat and mass conservation equations that govern the performance of ventilated beds of respiring grains are derived. It is shown that as the grain substrate is oxidised one must consider the energy associated with binding water to the substrate. Two extreme cases are studied, namely the one in which the bed of respiring grains is deemed to bridge as the grain kernels oxidise and the one in which the bed slumps under the influence of gravity. It is important to obtain sorption data of cereal grains at lower moisture contents than is customary if solutions of the equations that govern heat and moisture transfer are to more accurately reflect reality.

1.0 INTRODUCTION

When the relative humidity of intergranular air exceeds about 70%, fungal activity is likely to increase. The storage fungi consume the grain kernels, and as they do so their respiration leads to the generation of heat, moisture and carbon dioxide. The higher grain temperatures and moisture contents are likely to promote increased mould activity hence the process is auto-catalysing. Moulds not only reduce the dry matter loss and destroy the useful properties of the grains, but they can produce mycotoxins that are poisonous in very low concentrations, typically parts per billion, to humans and domestic animals. It is therefore good agricultural practice to ensure that grains are stored under conditions such that their intergranular moisture contents are initially less than about 65%. Of itself, this criterion will not prevent mould activity because temperature gradients in the grain bulk can cause natural convection currents and molecular diffusion to transport moisture from warm regions to cooler regions of a grain bulk. This has the effect of locally raising the grain moisture content which may result in mould activity. Like the rate of insect population growth, loss of seed viability, discolouration and other indicators of storage quality, the rate of mould activity appears to be a function of the enthalpy of the intergranular air. The lower the enthalpy, the lower the deleterious activity. Ventilation of stored grain is therefore a useful management tool to reduce mould activity by reducing the temperature. Lower temperatures also reduce the propensity for moisture migration to occur because the intergranular vapour pressure of water is reduced, as are temperature gradients.

Previous researchers have failed to recognise that as the grain kernels oxidise and the dry matter is consumed not only is water formed as a result of combustion, but the water that is bound to the grain substrate is also released. Furthermore, when the grain substrate is consumed the amount of energy released is lower than that expected if the grains were perfectly dry. This is because the bound water reduces the surface energy of the grain substrate. The analysis presented in this paper will address these issues.

Although the physical and chemical processes that occur in respiring bulks of grains are very complicated we shall make some simplifying assumptions. At this stage the assumptions represent idealised behaviour, but they provide an excellent starting point for further research and analysis. For example, as grain kernels are consumed we might assume that the bed of grain bridges, that is to say that it does not collapse, but the void fraction of the air increases.

Extreme cases of bulks of grain that bridge are observed when grain stores containing paddy are being unloaded. It is not uncommon for the angle of repose of the grain to be 90^0, possibly as a result of a high coefficient of friction between the grain kernels and extraneous matter in the grain bulk. The other extreme to be considered is the bed of grain that slumps as it rots away, a phenomenon occasionally observed close to grain stores when small piles of grain are exposed to the weather. These are idealized situations, and in reality both of these may occur simultaneously.

The respiration process in stored grains is represented by the oxidation of hexose, ie.

$$C_6H_{12}O_6 + 6O_2 = 6CO_2 + 6H_2O, \quad \Delta H = q_0 \qquad \text{A2.1}$$

where q_0 is the heat of reaction of one kilogram of hexose at $25^o C$. This specification of temperature implies that the moisture is formed in its condensed state, ie liquid water. If the heat of reaction had been written such that the water formed as a vapour it would assume a lower absolute value because it would not have included the heat of condensation.

2.0 ANALYSIS

In this work we shall first address the problem of the bed of grain that bridges as the substrate of the grain kernels is consumed. The differential equations that govern heat and moisture transfer in the bed of grains will be derived and expressed in terms of volume averaged quantities (*sensu* Thorpe and Whitaker, 1992a,b). However, Thorpe (1994) demonstrates that the governing equations may be derived from the more rigorously based point equations generally associated with continuum mechanics.

2.1 Bridging bed

2.1.1 Mass continuity

As we are dealing with a chemical reaction, namely the oxidation of cellulosic material, it is necessary to account for all of the chemical species involved. In the intergranular spaces these are taken to number four, namely moisture vapour, carbon dioxide, oxygen and non-reacting elements such as nitrogen, the inert gases and so on. We designate these four components by the subscripts 1, 2, 3 and 4 respectively. It is recognized that the grain substrate also reacts, and we must account for any water associated with the substrate as it disappears. The appropriate mass continuity equations for the bridging case are considered first.

Moisture balance

$$\frac{\partial}{\partial t}\left(\varepsilon_\sigma \rho_\sigma W\right)+\frac{\partial}{\partial t}\left(\varepsilon_\gamma \rho_1\right)+\nabla\cdot\left(\varepsilon_\gamma \rho_1 \mathbf{v}_1\right)=S_1 \qquad \text{A2.2}$$

where S_1 is a source term arising from the liberation of moisture as a result of respiration.

Carbon dioxide

$$\frac{\partial\left(\varepsilon_\gamma \rho_2\right)}{\partial t}+\nabla\cdot\left(\varepsilon_\gamma \rho_2 \mathbf{v}_2\right)=S_2 \qquad \text{A2.3}$$

Oxygen

$$\frac{\partial\left(\varepsilon_\gamma \rho_3\right)}{\partial t}+\nabla\cdot\left(\varepsilon_\gamma \rho_3 \mathbf{v}_3\right)=S_3 \qquad \text{A2.4}$$

Nitrogen and other non-reacting gases

$$\frac{\partial(\varepsilon_\gamma \rho_4)}{\partial t} + \nabla \cdot (\varepsilon_\gamma \rho_4 \mathbf{v}_4) = 0 = S_4 \qquad \text{A2.5}$$

Mass balance on the solid substrate

$$\frac{\partial(\varepsilon_\gamma \rho_\sigma)}{\partial t} = S_5 \qquad \text{A2.6}$$

2.1.2 Thermal energy continuity

Having established the mass balance equations in a respiring bed of grain that bridges, the corresponding thermal energy continuity equations are developed thus:

$$\frac{\partial}{\partial t}(\varepsilon_\sigma \rho_\sigma H) + \sum_{i=1}^{4} \left\{ \frac{\partial}{\partial t}(\varepsilon_\gamma \rho_i h_i) + \nabla \cdot (\varepsilon_\sigma \rho_i \mathbf{v}_i h_i) \right\} = k_{eff} \nabla^2 T \qquad \text{A2.7}$$

This may be expanded as follows:

$$H \frac{\partial(\varepsilon_\sigma \rho_\sigma)}{\partial t} + \varepsilon_\sigma \rho_\sigma \frac{\partial H}{\partial t} + \sum_{i=1}^{4} \left\{ h_i \frac{\partial(\varepsilon_\gamma \rho_i)}{\partial t} + h_i \nabla \cdot (\varepsilon_\gamma \rho_i \mathbf{v}_i) \right\} + \sum_{i=1}^{4} \left\{ \varepsilon_\gamma \rho_i \frac{\partial h_i}{\partial t} + \varepsilon_\gamma \rho_i \mathbf{v}_i \cdot \nabla h_i \right\} = k_{eff} \nabla^2 T \qquad \text{A2.8}$$

In equations A2.7 and A2.8 we have defined the enthalpy, H, of moist grains as

$$H = h_\sigma^\circ + c_\sigma (T - T^\circ) + W(h_l^\circ + c_l (T - T^\circ)) + H_W \qquad \text{A2.9}$$

where h_σ^o is the enthalpy of the grain substrate at the reference temperature T^o, W is the moisture content of the grain (dry basis), c_σ is the specific heat of the substrate and H_W is known as the integral heat of wetting, defined by

$$H_W = \int_0^W h_w dW \qquad \text{A2.10}$$

where h_w is the differential heat of wetting. The differential heat of wetting is negative, hence the integral heat of wetting is also negative. This implies that as the moisture content of the grain increases, the enthalpy of the grain decreases. We can think of the pores inside the grain kernels as having energy available for attracting water molecules. When the water molecules are adsorbed on the surfaces of the pores the surface the surface energy is used to bind the molecules, and the enthalpy of the grain is lower. The heat of sorption, h_s, is given by

$$h_s = h_v - h_w \qquad \text{A2.11}$$

Recognising that h_w is negative then h_s is numerically greater than the latent heat of vaporization, h_v, of free water. The heat of sorption is the total amount of energy that must be supplied to evaporate one kilogram of moisture bound to the grains. When a water molecule is bound to the grain surface its movement is restricted because of the force of attraction to the surface. If the water molecule is to be removed from the surface then energy must be supplied, not only to give it the kinetic energy it assumes in the gaseous state, but also sufficient energy to break its bond with the surface. This energy, h_s, is the sum of the latent heat of vaporization, h_v, and the negative of the differential heat of sorption as indicated by equation A2.11.

The enthalpies, h_i, of species 2,3 and 4 are defined at the reference temperature, T^o, by

$$h_i = h_i^o + c_i\left(T - T^o\right) \qquad \text{A2.12}$$

in which c_i is the specific heat of the ith species.

The enthalpy of water vapour is given as

$$h_1 = h_1^o + c_1\left(T - T^o\right) + h_v \qquad \text{A2.13}$$

where h_l^o is the enthalpy of liquid water at the reference temperature T^o, c_l is the specific heat of liquid water and h_v is the latent heat of free water at the temperature T. Equation 13 indicates that the enthalpy of water vapour is calculated by first calculating the enthalpy of liquid water at temperature T, and further energy is added to the water by vaporizing it at temperature T.

The heat of oxidation, Q_r, of the substrate is defined as the difference between the sum of the enthalpies of products of reaction and the reactants. Now, for every kilogram of substrate that is oxidized heat is liberated together with

$$\left(\frac{6\times 44}{180}\right) = 1.47\text{kg of } CO_2 \qquad \text{A2.14}$$

$$\left(\frac{6\times 18}{180}\right) = 0.6\text{kg of water} \qquad \text{A2.15}$$

$$\left(\frac{6\times 32}{180}\right) = 1.07\text{kg of oxygen is consumed} \qquad \text{A2.16}$$

The heat of oxidation, q_0, of one kilogram of drycellulosic material is thus

$$q_0 = 1.47\times h_2 + 0.6(h_1 - h_v) - 1.07h_3 - (H - W(h_1 - h_v) - H_W) \qquad \text{A2.17}$$

In equation A2.17, the heat of vaporization, h_v, is subtracted because the enthalpy, h_l, is of water vapour, whereas q_0 is defined on the basis of liquid water being formed. The term $H - W(h_1 - h_v) - H_W$ refers to the enthalpy of bone dry grain kernel. The rate of liberation of heat per unit volume, Q_r, is therefore given by

$$-Q_r = \sum_{i=1}^{4} h_i S_i - h_v S_1 + S_5(H - W(h_1 - h_v) - H_W) \qquad \text{A2.18}$$

From the mass balance equations A2.1 to A2.5 we can write the above as

$$Q_r = -\sum_{i=1}^{4}\left\{h_i\left(\frac{\partial(\varepsilon_\gamma \rho_i)}{\partial t} + \nabla\cdot(\varepsilon_\gamma \rho_i \mathbf{v}_i)\right)\right\} - \frac{\partial(\varepsilon_\sigma \rho_\sigma)}{\partial t}\left(h_\sigma^0 + c_\sigma\left(T - T^0\right)\right)$$
$$+ h_v S_1 - h_1 \frac{\partial}{\partial t}(\varepsilon_\sigma \rho_\sigma W) \qquad \text{A2.19}$$

Recognising that

$$\frac{\partial H}{\partial t} = \frac{\partial H}{\partial W}\frac{\partial W}{\partial t} + \frac{\partial H}{\partial T}\frac{\partial T}{\partial t} \qquad \text{A2.20}$$

or

$$\frac{\partial H}{\partial t} = \left\{c_1(T - T_0) + H_W\right\}\frac{\partial W}{\partial t} + \left\{c_\sigma + Wc_1 + \frac{\partial H_W}{\partial T}\right\}\frac{\partial T}{\partial t} \qquad \text{A2.21}$$

enables us to write the overall enthalpy balance, equation A2.8, as

$$\left\{W\left(h_1^0 + c_1\left(T - T^0\right)\right) + H_W\right\}\frac{\partial(\varepsilon_\sigma \rho_\sigma)}{\partial t} + \varepsilon_\sigma \rho_\sigma\left\{h_1^0 + c_1(T - T_0) + h_w\right\}\frac{\partial W}{\partial t} +$$
$$\varepsilon_\sigma \rho_\sigma\left\{c_\sigma + Wc_1 + \frac{\partial H_W}{\partial T}\right\}\frac{\partial T}{\partial t} + h_v S_1 - \left\{h_1^0 + c_1\left(T - T^0\right) + h_v\right\}W\frac{\partial(\varepsilon_\sigma \rho_\sigma)}{\partial t}$$
$$-\varepsilon_\sigma \rho_\sigma\left\{h_1^0 + c_1\left(T - T^0\right) + h_v\right\}\frac{\partial W}{\partial t} + \sum_{i=1}^{4}\left\{\varepsilon_\gamma \rho_i \frac{\partial h_i}{\partial t} + \varepsilon_\gamma \rho_i \mathbf{v}_i \cdot \nabla h_i\right\}$$
$$= k_{eff}\nabla^2 T + Q_r \qquad \text{A2.22}$$

Simplifying leads to

$$\left\{c_\sigma + Wc_1 + \frac{\partial H_W}{\partial T}\right\}\frac{\partial T}{\partial t} - h_s \varepsilon_\sigma \rho_\sigma \frac{\partial W}{\partial t} - \rho_\sigma \frac{\partial \varepsilon_\sigma}{\partial t}\int_0^W h_s dW$$
$$+\sum_{i=1}^{4}\left(\varepsilon_\gamma \rho_i \frac{\partial h_i}{\partial t} + \varepsilon_\gamma \rho_i \mathbf{v}_i \cdot \nabla h_i\right) = k_{eff}\nabla^2 T + Q_r - h_v S_1 \qquad \text{A2.23}$$

In arriving at the above equation we have used the identity for the differential heat of sorption, equation A2.11, and formed the identity

$$H_W - h_v W = \int_0^W h_w dW - h_v\int_0^W dW = -\int_0^W h_s dW \qquad \text{A2.24}$$

Now $$\frac{\partial h_i}{\partial t} = c_i \frac{\partial T}{\partial t} \qquad i = 2,3,4$$ A2.25

and $$\frac{dh_l}{dt} = c_l \frac{\partial T}{\partial t} + \frac{\partial h_v}{\partial T} \cdot \frac{\partial T}{\partial t}$$ A2.26

Similarly:

$$\varepsilon_\gamma \rho_i \mathbf{v}_i \cdot \nabla h_i = \varepsilon_\gamma \rho_i \mathbf{v}_i (c_p)_i \cdot \nabla T \qquad i = 2,3,4$$ A2.27

and $$\varepsilon_\gamma \rho_l \mathbf{v}_l \cdot \nabla h_l = \varepsilon_\gamma \rho_l \mathbf{v}_l (c_p)_l \cdot \nabla T + \varepsilon_\gamma \rho_l \mathbf{v}_l \frac{\partial h_v}{\partial T} \cdot \nabla T$$ A2.28

The mass average velocity, $\mathbf{v}_\gamma$, is defined by Bird *et al* (1960) as follows

$$\rho_\gamma \mathbf{v}_\gamma = \sum_{i=1}^{4} \rho_i \mathbf{v}_\gamma$$ A2.29

Since the composition of the intergranular fluid is dominated by air, we have

$$\rho_\gamma \mathbf{v}_\gamma \cong \rho_a \mathbf{v}_a$$ A2.30

Now $$\mathbf{v}_l = \mathbf{v}_a + \mathbf{u}_l$$ A2.31

where $\mathbf{u}_l$ is the diffusion velocity of water vapour through the intergranular spaces, which is several orders of magnitude less than $\mathbf{v}_a$.

