Monitoring a Commercial Barley Store in the North of England and Comparison with a Computer Simulation of Germination

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The temperature, moisture and germination variations in a commercial barley store were monitored over two seasons. Initial mean temperatures of 49 and 46°C were observed. These were higher than the safe temperatures for germination predicted by the computer simulation, but still produced maltable barley. This suggested that the model was too conservative. During cooling the air was heated and the bed dried by an average of 1.5%. This 'dryeration' effect helped the barley to withstand the higher temperatures. Differential fan control and off-peak running were tested and the higher 6°C differential control was shown to reduce rewetting. However, lower and more uniform temperatures were achieved with a 2°C differential. The downward flow system was essential to avoid condensation and did not pose any other serious problems. Some of the maltsters' reservations regarding cooling below 15°C, due to concerns over secondary dormancy and reheating to steep temperatures, should be alleviated by this work. Given the range of fan control options that still need to be investigated, computer simulation of the cooling, drying and germination in storage is recommended as a lower cost option than commercial testing.

Key Words: *Barley, storage, germination, dormancy, viability, moisture, cooling.*

INTRODUCTION

In the last decade, a number of workers[14,25] have been involved in the development of ambient cooling with fan control as part of an integrated storage strategy to reduce pesticide use in grain. This work was initially concerned with grains stored at around 15% moisture content, but more recently its application to malting barley has been investigated[7]. Cooling malting barley presents additional problems, particularly in Northern Europe where dormancy may be present. Firstly, in order to break any dormancy, maltsters prefer a period of 'warm' storage before any cooling. However, this offers an opportunity for insect development. Malting barley stored at ~12% m.c. may also be vulnerable to rewetting during cooling with ambient air. Despite these additional difficulties, there is general agreement[10] that at 12% m.c. and 15°C or below there is considerable scope for the safe storage of malting barley. As part of this project[7], commercial stores in the north and south were monitored to examine some of the problems. This work presents the results for the northern store.

Recent work on the mathematical description of dormancy[11,26,27], when combined with the model of viability[16], enables the germination history of a stored barley to be predicted. In this work, this takes the form of a computer simulation based on a 'Double Probit Germination Model', providing predictions for comparison with the monitored germination changes.

SIMULATION MODEL

The change in germinative energy of malting barley can be considered as a combination of two processes:

(i) A break of dormancy where the percentage of the viable corns that can germinate in the 4ml, 3 day test, g_d is increasing.
(ii) A loss of viability where the percentage of corns that can ultimately germinate, in the absence of dormancy, g_v (germinative capacity) is declining.

This is illustrated in Figure 1. The combination of the two effects results in the characteristic germination history curve, which predicts the germinative energy as $g = g_v \times g_d / 100$.

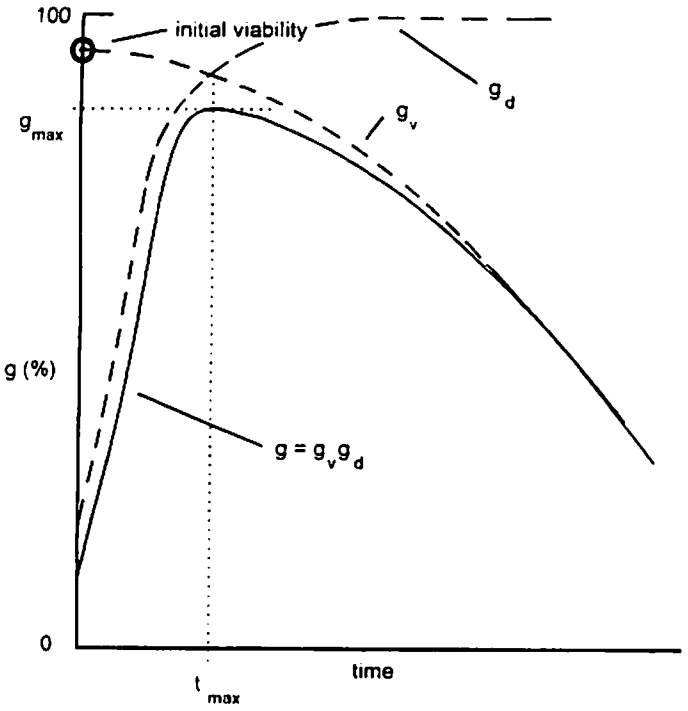

FIG. 1. Germination history of a barley in storage; g is the germinative energy; g_v is the germinative capacity; g_d is the percentage of viable corns to have broken dormancy.