2.1.3 Modelling equations

By making use of the approximations discussed above we are able to arrive at the following thermal energy transport equation

$$\left\{c_\sigma + Wc_1 + \frac{\partial H_W}{\partial T}\right\}\frac{\partial T}{\partial t} - h_s\varepsilon_\sigma\rho_\sigma\frac{\partial W}{\partial t} - \rho_\sigma\frac{\partial\varepsilon_\sigma}{\partial t}\int_0^W h_s dW$$

$$\varepsilon_\gamma\rho_a\mathbf{v}_a\cdot\nabla T + \varepsilon_\gamma\rho_a\mathbf{v}_a w\left(c_1 + \frac{\partial h_v}{\partial T}\right)\cdot\nabla T = k_{eff}\nabla^2 T + Q_r - h_v S_1 \qquad \text{A2.32}$$

By stoichiometry

$$S_5 = -1.6S_1 \qquad \text{A2.33}$$

so that the moisture balance equation becomes

$$\varepsilon_\sigma\rho_\sigma\frac{\partial W}{\partial t} + \varepsilon_\gamma\rho_A\mathbf{v}_A\cdot\nabla w = S_1 + 1.6S_1W = S_1(1+1.6W) \qquad \text{A2.34}$$

2.2 A slumping bed of grain

2.2.1 Mass continuity

Analysis of the slumping bed of grains is similar to that of the bridging bed, but the grains fall under the effects of gravity as the grain substrate disappears. The mass balance equation on the grain kernels is expressed as

$$\frac{\partial(\varepsilon_\sigma\rho_\sigma)}{\partial t} + \nabla\cdot(\varepsilon_\sigma\rho_\sigma\mathbf{v}_\sigma) = S_5 \qquad \text{A2.35}$$

and the moisture conservation equation is

$$\frac{\partial}{\partial t}(\varepsilon_\sigma\rho_\sigma W) + \rho\varepsilon_\sigma\mathbf{v}_\sigma\cdot\nabla W + \rho\varepsilon_\sigma W\nabla\cdot\mathbf{v}_\sigma$$

$$+\frac{\partial}{\partial t}(\varepsilon_\gamma\rho_1) + \nabla\cdot(\varepsilon_\gamma\rho_1\mathbf{v}_1) = S_1 \qquad \text{A2.36}$$

whilst the mass conservation equations on the carbon dioxide and oxygen remain the same as for the bridging case.

2.2.2 Thermal energy conservation

The thermal energy conservation equation for the slumping bed of grains is written as

$$\frac{\partial}{\partial t}(\varepsilon_\sigma\rho_\sigma H)+\nabla\cdot(\varepsilon_\sigma\rho_\sigma \mathbf{v}_\sigma H)+\sum_{i=1}^{4}\left\{\frac{\partial}{\partial t}(\varepsilon_\gamma\rho_i h_i)+\nabla\cdot(\varepsilon_\sigma\rho_i \mathbf{v}_i h_i)\right\}=k_{eff}\nabla^2 T \qquad \text{A2.37}$$

in which may be inserted the definitions of the enthalpies h_i and H to obtain

$$\begin{aligned}
&\varepsilon_\sigma\rho_\sigma\left(h_w^0+c_w\left(T-T^0\right)+h_w\right)\frac{\partial W}{\partial t}\\
&\varepsilon_\sigma\rho_\sigma\left(c_\sigma+Wc_l+\frac{\partial H_W}{\partial T}\right)\frac{\partial T}{\partial t}\\
&+\varepsilon_\sigma\rho_\sigma\left(h_\sigma^0+c_\sigma\left(T-T^0\right)+H_W+W\left\{h_l^0+c_l\left(T-T^0\right)\right\}\right)\nabla\cdot\mathbf{v}_\sigma\\
&\varepsilon_\sigma\rho_\sigma\mathbf{v}_\sigma\cdot\left\{h_l^0+c_l\left(T-T^0\right)+h_w\right\}\cdot\nabla W\\
&+\varepsilon_\sigma\rho_\sigma\mathbf{v}_\sigma\left\{c_\sigma+Wc_l+\frac{\partial H_W}{\partial T}\right\}\cdot\nabla T\\
+&\sum_{i=1}^{4}\left\{h_i\frac{\partial(\varepsilon_\gamma\rho_i)}{\partial t}+h_i\nabla\cdot\left(\varepsilon_\gamma\rho_i\mathbf{v}_i\right)\right\}+\sum_{i=1}^{4}\left\{\varepsilon_\gamma\rho_i\frac{\partial h_i}{\partial t}+\varepsilon_\gamma\rho_i\mathbf{v}_i\cdot\nabla h_i\right\}=k_{eff}\nabla^2T
\end{aligned} \qquad \text{A2.38}$$

The definition of the heat of reaction, equation A2.18, may be used in equation A2.38 to obtain the thermal energy conservation equation for a slumping bed of grains, namely

$$\begin{aligned}
&\varepsilon_\sigma\rho_\sigma\left\{c_\sigma+Wc_l+\frac{\partial H_W}{\partial T}\right\}\frac{\partial T}{\partial t}-\varepsilon_\sigma\rho_\sigma h_s\frac{\partial W}{\partial t}\\
&-\varepsilon_\sigma\rho_\sigma\nabla\cdot\mathbf{v}_\sigma\int_0^W h_s dW-\varepsilon_\sigma\rho_\sigma h_s\mathbf{v}_\sigma\cdot\nabla W\\
&+\varepsilon_\sigma\rho_\sigma\left\{c_\sigma+Wc_l+\frac{\partial H_W}{\partial T}\right\}\mathbf{v}_\sigma\cdot\nabla T\\
&+\varepsilon_\gamma\rho_a\mathbf{v}_a\cdot\nabla T+\varepsilon_\gamma\rho_a\mathbf{v}_a w\cdot\left(c_w+\frac{\partial h_v}{\partial T}\right)\cdot\nabla T\\
&=k_{eff}\nabla^2T+Q_r-h_vS_l
\end{aligned} \qquad \text{A2.39}$$

3.0 DISCUSSION

The equations that govern heat and moisture transfer in beds of respiring grains that bridge, equations A2.32 and A2.34, contain additional terms not encountered in the work of previous authors. For example, in equation A2.32 we observe the term $\rho_\sigma \dfrac{\partial\varepsilon_\sigma}{\partial t}\int_0^W h_s dW$ which is essentially the rate of disappearance of substrate per unit volume of grain bed multiplied by the integral heat of sorption. This term represents the surface energy used to bind moisture to the substrate of the grain that is being consumed by respiration. In grain with a moisture content of 18% wet basis and a temperature of 30°C it can be ascertained from graphical data provided by Thorpe (1986) that the term has a value on the order of 5. This is in the same order of the term $\varepsilon_\gamma \rho_a \mathbf{v}_a \cdot \nabla T$ when air flows result from natural convection currents. However, the term is necessarily lower that the heat source resulting from respiration. It will also be observed that in equation A2.32 the heat source term is slightly reduced to account for the fact that water vapour is deemed to form as a result of respiration, although some of this may be subsequently be adsorbed by the grain. The energy associated with this adsorption is subsumed in the term $h_s \varepsilon_\sigma \rho_\sigma \,\partial W/\partial t$. It can be observed that equation A2.32 contains a term, $\partial H_W/\partial T$, rarely, if ever, encountered in the grain storage literature, and this arises from an effect of temperature on the enthalpy of moist grains. Its magnitude is on the order of 0.1 of the other terms in the premultiplier of $\partial T/\partial t$. It can seen from equation A2.34 that the rate of change of grain moisture content, $\partial W/\partial t$, is augmented by the liberation of moisture arising directly from respiration, as well as that liberated as a result of the substrate disappearing signified by the amount $1.6 S_1 W$.

Equation, A2.39, that governs the thermal energy transport in a respiring bed of grains that slumps contains several terms that result from the convection of energy in the grains. The term $\varepsilon_\sigma \rho_\sigma \nabla \cdot \mathbf{v}_\sigma \int_0^W h_s dW$ arises from the transport surface energy associated with the disappearance of the grains substrate, and the term $\varepsilon_\sigma \rho_\sigma h_s \mathbf{v}_\sigma \cdot \nabla W$ arises from the convection of the heat of sorption. Sensible heat is convected by the moving bed of grains, and this is represented by $\varepsilon_\sigma \rho_\sigma \{c_\sigma + W c_w + \partial H_W/\partial T\} \mathbf{v}_\sigma \cdot \nabla T$. Again the term $\partial H_W/\partial T$ has been retained.

If the above, more complete representations are to be used to simulate heat and moisture transfer in respiring beds of grains it is essential that accurate values of the differential heat of wetting, h_s, be determined for grain moisture contents very close to zero ($W = 0.01$), say. The values may also be used to calculate the integral heat of wetting, H_W. Because the term $\partial H_W/\partial T$ occurs in analyses of beds of grain that do not respire, extension of the sorption data to regions of low moisture content is regarded as important.

4.0 CONCLUSIONS

Equations that govern heat and mass transfer in bulks of ventilated grains have been derived. Mass and energy source terms associated with moisture that is bound to the grains substrate appear in the equations. Two extreme cases are analysed, namely bulks of grain that bridge and bulks that slump as the substrate is consumed. It is pointed out that values of the differential heat of sorption, h_s, be determined for a wider range of moisture contents than is customary if the equations that govern heat and moisture transport in grains are to be solved to more accurately reflect reality.

5.0 ACKNOWLEDGEMENT

The author is grateful to Professor I. D. G. Mackie, Head, Department of Civil and Building Engineering, for encouraging this research to be carried out.

6.0 NOTATION

a	Refers to dry air
c	Specific heat, J/kg/K
H	Enthalpy of grain kernel, J/kg
h_i	Enthalpy of ith species, J/kg
h_i^o	Reference enthalpy of ith species, J/kg
h_s	Differential heat of sorption, J/kg
h_v	Heat of vaporisation of free water, J/kg
h_w	Differential heat of wetting, J/kg
h_w^o	Reference enthalpy of water, J/kg
H_W	Heat of wetting of grain, J/kg

i	Represents ith species
k_{eff}	Effectiove thermal conductivity of grain bulk, W/m/K
q_o	Heat of respiration of grain, J/kg
Q_r	Volumetric heat of respiration, W/m^3
S_i	Volumetric rate of mass generation, kg/s/m^3
T	Temperature, K
T^o	A reference temperature, K
$\mathbf{u}$	Diffusion velocity, m/s
$\mathbf{v}$	Velocity, m/s
w	Humidity of air, kg/kg
W	Grain moisture content, kg/kg

Greek symbols

γ	Refers to the intergranular air
ε	Void fraction
σ	Refers to the grains
ρ	Density, kg/m^3

7.0 REFERENCES

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APPENDIX 3

Commercial literature on mobile grain coolers and natural aeration and fan control equipment supplied by M^cBea Grain Protection Services, Melbourne, Victoria

The M^cBea Mobile Grain Coolers have been developed by the candidate on the basis of the concept of using the tooling and componentry of quantity produced standard commercial roof-top air conditioning packaged units. The current Mobile Grain Cooler Model RM180GC is based on the RM180H heat pump which has been in production at Lovelock Luke Emailair, Blackburn, Victoria for many years and which has service support throughout Australia and New Zealand.

For the grain silo cooling application, the refrigeration system has been modified to avoid flooding of the condenser at low ambient and ice-up of the evaporator assembly which comprises two standard air conditioning coils in series. In the unlikely event that the evaporator becomes blocked with grain dust, there will be very little delay in replacing the standard production coils, whereas a special coil common in other grain coolers may take two months to obtain from local suppliers. The indoor air fan of the heat pump is replaced by a high pressure centrifugal fan especially selected not only to provide the ability to deliver refrigerated air via severely restricted openings (Fig. 2.1) but also to limit the relative humidity of the air leaving the Cooler to a level which will avoid the development of mould and risk of toxins. Unlike other grain coolers, the fan is located downstream of the evaporator and this avoids the need to provide special humidity control after heat and air flow straightening devices between the fan outlet and evaporator. Both these costly features of other grain coolers are therefore eliminated. It is understood that the German grain cooler is being modified to take advantage of this simple design feature initiated by the candidate.

The control of the Cooler is very simple in that it runs continuously until the cooling front has emerged from the top of the grain bulk. This can be detected by the special monitoring equipment developed by the candidate as described in Section 4.4 and Appendix 4, and which was used by the operator for the silos shown in Fig. 2.1 to determine when to move the Cooler to the next silo. The observations that were made are shown in Fig. A3.1. Alternatively, the operator may estimate the time taken based on the nominal grain cooling capacity signified by the model number. For example, the Model RM180GC has a grain cooling capacity of 1800 tonnes per month.

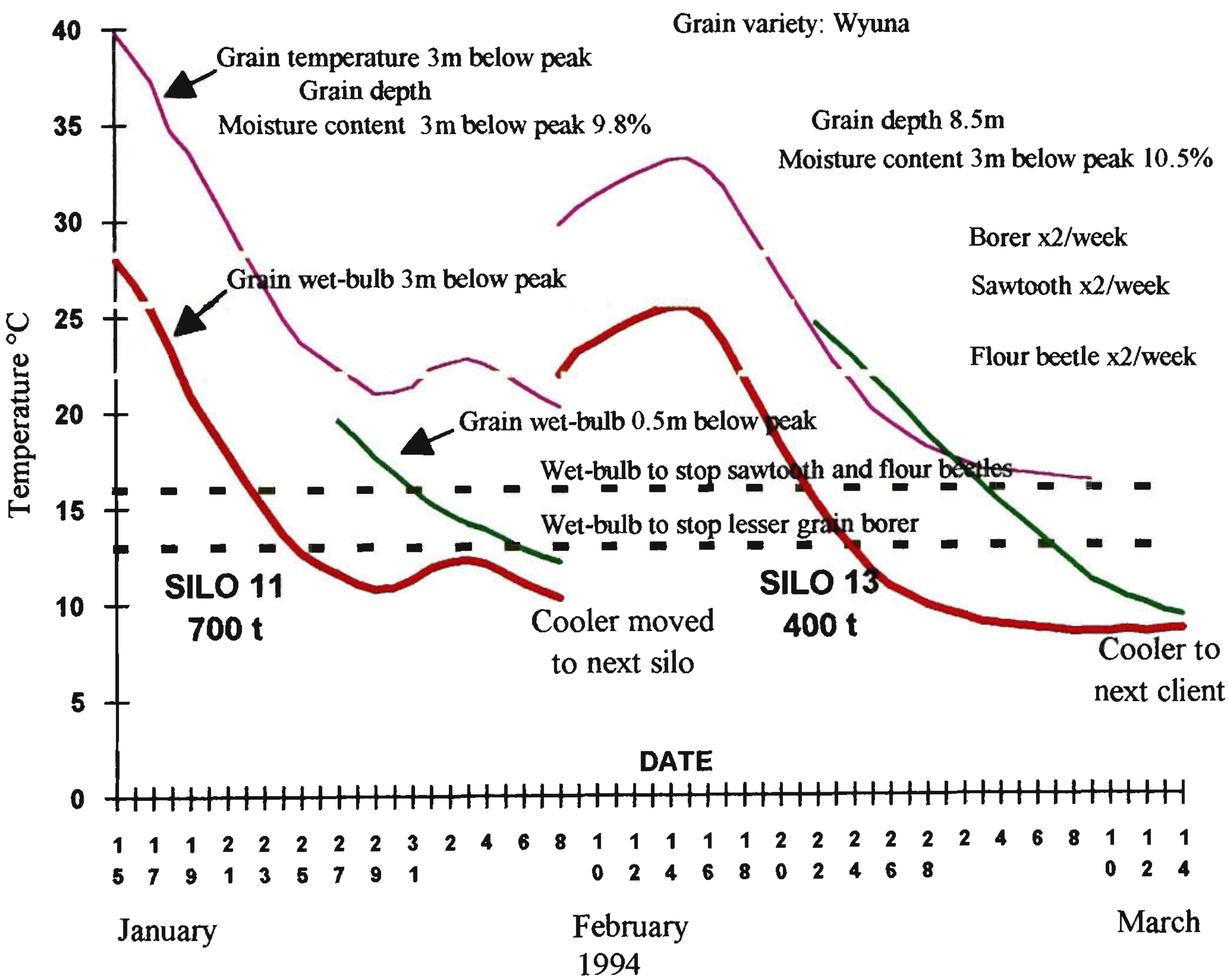
M^c^BEA SERVICES

Registered Office: 2 Gilbert Court, Parkdale, Victoria 3195, AUSTRALIA
Tel: (03) 580 5814 International +61 3 580 5814 Fax: (03) 587 6404

GRAIN WET-BULB TEMPERATURE REDUCTION IN SILOS OF WHEAT USING A M^c^BEA MOBILE GRAIN COOLER CONNECTED TO THE AUGER TUBE

January-March 1994

Grain wet-bulb temperatures 3m and 0.5m below peak



Courtesy L G Moore Holdings, Horsham, Victoria

Fig. A3.1 - Grain temperature and wet-bulb temperature measurements in the top one third of two bulks using M^c^Bea Services MS1 Deep Probe Grain Wet-bulb Temperature Measuring System to identify the progress and completion of cooling by a M^c^Bea Mobile Grain Cooler. Horizontal lines show the threshold wet-bulb temperatures for multiplication of three grain infesting insects of concern to the operator, and the wet-bulb temperatures at which the populations would double in a week
Reproduced with the permission of M^c^Bea Grain Protection Services, Melbourne

When the Cooler is towed from one silo site to another, the oil and any liquid refrigerant in the sump of the compressor will become mixed particularly if moving over rough terrain. A one hour time delay on switching on the power is incorporated in the control system to allow the sump heaters to boil off any liquid refrigerant before the oil is pumped into the crankshaft bearings. The same one hour time delay comes into operation when a fault occurs and the system overloads. Most overload faults that occur in remote areas result from poor power supply line conditions such as low voltage or phase failures caused by storm damage. The overloads in the McBea Mobile Grain Cooler system are all automatically resetting and, after the subsequent one hour time delay, the plant will attempt to restart. This special feature introduced by the candidate ensures that the plant continues to operate in circumstances where regular supervision is not feasible as in the case of many remote grain storage sites. In one case reported, a service local technician removed the auto reset feature on one of the Coolers on McBea's hire fleet and this resulted in almost no cooling of a silo full of organically grown wheat over a period of some two months. There was absolutely nothing wrong with the plant and, since restoring the auto reset feature, it has been operating satisfactorily ever since. The time delay also permits the operator to check the direction of the phases at a new site by pressing the push button on the control panel and observing the direction of the fan motor through a window provided for the purpose. An adaptor cable with reversed wiring is supplied as standard equipment so that the operator can remedy the effects of any wiring problem without having to call an electrician. At remote sites, this avoids any significant delay or illegal tampering with switchboards.

A special independent suspension system shown in Fig. 4.1 is provided for the trailer axle to absorb shock and ensure stability during towing over corduroy roads or rough terrain. This also minimises the risk of fatigue failure of the refrigeration system's copper tubing and capillaries. The trailer construction provides space for the storage during transport of the necessary flexible insulated ducting, the 30m long electrical extension cable, the phase reversing adaptor cable and the 10m long drain hose for leading condensed water off the evaporator coil to a suitable sump or drain.

All the design features mentioned above and the publicity brochure are attributable to the candidate.

McBea Services,
2 Gilbert Court,
Parkdale, Victoria 3195, Australia.
Telephone: (Melb.) (03) 580 5814
International + 61 3 580 5814

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REGIONAL LIFE

SWAN HILL

Brian Elder, McBea Grain Protection, Melbourne, John and Darren Pearson, Coarse Grain Trading, Kyalite, NSW, and local McBea representative Ken Shipp, Kerang, discuss grain cooling at the Swan Hill Field Days.

Grain cooling system ensures product quality

One of the most interesting stands at the Swan Hill Field Days was the McBea Services' site, where grain cooling equipment was displayed.

The coolers offer grain and food storage operators low cost solutions to quality loss problems and control of storage insect infestation.

The high degree of mobility of McBea coolers allow larger operators to service a multiplicity of sites and situations.

New opportunities now exist for the Australian grain and foods industries to acquire Australian manufactured equipment which has the potential for revolutionising storage practices and strategies.

Grain cooling can be used for maintaining germination of seed, cooling bag stacks, holding wet grain, slow drying of wet grain, preventing increase in free fatty acids, arresting deterioration of pregerminated grain and preserving soybean and similar short-life seed. Other advantages include reducing the number of fumigations, retarding surface caking build-up, drying grain at the silo walls and cooling grain in trucks.

Grain can be refrigerated in any situation such as on shed floors, in tanks or bins, in bags stacks or on the ground outside.

For further information, contact McBea Services (03) 580 5814.

Organic growing promoted

People interested in organically grown fruit and vegetables found plenty to see at the Mid-Murray Organic Growers Association stand at the Swan Hill field days this year.

The association was originally known as the Swan Hill and District Organic Growing Group when it was formed in 1989.

It brought together local organic growers who were keen to provide information to commercial growers, home gardeners and other interested people.

Commercial growers in the group felt incorporation would allow for more emphasis on commercial growing practices, as well as allowing access to government funding and support for research and industry development.

The association has held its own field days and other promotional activities.

Developments in the organic farming industry are passed onto members and the association helps to source propagating and processing materials, equipment and information for members.

The association is also seeking market opportunities for organic produce within Australia and overseas.

Interested people can contact (050) 329-236 for more information.

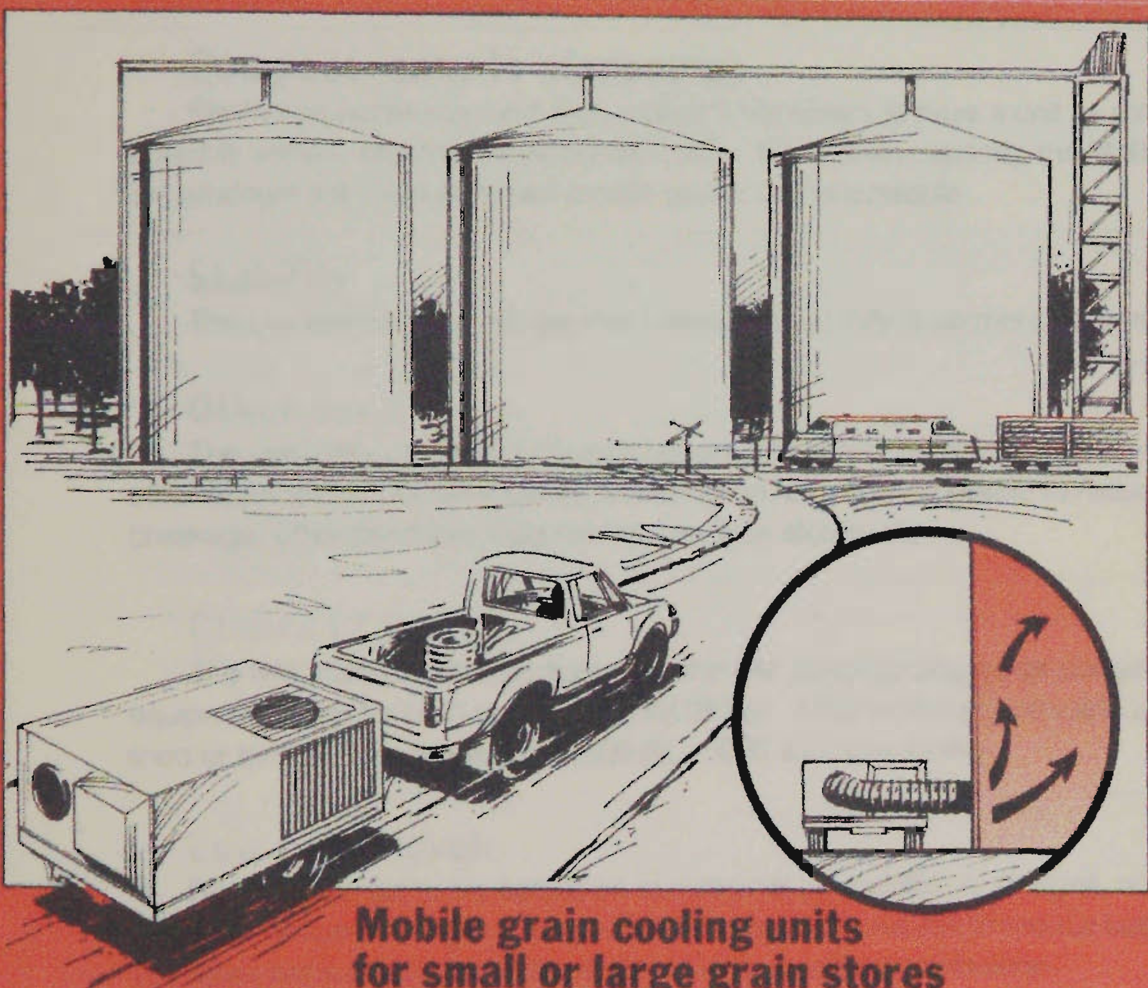
McBEA
GRAIN COOLING UNITS

RM SERIES
TRAILER MOUNTED

For protection of bulk-stored cereal grains, oilseeds, pulses, pellets

Stop • quality loss • weevil attack • mould growth • caking • insecticide breakdown

Maintain • viability • freshness • wholeness • reputation



Mobile grain cooling units for small or large grain stores

MODEL	RM180GC	RM500GC
Nominal cooling capacity*	18kW	50kW
Nominal air flow	400L/s	1100L/s
Grain cooled per month**	1800 tonnes	5000 tonnes

* At 35°C DB/24°C WB ambient
** Approximate capacity

Cold grain - Safe grain

Year round protection

McBea Grain Cooling Units provide continuous protection of bulk-stored grains, seeds and pulses when permanently installed on silos.

Short-term cooling

The mobility of the unit allows intermittent snap cooling of a number of silos at different locations.

Compact, easy to manoeuvre

Restricted access around silos makes it necessary to have a unit as small as possible without creating servicing difficulties. For a given capacity, the McBea Units are amongst the most compact mobile grain coolers available.

Stability

The low centre of gravity permits towing of the Units at normal road speeds.

Other uses

The versatility of the Unit creates opportunities for imaginative users to discover other applications not necessarily for bulk grain, e.g. cooling pellets to reduce breakage, other products, bag stacks, produce stores, etc.

Choice of models

The two standard models based on the RM Series packaged air conditioning equipment cater for both small silos (RM180GC–1800 tonnes/month) and large shed or bin type grain stores (RM500 GC–5000 tonnes/month).

Low noise levels

Because the Units are based on commercial air conditioner designs, noise will hardly be noticed. At night, the out-door fan speed decreases to reduce noise further. The trailer tyres add to the features for isolating mechanical vibration.