Theory: A Double Probit Germination Model

The changes in g_v and g_d with time are predicted using probit analysis. This assumes that the germination changes due to break of dormancy and loss of viability follow the cumulative normal distribution function[17] defined as

$$p = \phi(X) = \frac{1}{\sqrt{2\pi}} \int_{-\infty} e^{-x^2/2}\, dX \qquad (1)$$

where the probit value, $X = (t - \bar{t})/\sigma$, $\bar{t}$ is the time at p = 0.5 and the germination parameters are given as g_v or g_d =100 x p.

For the falling viabilty curve we write

$$g_v = 100\, \phi\, (K_i - t\, /\sigma_v) \qquad (2)$$

where K_i is the probit value of initial germination and σ_v is the standard deviation in Eqn. 1 when applied to viability loss[16] given by

$$\log_{10} \sigma_v = 9.983 - 5.896 \log_{10} M - 0.04\, T - 0.000428\, T^2 \qquad (3)$$

where M is moisture content (%) and T the grain temperature (°C). Moisture contents in this work are on a % wet basis throughout.

For the rising break of dormancy germination curve we write

$$g_d = 100\, \phi\, (X_i + t\, /\sigma_d) \qquad (4)$$

The value of σ_d for break of dormancy is taken from work on the variety, Triumph[11,26] as

$$\log_{10} \sigma_d = 1.91 - 0.0352\, T \qquad (5)$$

Recent work on the varieties Blenheim and Pipkin[27] has shown that Triumph has a higher σ_d value. Cochrane[13] also observed that during storage Triumph was slower to emerge from dormancy than Blenheim, Camargue, Golden Promise and Tyne. Values of σ_d for Triumph are therefore used in this study as indicative of a 'worst case scenario'.

The standard deviations, σ_v and σ_d have units of time and define the rates of the two processes. It should be noted that σ_v is a strong function of moisture content and temperature[16], while σ_d is a function of temperature only[12,26].

The program to implement the *Double Probit Germination Model* was written in the BASIC language. Equations that approximate the function defined in Eqn. 1 and its inverse were obtained from the handbook of mathematical functions of Abramowitz and Stegun[1].

Data input assumptions

In order to predict germinability changes during warm storage prior to cooling the following 'worst case scenario' assumptions were made:

(i) The required germinative energy is a minimum of 95%.

(ii) A typical worse case dormancy level is 10%. In a collection of 33 dormant samples[11], four out of 33 were below 10% at levels of 6%, 8%, 6% and 8.5%.

TABLE I. Time in days to break dormancy, maximum germinative energy achievable and time to the maximum at a range of storage temperatures and moisture contents.

°C	MC = 11%			MC = 12%			MC = 13%		
	$t_{10\text{-}95}$	g_{max}	t_{max}	$t_{10\text{-}95}$	g_{max}	t_{max}	$t_{10\text{-}95}$	g_{max}	t_{max}
10	115	97.6	176	116	97.4	168	118	96.9	161
15	77	97.6	116	78	97.2	110	79	96.7	105
20	52	97.4	76	52	97.0	72	54	96.3	68
25	35	97.2	49	35	96.7	46	37	95.7	44
30	23	96.9	32	24	96.1	30	-	94.6	28
35	16	96.3	20	19	95.0	19	-	92.5	17
40	12	95.3	13	-	92.8	12	-	88.1	11
45	-	93.0	8	-	88.3	7	-	79.3	6

$t_{10\text{-}95}$ = time to increase germinative energy from 10% to 95%

g_{max} = maximum germinative energy that can be achieved at a given temperature

t_{max} = time to achieve g_{max}

(iii) The initial viability, K_i was taken as 98%. This viability refers to a value based on the ageing test. The hydrogen peroxide test[4] is the best commonly used indicator of this and the maltsters on the steering committee agreed 98% to be a reasonable value to take as a typical worst case. Previous work[11] on five barleys aged at 38°C, one of which was replicated at four moisture contents, gave values close to but above 98%.

(iv) The mean moisture content in storage was 12%. Due to variations in drier performance 11% and 13% were also examined.

Simulation results

Based on these assumptions, the *Double Probit Germination Model* predicts the effect of temperature and moisture content on the germinative energy changes with storage time. The results are presented in Table I. All germination values refer to the 4ml, 3day test[4].

At 12% m.c. and 35°C, the germinative energy can be raised from 10% to 95% in 19 days. However, regions of the store at 13% m.c. would suffer viability damage and would not attain an energy of 95%. At 13% m.c. and 30°C, 95% is almost achievable in 28 days. At 11% m.c. and 40°C, 95% is achieved in 12 days.