Straightforward maintenance and service

Most local refrigeration mechanics anywhere in the world could easily service the Unit, and quickly recognise the standard air conditioning configuration and observe that the system is comprised of commonly used refrigeration components.

McBEA SERVICES 2 Gilbert Court Parkdale Victoria 3195 Australia Tel (03) 580 5814 International +61 3 580 5814

The Cooling Process

The Cooling Unit draws air in through a filter and refrigeration coil, then delivers it at a low temperature to air distribution ducting in the silo via a flexible insulated duct and a suitable connection. Hot grain near the ducting quickly heats the air which then travels through the rest of the grain and leaves at a high temperature. The cooling effect first appears as a cold zone around the ducting and as more air is forced through the grain this zone enlarges progressively. Eventually the cold zone will extend throughout the whole bulk and the air leaving the grain will be cold. The Unit can then be switched off or removed to another silo.

Benefits

Refrigerating bulk-stored grain has many advantages:

- **Eliminates** harmful air currents which cause surface caking and mould
- **Lowers** the pressure of the water vapour in the air between the grains to greatly reduce diffusion thus preventing the build-up of moisture on the walls and floor
- **Overcomes** condensation problems under the roof by decreasing the dew-point temperature of the air in the silo
- **Reduces** the risk of aflatoxins from mould growth
- **Prevents** development of grain infesting insects (weevils, beetles and moth larvae)
- **Retards** loss of seed viability
- **Maintains** freshness
- **Postpones** retreatment with insecticides by preventing rapid breakdown
- **Offers** safe, quality storage without chemical treatment
- **Facilitates** the circulation of a fumigant throughout the whole bulk
- **Provides** a rapid means of venting a silo after a fumigation*
- **Allows** grain to be taken from the silo and used at any time
- **Replaces** traditional role of turning grain to break up hot spots
- **Permits** full use of total storage capacity – no empty bins needed
- **Instills** confidence in holding grain for commercial advantage
- **Removes** heat caused by respiration of the grain, insects and moulds
- **Arrests** deterioration of wet grain in storage whilst awaiting transfer to a drier

*NB: Absorbed fumigant may continue to be released from the stored seed kernels after rapid venting.

Operating Cost

The approximate cost of running the unit can be calculated easily using the ruling price for electrical energy and the average rate of 5kWh per tonne of grain. Low cost off-peak electricity can be used to advantage.

Grain Cooling Capacity

MODEL No.	COOLING RATES (tonnes per month)**
RM180GC	1800
RM500GC	5000

** Based on intake air at 35°C DB/24°C WB and final grain wet-bulb of 13°C.

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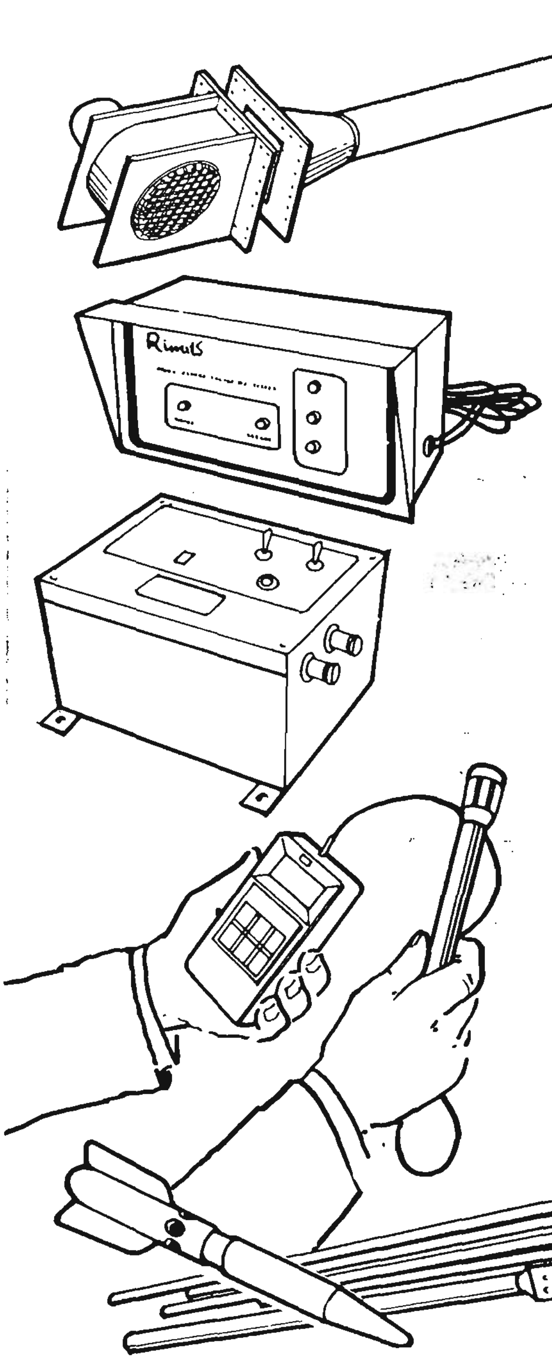
Other grain cooling and quality control products from McBea

"Australian research working"

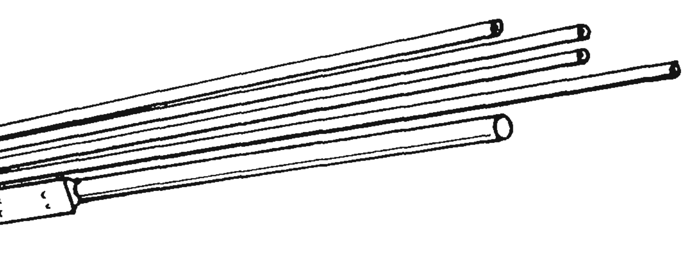


Natural aeration equipment for any application. High-pressure low-flow fans of simple design - no belts - designed for the job, interchangeable duct connections. Industry-funded research used in development of cooling system.

Aeration controllers operating on Australian patented time-proportioning principle. Electronic version providing dual output for simultaneous control of aeration fans on silos containing grain at different temperatures. Robust electro-mechanical version with alternate settings for hot grain (as harvested or out of a drier) - RAPID - or progressively aerated grain - NORMAL. Simple mechanism means that faults can be remedied by competent local electrician.

Maintenance free air wet-bulb temperature sensing equipment for insertion in grain. Also useful for moisture content measurements. Long cables supplied for intergranular air wet-bulb temperatures deep in bulks.

Inserting rods and clamp provided for grain wet-bulb cables, deep sampling probes, gas lines, etc.



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engineering services

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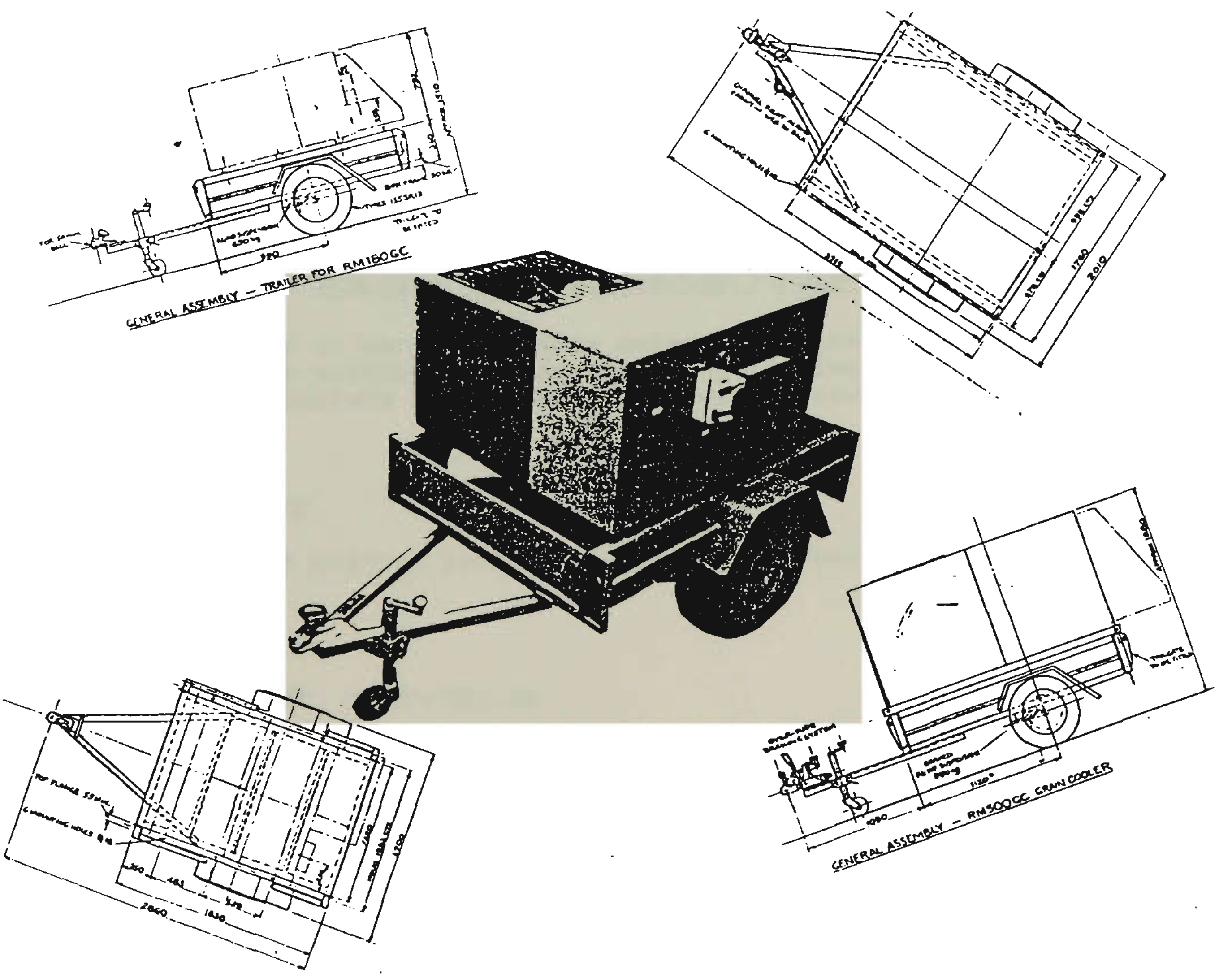
McBEA MOBILE COOLING UNITS

RM SERIES TRAILER MOUNTED

MOBILE REFRIGERATION PLANT

For protection & quality control of farm produce & stock feed

STOPS - quality loss, mould growth, insecticide breakdown
MAINTAINS - crop standard for marketing, freshness, reputation



Used for pre-cooling of produce on farm before loading into cool store
Can be used with palletised produce and feed or for cooling livestock sheds

McBea Services, 2 Gilbert Court, Parkdale Vic 3195. Tel (03) 580 5814

THE COOLING PROCESS

Refrigerated air from the Cooler passes into the product or space and quickly replaces the hot air. The cold air in contact with produce is soon warmed by the heat of the product and therefore must be replaced again and again until the product is cooled. Once cooled, the product will remain cool for a long time unless hot outside air is forced through it or the product is respiring and generating its own heat. Most horticultural products respire less as the temperature is lowered. Dry produce or dry grain and seed do not appear to respire at all.

YEAR ROUND PROTECTION

McBea Cooling Units provide continuous protection of produce and stock feed and can also be used for cooling housed livestock.

SHORT TERM COOLING

The mobility of the Unit allows intermittent snap cooling of a number of storages at different locations.

COMPACT, EASY TO MANOEUVRE

Restricted access in many situations makes it necessary to have a unit as small as possible without creating servicing difficulties. For a given capacity, McBea Coolers are the most compact and versatile units available.

STABILITY

The low centre of gravity permits towing of the Coolers at normal road speeds.

LOW NOISE LEVELS

Because the Coolers are based on commercial air conditioner designs, noise will hardly be noticed. At night, the out-door fan speed decreases to reduce noise further. The trailer tyres also isolate mechanical vibration.

STRAIGHTFORWARD MAINTENANCE & SERVICE

Most local refrigeration mechanics anywhere in the world could easily service the Cooler and quickly recognize the standard air conditioner configuration and observe that the system is comprised of commonly used refrigeration components.

McBea Services, 2 Gilbert Court, Parkdale Vic 3195. Tel (03) 580 5814

OTHER USES OF McBEA MOBILE COOLERS . . .

COOLING:

Pigs and livestock sheds
Aircraft undergoing maintenance in hangars
Work areas in factories, packing sheds, etc
Large marquees and other enclosed outdoor structures
For cooling jobs at sporting venues
Controlling the quality of produce in bag stacks
Removing respiration heat of bulk-stored potatoes
Cooling beverages before loading into coolroom
Solidifying polyethylene film during plastic bag manufacture
Roses and other sensitive flowers in glass houses
Boning rooms at abattoirs

DRYING:

Drying honey in the humid tropics
Slow drying of wet grain in silos
Low temperature drying of grass seeds.

HEATING:

The out-door fan which exhausts hot air upwards from the Cooler can be used to heat a space if the cold air from the Cooler outlet is ducted to outside. An additional duct to bring outside air into the inlet of the Cooler is required. Wheeling the Cooler into the space to be heated is preferable to ducting the hot air from the fan.

BENEFITS

Reduces chemical dependency
Maintains fruit quality leading to high sugar values
Pre-cools produce and packaged beverages before loading into coolroom keeping coolroom temperature even.
Stops growth of rhizopus mould and other fungal growths
Eliminates caking and mould in silos
Inhibits attack by insects
Removes internal heat
100% fresh air
Versatile

OPERATING COST

The approximate cost of running the unit can be calculated easily using the ruling price of electrical energy and an average power consumption for the Model in use - 12kW for RM180GC; 34kW for RM500GC. Approx $1 or $3 per hour
Low cost off-peak electricity can be used to advantage.
Converters available for sites where single phase power only is available.

COOLING CAPACITY

Model No.	Refrigerating effect on in-going air	Cooling rates for produce	Nominal air flow cubic metres per sec
RM180GC	18kW	60 tonnes/day	0.4
RM500GC	50kW	150 tonnes/day	1.1

Capacity is based on ambient of 35°C and cold air remaining in contact with product long enough to remove heat. For large objects such as rock melons, the cooling rate may be affected by the time taken for heat to flow from inside the object to its surface where the refrigerated air can remove it.

McBea Services, 2 Gilbert Court, Parkdale Vic 3195. Tel (03) 580 5814

McBEA
GRAIN PROTECTION
100% Australian Owned
Established 1978

M^{c}BEA SERVICES

Registered Office: 2 Gilbert Court, Parkdale, Victoria 3195, AUSTRALIA
Tel: (03) 580 5814 International +61 3 580 5814 Fax: (03) 587 6404

ALL PRICES IN AUSTRALIAN DOLLARS EX WORKS MELBOURNE

Mobile Grain Coolers

"RM180GC" with enhanced humidity control	$24,100
In-store Grain Drying Attachment for RM180GC	$ 1,970
Short Term Hire	$ 110 first day
(decreasing by $5 each subsequent day to $40 per day flat rate after a fortnight)	
Long Term Hire	$1210 per month
(payable in advance - equivalent to $40 per day)	

Also Available:-

* Ducting for Inside Grain Storages
* Complete Natural Aeration Systems
* Temperature/Moisture Content Measuring Instruments
* Silo level Indicators
* Climatic Analysis and Grain Storage Consulting Services.

When hiring:-

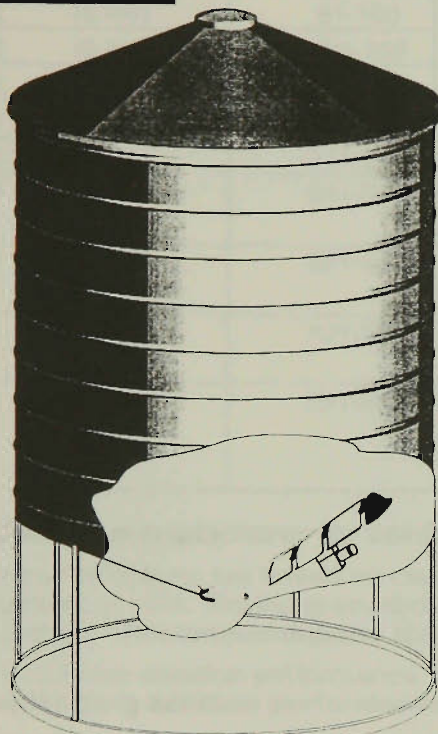
* All Coolers are insured.
* Delivery charges to and from site to be met by client.
* Where three phase power is not available a diesel generator set can be provided at an additional hire cost if not available locally.

12 months warranty applies to all new Grain Coolers purchased.

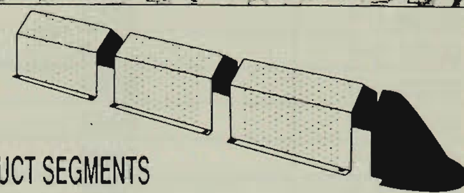
GCPRICES.WPS 26 February 1994

DOWNFIELDS ENGINEERING PTY LTD

EFFECTIVE GRAIN AERATION EQUIPMENT FOR CONICAL STEEL BASE SILOS

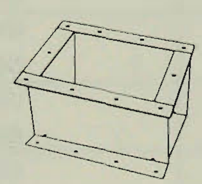


SYSTEM LAYOUT



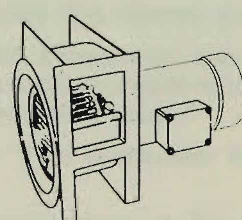
DUCT SEGMENTS

- various lengths and sizes to give correct air distribution for different silo models.



FAN SPACER

- Enables fan to be quickly removed even when silo is full of grain.



FAN UNIT

- Sized to give correct airflow for different silo models.

ADVANTAGES OF A DOWNFIELDS SYSTEM

- Self cleaning design. Ducting made in segments which fit down flush with the silo cone.
- Non-clogging louver perforations give the flexibility of being able to store both large and small grains.
- Fan has unique design features to accommodate a fumigation kit and can be used with either a fully sealed silo or else with a gas recirculation system.
- Fan is located out of the weather to give maximum motor protection.
- Easy to install.
- Packaged for safe and economical shipping.

Selection Chart for "CS" Series Aeration Equipment

Based on silo diameter and tonnes capacity *

Minimum silo diameter	Tonnes	Fan unit	Ducting
12ft (3.6m)	30-40	F185	F-1.2/200
12ft (3.6m)	41-50	F185	F-1.4/200
15ft (4.5m)	51-70	F185	F-1.8/200
15ft (4.5m)	71-80	F370	F-1.8/200
18ft (5.4m)	81-100	F370	F-2.1/200
20ft (6.1m)	101-150	F370	F-2.4/200
20ft (6.1m)	151-180	F650	F-2.4/250
20ft (6.1m)	181-210	F650	F-2.7/250
24ft (7.5m)	211-240	F650	F-3.5/250
24ft (7.5m)	241-320	F370 F370	F-2.7/200 F-2.7/200
30ft (9.1m)	321-400	F370 F650	F-2.7/200 F-4.2/250
30ft (9.1m)	401-520	F650 F650	F-4.2/250 F-4.2/250
30ft (9.1m)	521-600	F650 F650 F650	F-4.2/250 F-4.2/250 F-4.2/250

*** Consult manufacturer for configurations outside the above guidelines**

- These selections are based on clean whole grain with a maximum moisture content of 14%. Storing grain above 14% requires careful consideration. Refer to brochure **"Recommendations for aerating high moisture grain"**
- To optimise aeration performance, consult brochure **"Fan controller for optimising aeration performance"**
- For effective fan performance, air must be able to escape through the silo roof. Check suggestions in the brochure **"Ventilation of silo roofs when using aeration."**

Manufactured by:

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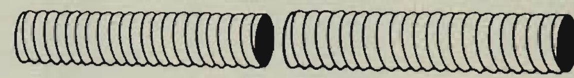
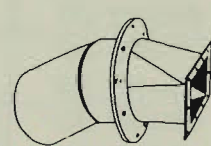
DOWNFIELDS ENGINEERING PTY LTD

EFFECTIVE GRAIN AERATION EQUIPMENT FOR CONICAL CONCRETE BASE SILOS



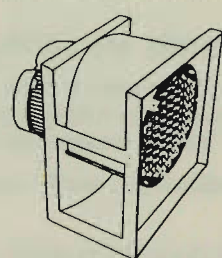
DUCT SEGMENTS

- various lengths and sizes to give correct air distribution for different silo models.



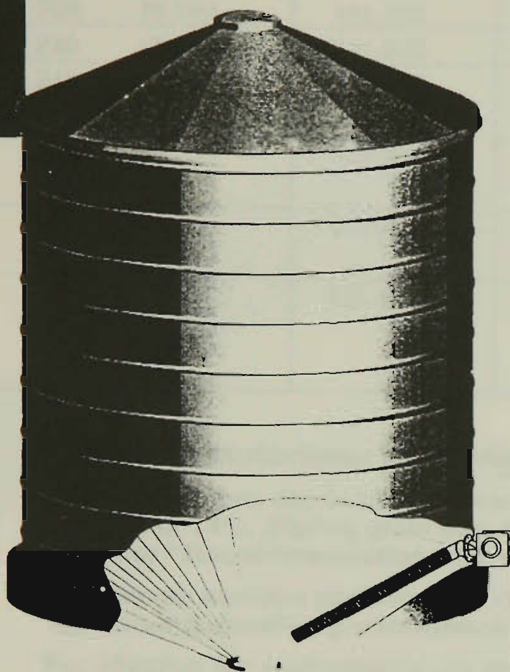
WALL TRANSITION

- Adjustable to suit various cone slopes.



FAN UNIT

- Sized to give correct airflow for different silo models.



SYSTEM LAYOUT

ADVANTAGES OF A DOWNFIELDS SYSTEM

- Ducting supplied in segments to facilitate easy removal for silo clean–down.
- Corrugated tubular duct for greater strength to support large grain depths.
- Fine perforations giving the flexibility of being able to store both large and small grains.
- Fan has unique design features to accommodate a fumigation kit and can be used with either a fully sealed silo or else with a gas recirculation system.
- Easy to install.
- Compact for safe and economical shipping.

Selection Chart for "CC" Series Aeration Equipment

Based on silo diameter and tonnes capacity *

Minimum silo diameter	Tonnes	Fan unit	Transition	Ducting
15ft (4.5m)	50-70	F185	CC-130/200	T-1.8/200
15ft (4.5m)	71-80	F370	CC-145/200	T-1.8/200
18ft (5.4m)	81-100	F370	CC-145/200	T-2.1/200
18ft (5.4m)	101-150	F370	CC-145/200	T-2.4/200
20ft (6.1m)	151-180	F650	CC-190/250	T-2.4/250
20ft (6.1m)	181-210	F650	CC-190/250	T-2.7/250
24ft (7.5m)	211-240	F650	CC-190/250	T-3.5/250
24ft (7.5m)	241-320	F370 F370	CC-145/200 CC-145/200	T-2.7/200 T-2.7/200
30ft (9.1m)	321-400	F370 F650	CC-145/200 CC-190/250	T-2.7/200 T-4.2/250
30ft (9.1m)	401-520	F650 F650	CC-190/250 CC-190/250	T-4.2/250 T-4.2/250
30ft (9.1m)	521-600	F650 F650 F650	CC-190/250 CC-190/250 CC-190/250	T-4.2/250 T-4.2/250 T-4.2/250

*** Consult manufacturer for configurations outside the above guidelines**

- These selections are based on clean whole grain with a maximum moisture content of 14%. Storing grain above 14% requires careful consideration. Refer to brochure **"Recommendations for aerating high moisture grain"**
- To optimise aeration performance, consult brochure **"Fan controller for optimising aeration performance"**
- For effective fan performance, air must be able to escape through the silo roof. Check suggestions in the brochure **"Ventilation of silo roofs when using aeration."**

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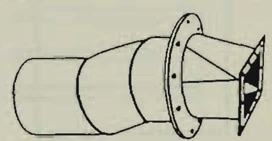
DOWNFIELDS ENGINEERING PTY LTD

EFFECTIVE GRAIN AERATION EQUIPMENT FOR BULK GRAIN SHEDS

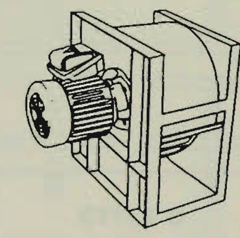
DUCT SEGMENTS

- various lengths and sizes to give correct air distribution for different shed sizes.



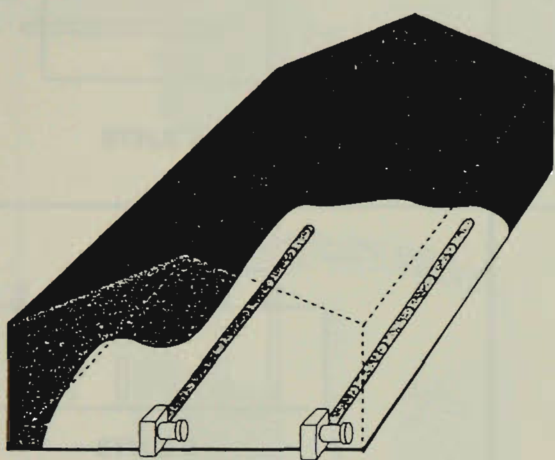
WALL TRANSITION

- Suits various shed wall profiles.



FAN UNIT

- Sized to give correct air performance for various shed sizes.



SYSTEM LAYOUT

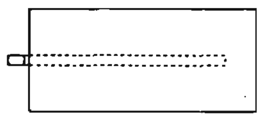
ADVANTAGES OF A DOWNFIELDS SYSTEM

- Ducting supplied in segments to facilitate easy installation and retrieval when filling and emptying the shed.
- Robust corrugated tubular duct for maximum life.
- Fine perforations giving the flexibility of being able to store both large and small grains.
- Special "dog leg" transition simplifies connection of fan and ducting through the shed wall.
- Fan is designed to allow a fumigation kit to be added.
- Packaged for economical shipping.

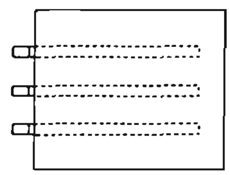
Selection Chart for Bulk Grain Shed Aeration Equipment

Based on shed width x length x height and tonnes capacity*

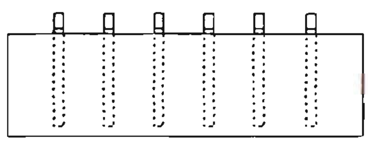
In flat storages, one or more ventilation ducts are required and the layout of the duct system becomes important. The principle is to keep the air paths through the grain as nearly equal as possible. As there are so many combinations of the shed widths, lengths and grain height at the wall, it is impractical to provide a selection chart. Each storage shed must be considered individually to give optimum results. However the diagrams below are included to illustrate the preferred duct layouts for a range of bulk sheds.



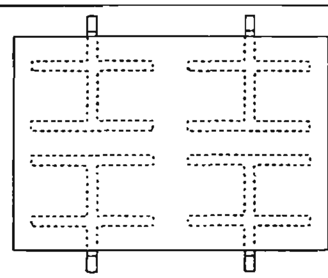
STYLE A



STYLE B



STYLE C



STYLE D

*** Consult manufacturer for configurations outside the above guidelines**

- These selections are based on clean whole grain with a maximum moisture content of 14%. Storing grain above 14% requires careful consideration. Refer to brochure **"Recommendations for aerating high moisture grain"**
- To optimise aeration performance, consult brochure **"Fan controller for optimising aeration performance"**
- For effective fan performance, air must be able to escape through the shed roof. Check suggestions in the brochure **"Ventilation of silo roofs when using aeration."**

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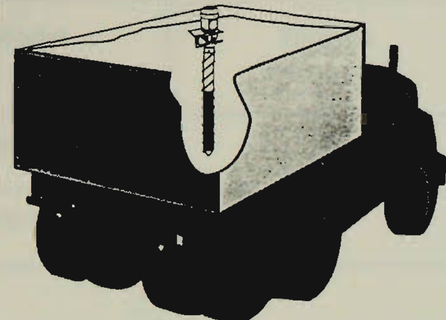
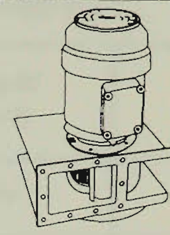
DOWNFIELDS ENGINEERING PTY LTD

EFFECTIVE GRAIN AERATION EQUIPMENT FOR TEMPORARY APPLICATIONS

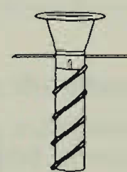


TYPICAL APPLICATIONS



FAN UNIT

- Supplied with lead ready to plug in and operate.



TRANSITION SECTION

- Robust fan connection and wind–in tube section.

DUCT SECTION

- Special "flight" attachments to wind duct deep down into the grain.

ADVANTAGES OF A DOWNFIELDS SYSTEM

- Tubular ducting has fine perforations giving the ability to ventilate small seeds and grains.
- Large handle is conveniently located to make it easier to wind the ducting into the grain.
- Powerful fan unit enables the grain mass to be ventilated rapidly.

Selection Chart For Temporary Aeration Applications

The Downfields "Porta-vent" aeration unit is designed for spot ventilation of small bulk grain bins or containers. The amount of grain that this unit can treat in one position is dependent on the grain mass height to width ratio relative to the perforated spear position within the mass. As a general guide, the longest airpath through the grain to the ducting should not be more than 1.7 times the shortest airpath. The following chart indicates maximum recommended useage under ideal conditions.

Model	Tonnes (maximum)	Grain Depth (maximum)	Moisture (maximum)
F185 Porta	20	3.0 metre	13%
F370 Porta	20	3.0 metre	15%

*** Consult manufacturer for configurations outside the above guidelines**

- These selections are based on clean whole grain with a maximum moisture content of 15%. Holding grain above 13% requires careful consideration. Refer to brochure **"Recommendations for aerating high moisture grain"**
- To optimise aeration performance, consult brochure **"Fan controller for optimising aeration performance"**
- For effective fan performance, air must be able to escape through the silo or bin roof. Check suggestions in the brochure **"Ventilation of silo roofs when using aeration."**

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McBea Grain Protection Services

2 Gilbert Court, Parkdale Vic 3195 AUSTRALIA
Tel:(03) 580 5814 International +61 3 580 5814 Fax (03) 587 6404

GRAIN AERATION EQUIPMENT FOR TYPICAL STORAGES

SILOS	Small Seed	Conical Steel	Conical Steel	Conical Concrete	Flat Concrete	
SILO CAPACITY	30 tonne	70 tonne	150 tonne	250 tonne	800 tonne	over 1000 t
DUCT	$74.00	$100.00	$130.00	$193.00	$767.00	
SPACER	$22.00	$22.00	$22.00	$161.00	$166.00	
Sub total: Ducting Only	$96.00	$122.00	$152.00	$354.00	$933.00	
FAN	$272.00	$272.00	$287.00	$455.00	$1,466.00	
Total Air moving System	$368.00	$394.00	$439.00	$809.00	$2,399.00	POA
ACCESSORIES:-						
WEATHER SHIELD	n/a	n/a	$20.00	$28.00	n/a	
ROOF VENT	$99.00	$99.00	$99.00	$99.00	$99.00	

SHEDS	
SHED SIZE	12m x 24m
DUCTING	$2,600.00
TRANSITION	$332.00
Sub total: Ducting Only	$2,932.00
FAN	$2,932.00
Total Air moving System	$5,864.00
ACCESSORIES:-	
WEATHER SHIELD	n/a
ROOF VENT	$198.00

"Screw-in" Aerator (for temporary storages) $402.00

AERATION CONTROL EQUIPMENT:-

RIMIK AERATION CONTROLLER	$650 00
4 FAN SWITCHING PANEL	$635.00
1 FAN SWITCHING PANEL	$195.00
COMBINED CONTROLLER/PANEL	$795.00
FAN/MOTOR/CONTROLLER KIT*	Appr.$1500.00

* Assembly selects coldest air and dries it i.e. decreases its relative humidity.

NOTE: The above prices for aeration ducts and fans are a general guide only.
Prices do not include sales tax , freight and handling charges.

W B Elder
1st Sep 94

For an accurate quotation, please complete the section below, tear off and send to McBea Services at the above address.

Name..

Address...

Telephone...

Please circle your requirements

Silos
Maker:- Boyd Jaeschke Nelson Sherwell Other Other

Material:- Steel Concrete

Design:- Flat base Conical base Above-ground (Y / N)

Capacity in tonnes ==> Diameter ==>

Sheds
Width ==> Length ==>

Wall Height ==> Materials:- Steel Concrete Other

McBEA GRAIN PROTECTION

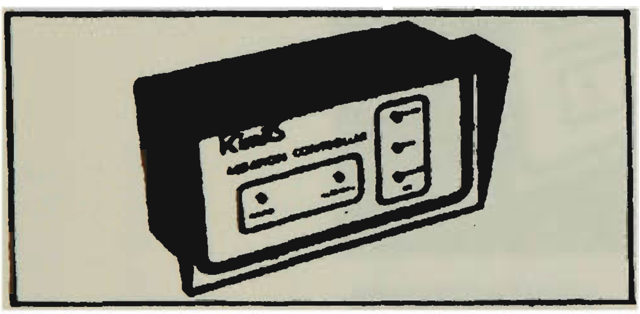
RIMIK AERATION CONTROLLER

A MUST FOR PROPERLY MANAGED GRAIN STORAGES

RIMIK Features

- The RIMIK aeration controller (built under CSIRO license) **automatically** controls your aeration fans. It ensures that the optimum use is made of natural cold air. The coldest possible air is used by the aeration fans irrespective of the current climatic conditions.

- A RIMIK aeration controller will control any number of aeration fans thus providing low-cost automatic control. A mixture of RAPID and NORMAL settings can be used on different silos.



- RIMIK aeration controllers provide independent RAPID and NORMAL outputs in the one unit. This makes it possible to rapidly cool silos filled with newly-harvested grain, as well as providing the cooling needed for long-term storage.

- RIMIK aeration controllers incorporate the latest microprocessor technology. This allows the system to continually check its own operation and warn the operator of any malfunctions.

- RIMIK aeration controllers incorporate non-volatile memory. Set points are remembered so that the unit can be turned off and it will restart from where it left off when power is restored. This feature is important in areas where power cuts are frequent.

How can Aeration help you?

Aeration is a tried and proven method of protecting grain in storage. Cool air at low flow rates is blown through the grain on a regular basis. Over a period of time the grain is cooled to temperatures well below the prevailing average.

The effect of this cooling is beneficial in the following ways:

1. Temperature variations in the grain mass are evened out preventing hot spots and moisture concentrations.
2. The bulk temperature of the grain mass is reduced, inhibiting mould and insect growth.
3. The bulk temperature is lowered so that the grain is maintained in conditions suitable for long term storage.
4. Insecticide effectiveness and seed germination are maintained for far longer periods where grain is cooled by aeration.

Aeration can provide safe storage conditions for most grains. By using a RIMIK aeration controller to achieve controlled aeration you get the best possible results from your aerated storage system.

How the RIMIK Aeration Controller works

Small fans and matched ducting are used to blow cool air through the grain in storage.

The controller that determines when to turn the fans on or off is the key to the effectiveness of the whole system.

The aeration system will be completely successful **only** if the fans are turned on when the ambient air temperature is coolest.

The RIMIK aeration controller determines when the air is at a suitable temperature to turn on the fans. During each week of operation it selects, on average, the coldest 24 hours in the week on NORMAL mode and 84 hours in the week on RAPID mode to turn on the fans. The controller automatically adjusts to the current weather conditions. During warmer weather the fans are kept off; in colder weather the fans are kept on longer to take advantage of the colder air.

Other features of the RIMIK Aeration Controller

Grain straight from the header must be rapidly cooled to avoid deterioration in storage. The RAPID output of the controller provides the correct fan control for this situation. After several weeks of aeration in this mode the fan control can be switched to NORMAL. Because the RIMIK aeration controller has independent RAPID and NORMAL outputs some silos can be on RAPID while others are on NORMAL.

When aeration equipment is under automatic control it is important to know that the controller is functioning correctly. The RIMIK aeration controller continually checks on its own internal operation to ensure correct operation. A visual indicator shows that the system is functioning correctly. Visual and audible indicators alert the operator to any malfunctions.

Harvesting moist grain

When harvesting moist grain, the grain dryer may not keep up with the harvest rate. If moist grain is placed in aerated storage it can be kept for several days until dryer space is available. The RAPID mode of operation also caters for this situation.

SPECIFICATIONS

Input	240V, 50 Hz 5 amp
Outputs (2)	240V, 2 amp (each)
Width	260 mm
Height	145 mm
Depth	120 mm

Temperature probe length: 3 metres

Designed and Manufactured by:
RIMIK Pty. Ltd.
4 Mabel Street, Toowoomba. Qld. 4350 Australia.
Aeration controller covered by Patent No. 438732

Rimik Aeration Controller Model 10	$650
Selector switch and hour meter for one fan	$195
Selector switches and hour meters for four fans	$635

Selector switch provides the following control modes:-

0. OFF
1. RAPID - for removing initial harvest heat
2. NORMAL - for rest of storage period
3. MANUAL - for test or aeration of wet grain

March 1994

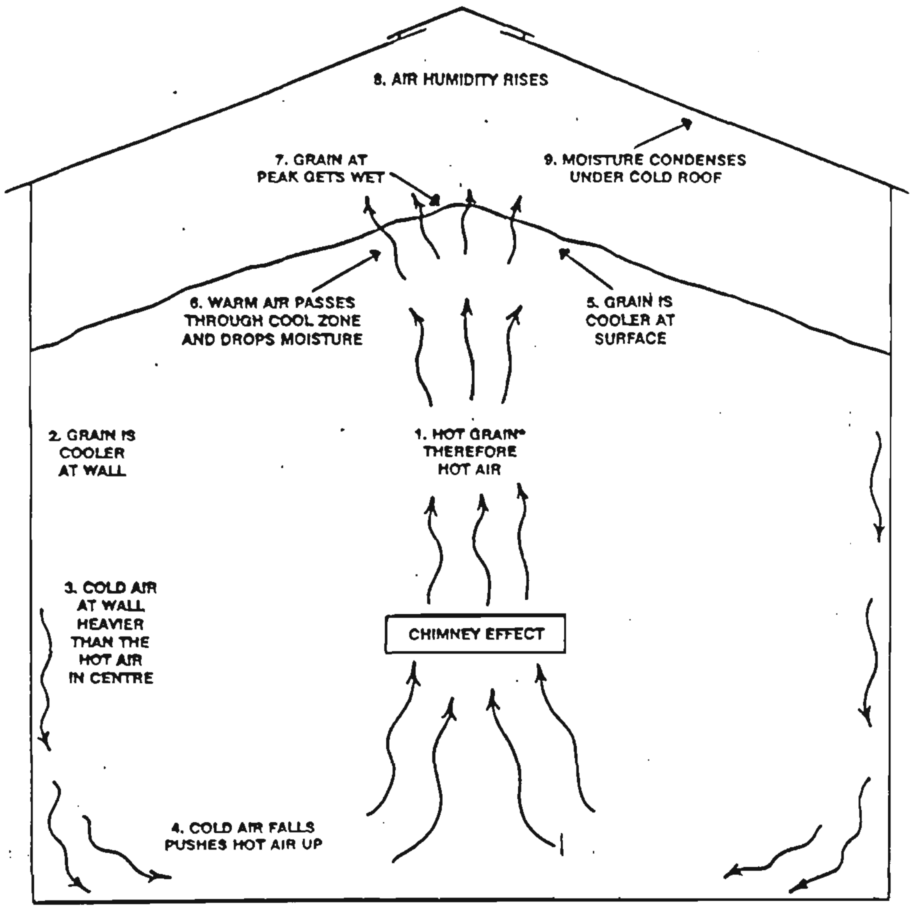
Available from:

MCBEA SERVICES
2 GILBERT CRT., PARKDALE
VICTORIA 3195 AUSTRALIA

TELEPHONE (03) 580 5814
INTERNATIONAL +61 3 580 5814
FAX (03) 587 6404

WHY SILOS SWEAT

AND WHAT CAUSES SURFACE CAKING



TO STOP THE ROT
USE A McBEA MOBILE GRAIN COOLER
AND

COOL IT!

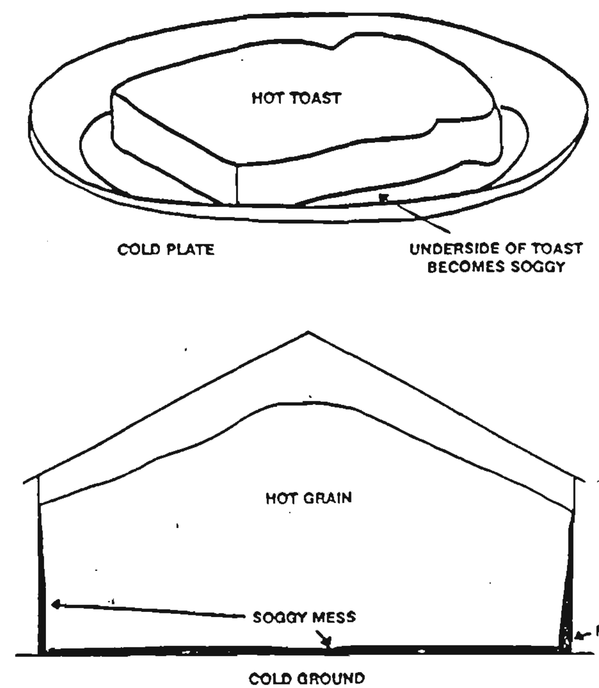
Fig. 1

*HARVESTED ON A HOT DRY DAY

WHY SILOS SEEM TO LEAK

AND WHAT CAUSES MOISTURE TO MIGRATE

The air between hot grain seeds in the middle of a silo holds a lot of moisture.
The air between cooler grain seeds at the wall and floor holds very little moisture.
So the moisture moves from the hot to the cold regions.
Moisture diffuses through air pockets like a scent diffuses through a room migrating from zones of high intensity to zones where the intensity is lower.
On reaching the wall or floor it can go no further so the moisture accumulates and WETS THE GRAIN!
The same process occurs when hot toast is put on a cold plate as illustrated:-



McBEA MOBILE GRAIN COOLERS
DECREASE GRAIN TEMPERATURE
PREVENT MOISTURE MIGRATION
PRESERVE THE GRAIN AND SILO

Fig. 2

APPENDIX 4

Commercial literature on Deep Probe Wet-bulb Temperature Measuring System supplied by McBea Grain Protection Services, Melbourne, Victoria

The unique features of this equipment developed by the candidate for the grain storage industry are outlined in Section 4.4, and an example of results of measurements which assisted an operator in the management of a M^{c}Bea Mobile Grain Cooler is shown in Appendix Fig. A3.1. It is the only commercially available system in the world with the ability to measure deep in a grain bulk the intergranular wet-bulb temperature which determines the rate of increase of grain infesting insect populations and is based on Australian grain industry funded research. Many of the other psychrometric properties output by the instrument have direct relevance to characteristic grain storage problems and the rate of drying of a bulk of grain during cooling. There is no other known hand held battery operated field instrument which provides all these readings. The deep probe system which facilitates the removal in situ of the temperature and humidity sensor assembly for calibration checks is believed to be unique. This also permits operators to use the one sensor assembly down a number of probe tubes which may be installed permanently in the silo with appropriate strengthening to resist movement or damage by moving grain.

McBEA SERVICES

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Tel: (03) 580 5814 International +61 3 580 5814 Fax: (03) 587 6404

WET-BULB TEMPERATURE INSTRUMENT FOR GRAIN QUALITY ASSESSMENT

The wet-bulb temperature of the air between the seeds of grain has been shown by Australian wheat industry funded research to be a very good measure of the suitability of loads for long term storage.

The rate of increase in populations of all grain infesting insects is directly related to the wet-bulb temperature. The rate of breakdown of protectant insecticides applied to grain is also closely correlated to the wet-bulb temperature of the intergranular air. The rate of loss of germination is similarly related

McBea Services has introduced the ***ms1*** hand-held measuring instrument with probe for inserting 12m into bulk grain for direct measurement of WET-BULB TEMPERATURE.

"Grain Wet-Bulb"

The instrument also measures the intergranular relative humidity. This can be converted to a grain moisture content using charts for those who still adhere to the long established belief that moisture is the best indicator of the rate of quality loss during storage. Wheat industry funded research proved decades ago that temperature was more important than moisture and recent research has shown that "grain wet-bulb" is an excellent criterion. McBea Services has a commitment to provide practical industrial equipment which facilitates the implementation of the results of this research and we are very pleased that the "**ms1**" is now available for the various grain industry sectors to take advantage of these research findings to improve grain storage.

The "**ms1**" can also be used to measure other properties of air such as air temperature, dew point, air moisture content (g/kg), the enthalpy (heat content) of the air and the partial pressure of the water vapour in the air as well as wet-bulb temperature and relative humidity.

A means of calibrating the instrument is included in the kit and any adjustments required are done automatically.

Other equipment provided by McBea includes the very versatile McBea Mobile Grain Coolers for refrigerating grain in silos, sheds or in any other storage structure, grain aeration systems with controls which make best use of the atmospheric air at a storage site, and moveable fluidized grain bed systems for disinfestation, seed drying or sterilization. McBea also provide consulting services and conduct training courses or offer speakers for seminars and meetings of interested bodies.

Fig. A4.1 - Pamphlet describing instrument developed by Novasina, Switzerland with McBea deep probe system for measuring intergranular air wet-bulb and other important quality control parameters

McBEA SERVICES

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GRAIN WET-BULB TEMPERATURE

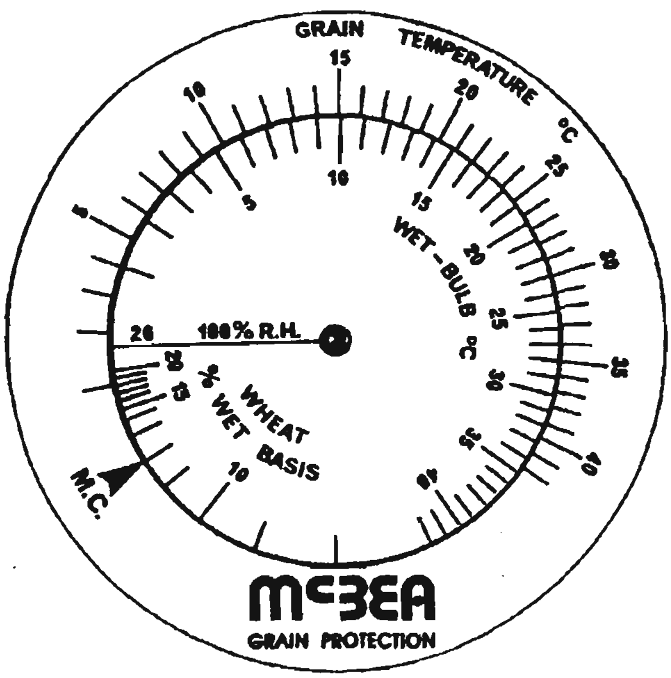
The best criterion for assessing the rate of quality loss in bulk stored grain is the wet-bulb temperature of the intergranular air.

The grain wet-bulb can be measured using a McBea "ms1" instrument and deep probe system. It can also be calculated from measurements of grain moisture content and temperature at the grain sampling point. The calculator below may be photocopied and the central disc cut out and pinned to rotate within the outer disc.

Set the arrow to the measured grain moisture content. Read off grain wet-bulb opposite the measured grain temperature.

Controlled aeration will bring the grain temperature to the value opposite the wet-bulb corresponding (approx) to the 9am atmospheric wet-bulb temperature recorded by a nearby Post Office.

Refrigeration using a McBea Mobile Grain Cooler will produce grain wet-bulbs from 5°C to 10°C depending on weather conditions.



QUALITY LOSS FACTORS

1. Grain Infesting Insects:

Insect	Wet-bulb to stop
Beetles	below 16°C
Borers	below 13°C
Weevils	below 10°C

2. Grain Protectants:

   To double half-life, reduce grain wet-bulb by 7°C.

3. Seed Germination:

   To double seed life, reduce grain wet-bulb by 7°C.

4. Caking, Moisture and Mould:

   Any cooling below outside temperature will eliminate.

REMEMBER: THE QUICKER THE COOLING, THE BETTER.

NOTE: The wheat scale may be used for barley, triticale, sorghum and peas; but not for oilseeds.

Fig. A4.2 - Reverse side of pamphlet in Fig. A4.1 showing a calculator designed by the candidate to determine the intergranular air wet-bulb temperature from grain temperature and moisture

McBea Services

2 Gilbert Court, Parkdale Vic 3195 AUSTRALIA
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PRICE LIST - MS1 WET-BULB TEMPERATURE PROBE FOR BULK GRAIN
All prices in Australian dollars ex works Melbourne
February 1994

	3m probe	15m probe
MS1 INSTRUMENT IN CARRY CASE WITH CONNECTION FOR PROBE CABLE*	$823.00	$1,023.00
Measures grain wet-bulb temperature - indicates insect population growth rate relative humidity - indicates mould growth (also grain moisture content) dew-point - indicates potential for the silo sweating water vapour pressure - indicates rate of moisture build-up at boundaries		
PROBE CABLE ASSEMBLY with aspirator bulb and sensor removal feature	$840.00	$1,140.00
EXTRA PROBE OUTER SHEATH for inserting sensor and connecting cable	$43.00	$51.00
INSERTING RODS KIT including carry bag. Rods detach from cable for use elsewhere	$264.00	$403.00
TOTAL PRICE FOR TYPICAL STARTING KIT INCLUDING ONE EXTRA SHEATH	**$1,970.00**	**$2,617.00**
CALIBRATION CELL (75%rh cell included in ms1 instrument case) Choose from the following relative humidities: 11%, 33%, 53%, 90%	$132.00	
* SENSOR FOR GENERAL USE - plugs into top of instrument and protected by cage	$368.00	
COMPUTER/PRINTER LINK (RS232 plus software - plots all values as below) Grain temperature Inter-granular relative humidity Dew-point temperature Absolute moisture content of the intergranular air g/kg **Grain wet-bulb temperature** Enthalpy of the air (heat content) kJ/kg Partial pressure of the water vapour between the seeds hPa	$495.00	

W B Elder
3/02/94

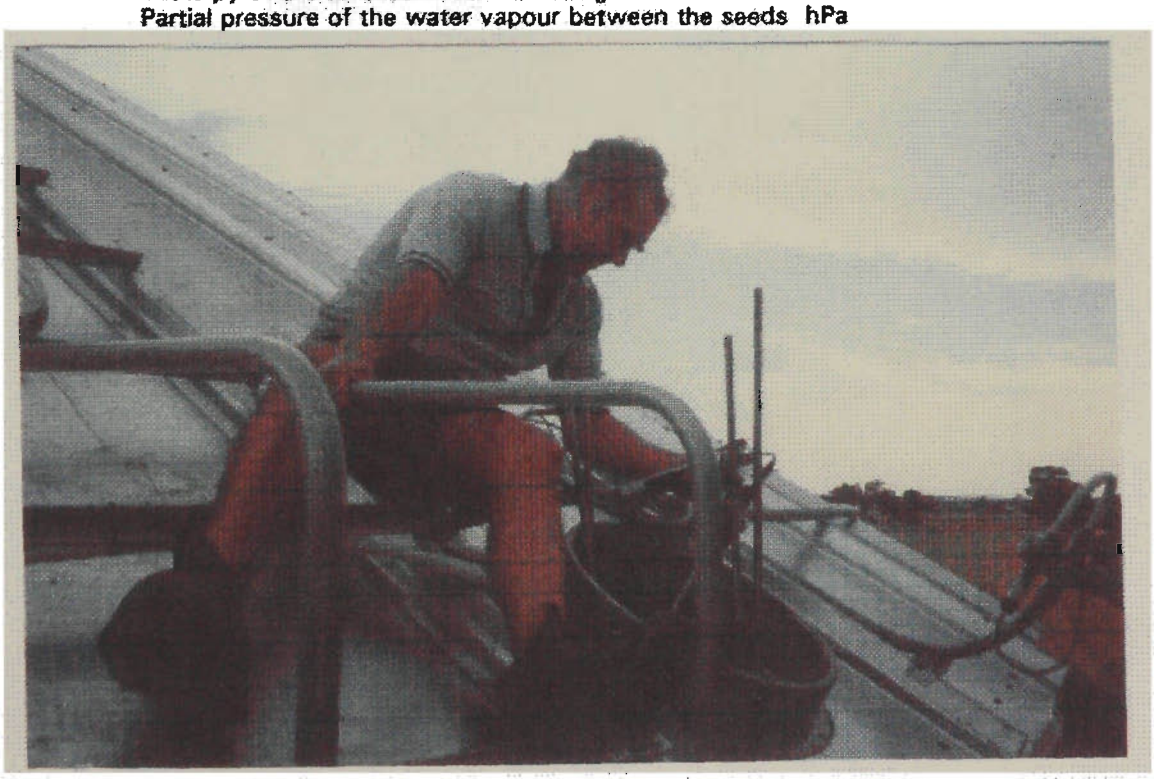


Fig. A4.3 - Price list which also shows relevance of MS1 Deep Probe readings on factors which lead to quality loss. System shown being used for chilled wheat in an 1100 tonne sealed silo
Courtesy G J Godde & Sons Pty Ltd, Culcairn, New South Wales

APPENDIX 5

Extracts copied with permission from commercial literature kindly supplied by overseas manufacturers of grain coolers

GRAIN COOLER works like this

The cooled air is distributed in the silo or flat store through a duct system which is placed on the existing base. The duct system is dimensioned in accordance with the base area and the store height, and is adjusted according to the size of unit used.

When the cooled air meets the warm grain a cooling zone is created. This created cooling zone moves upwards through the silo until it reaches the top.

At the bottom of the cooling zone is the desired final storage temperature and at the top the initial storage temperature.

The cooled air initially meets warm grain. Energy is being transferred and a temperature decline is begun.

Simultaneously the moisture content of the cooled air increases when a certain amount of drying takes place. The drying effect can be calculated to amount to 0.5 - 0.75 % for every 10°C (18°F) temperature reduction.

When the top level of the grain has attained a storage temperature that is 2-3°C (3.5-5.5°F) above the inblown, cooled air temperature, the refrigeratory process is deemed to be over.

Grain Cooler works fully automatically. As soon as required temperature, type of grain and moisture content are set on the machine, these will be kept throughout the cooling process, ambient conditions have no influence.

The system of the Grain Cooler may be used for all dry or wet granular products such as seed grain, barley for malting, bred cereals, fodder cereals, sorghum, maize, rice, sunflower seeds, rapeseed, flax, soybeans, coarse soybean meal, peanuts, grass seed, coffee beans, cocoa beans and nuts.

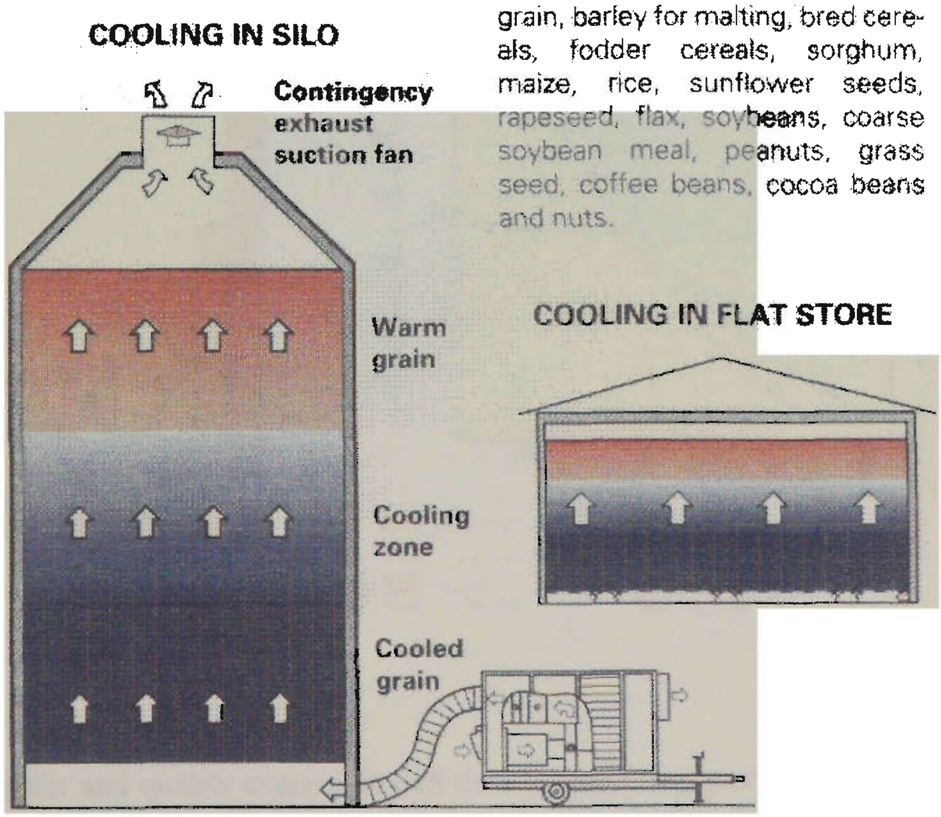


Fig. A5.1 - Description of grain cooling process. Temperature differences apply to European conditions where grain moistures are much higher than they are in Australia

Courtesy PM LUFT AB, Kvånum, Sweden

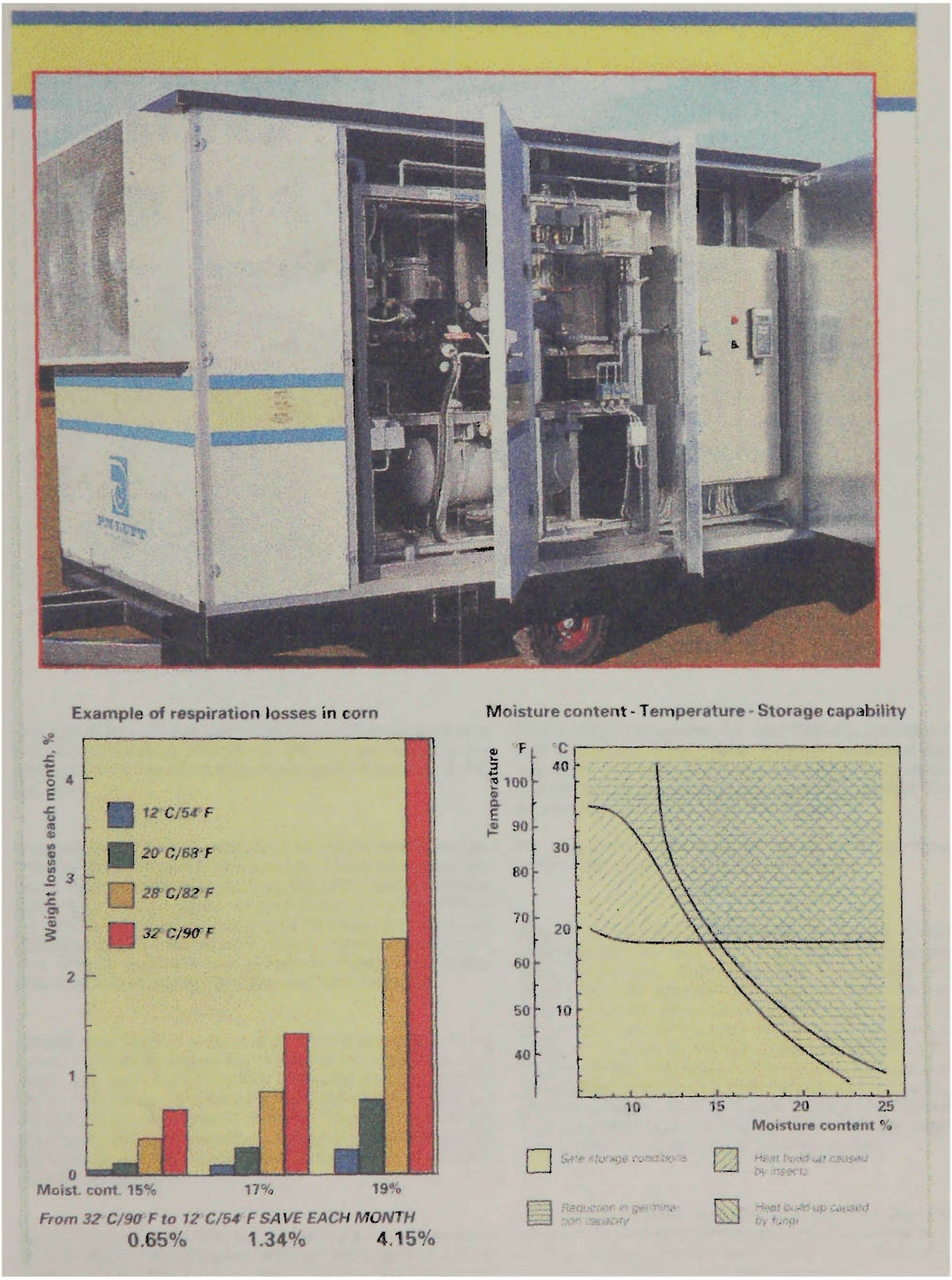
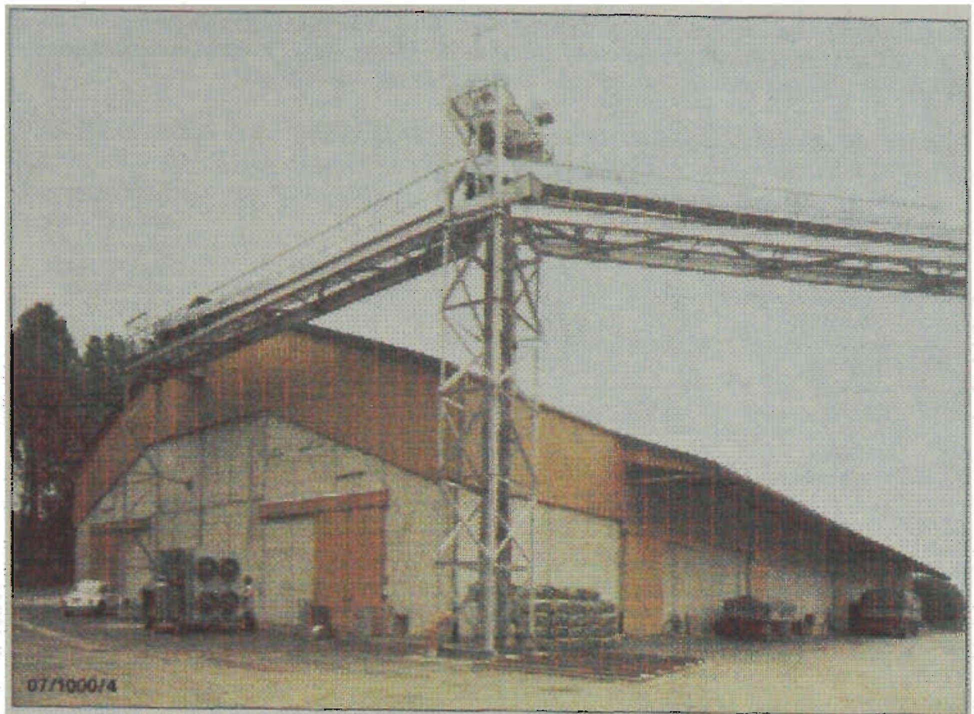


Fig. A5.2 - Swedish grain cooler and quality control benefit data for respiring stored grain

Courtesy PM LUFT AB, Kvånum, Sweden

GRANIFRIGOR® for floor storage plants



▲ GRANIFRIGOR® unit, type KK 270/350, serving a 12000 t storage plant with 3 separate cooling areas. The pyramid-shaped pile has an external and internal height of approximately 4 and 9 m respectively. Rapeseed with a moisture content of about 9 % is also stored in the warehouse.

Any type of floor storage plant, from the smallest garage box to the mammoth storage area can be fitted out quite easily for the cooling system. The pile dephts can range from less than 2 m to over 10 m.

The decisive factor for successful cooling is the expert arrangement of the cooling areas as a function of filling equipment, pile depth, storage moisture content, cooling period and the manner in which the storage plant is emptied. In accordance with the local conditions, we advise our clients on the type of unit to be employed and the most economical size of the cooling air ducts. This advisory service is also available to customers at a later date when further storage facilities need to be fitted out.

Correct dimensioning of the cold air ducts is dependent on the size of the units as well as the air volume throughput, the duct length, pile depth and the number of simultaneously connected ducts. With correct dimensioning, the cold air flows uniformly through the complete system of ducts. This means that all the grain layers are treated equally and lengthy, uneconomical cooling times are avoided. In each case, Sulzer Escher Wyss calculates the correct size.

Air distribution is particularly favourable in *the case of piles with uniform depth.* The clearance between the individual cooling ducts is at least 75 to 100 % of the pile depth. In the case of permanently installed air distribution systems, the clearance should never be less than the pile height, in fact it should always be exceeded. The greater the pile depth, the fewer the amount of ducts required, and the costs in respect of the air distribution equipment are made more attractive. The grain at the bottom of the pile between the ducts is also cooled.

With pyramid-shaped piles, it is more difficult to determine the air duct clearances. Sulzer Escher Wyss has developed a special system for this which is based on results of tests made over many years. All gradients are also taken into account. The cold air losses are kept to an absolute minimum.

We have constructed a large storage plant with an internal and external pile depth of 19 and 2 m respectively.

Cool air ducts made of wood, synthetic material, concrete or steel may be employed. The materials and the form are only really of secondary importance. Plans are available for customers wishing to build their own wooden ducts. We can also supply favourably priced steel ducts of galvanized perforated design, which are very practical to use. Short lengths of ducting (about 1 m) are laid on the floor and overlapped. When the store is to be emptied, they can be withdrawn from the pile quite easily and stacked on top of each other without taking up much space. Underfloor ducts, especially for new buildings, involve relatively high investment costs, but they are ideal for the air supply and very convenient when the store is being emptied.

No dust accumulates during the cooling process. Nevertheless, the warm air emerging from the grain must be allowed to escape into the open air. Open windows, hatches, roof cowls, doors or a blower-fan system are an absolute necessity.
Expert advice on equipment and operational economy – and thus real savings in costs – is most advantageous when planning any new undertakings. It also ensures safe and successful grain cooling.
Based on many years' experience, GRANIFRIGOR® has a leading position throughout the world.

8

Fig. A5.3- German grain cooler at end of shed-type grain store and important design factors for an efficient air distribution ducting system

Courtesy Sulzer-Escher Wyss GMBH, Lindau, F R Germany

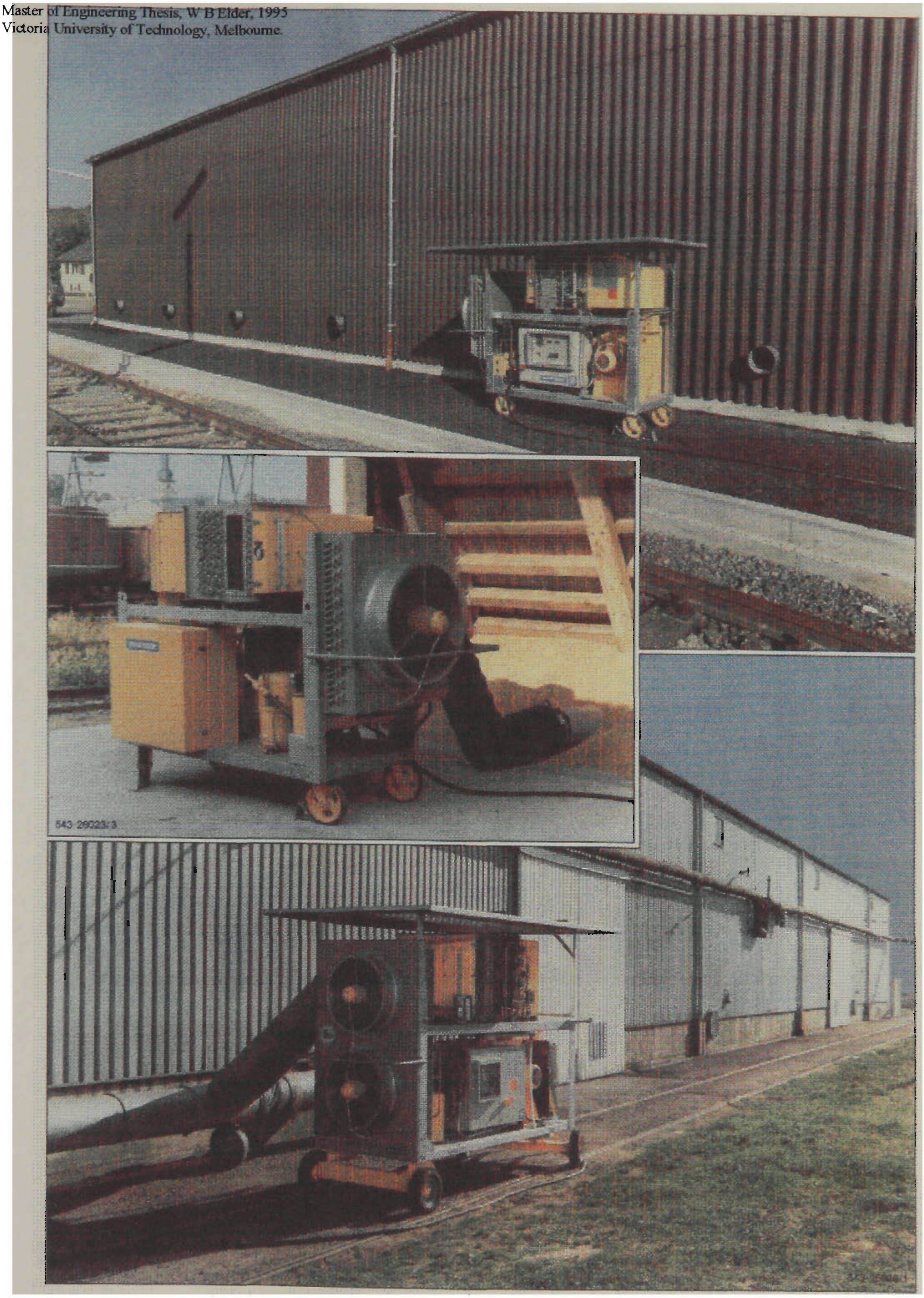


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Fig. A5.4 - Examples of various German grain coolers on shed-type grain stores
Courtesy Sulzer-Escher Wyss GMBH, Lindau, F R Germany