From these predictions, a reasonable compromise would be 24 days at 30°C and 12% m.c., which would give a germinative energy rise from 10% to 95%. However, any barley at 13% m.c. subjected to 24 days at 30°C, would end up with a slightly lower germinative energy calculated to be 93.6% (not shown on Table I). It should also be noted that 30°C is around the optimum for the development of storage insect pests[6,7]. To operate at temperatures around 40°C, these predictions indicate that a moisture content of 11% is required to protect viability. The results of Table I also show that at lower temperatures, requiring longer times to break dormancy, it is possible to achieve higher germinative energies. This is due to the sensitivity of viability loss to temperature.

MATERIALS AND METHODS

A silo of malting barley of 900 tonne capacity, located in the North East of England, was monitored for temperature, moisture content, germination and caged insects following the harvests of 1993 and 1994. A warm/cool storage strategy was investigated, particularly the control of the cooling fan.

Silo layout and fan

The steel silo was 11m (36ft) in diameter, with an eaves height of 12m (40ft) and a roof angle of 30°. The stored weight was taken as 800 tonne (grain depth at wall = 10.5m after settling) to allow for the additional headspace provided for sampling access. Allowing for an angle of repose of 28° at the surface[9], this gave a grain volume of 1100m^3 and a bulk density of 730kg/m^3, which is in reasonable agreement with the MAFF[2] figure of 700kg/m^3. The ventilation grids in the concrete base (5.6m^2 [flow area] = 4x15ftx1ft) were arranged in a square with the fan blowing into one corner. The silo was emptied from the centre of the base by an auger to the periphery, with a sweep auger to complete emptying.

The fan was a two stage Woods aerofoil axial fan (Code 19J2) of diameter 483mm, running at 2900 rev/min with blade angles of 16°/14°. The fan operated in suction mode drawing air down through the grain. The fan was controlled by a differential thermostat with a manual over-ride. Sensors measuring grain temperature 2m above the bin floor and ambient temperature at the silo roof entry were connected across the thermostat. When the grain temperature was above ambient by the set differential the fan came on. Elapsed hour meters recorded the fan running time.

Instrumentation

The most critical region of the bed in terms of insects and germination damage is the air exit region, as this is the last to be cooled after warm storage. In a downward aeration system this poses difficulties in monitoring. To draw samples from the bottom of the bed three tubes were inserted by means of a vacuum sampler. The tubes consisted of threaded gas pipe (internal diameter = 16mm) assembled from 0.91m (3ft) sections. The tubes were pushed down into the bed, whilst the vacuum sampler cleared the grain in their path. On striking the silo floor, the tubes were positioned by drawing them back one metre. As experience was gained, it was found to be effective to withdraw the tubes occasionally to avoid them being 'gripped' by the settling grain. This avoided problems with their final removal. One tube was located at the centre and two at just over half radius (~3.5m) with an angular displacement of 120°.

Four bound sets of temperature probes were inserted, three adjacent to the sampling tubes described above and a further probe at ~3.5m radius at 120° to adjacent probes. These were drawn down into the bed using the sampling tube insertion technique and then the tube was withdrawn. The thermocouple heights from the silo floor were 0.5, 1.25, 2.5 and 4m on all four probes, with additional thermocouples at 6, 8 and 10m on the centre and one other probe. Thermocouples at 2.5 and 4m were duplicated on all four probes. The other temperatures monitored in duplicate were atmospheric at silo air entry, headspace, grain surface and fan inlet and outlet. Temperature was monitored on three 16-channel data loggers and duplicate readings were wired to alternate data loggers for back up. Humidity at the silo air entry was measured using a thin film polymer capacitance sensor and transmitter connected to one of the logger

voltage channels. The fan on/off condition was also logged on a voltage channel. The loggers recorded data at hourly intervals.

Procedure

A regularly employed company procedure for breaking dormancy was to dry the barley to 12% ± 0.5% and to hold it in store at 40 to 45°C for 7 to 10 days before cooling. These temperatures were achieved by operating the drier without a cooling section. Although these temperatures were high, given the viability loss predicted by the computer simulation, we were interested in monitoring them as an existing successful practice. The procedure required by the company management during the cooling process was to switch the fans off during periods of rainfall. We would have preferred to try differential control as the sole means of minimising any rewetting, without this complicating factor. However, the company carried the commercial risk during the experiment and as agreed retained final management control. The operator recorded the switching off and on of the fan.

Samples of barley were taken from the silo to determine moisture content, germination and caged insect changes. Taking advantage of the need to raise and lower the sampling pipes as described above, moisture profiles were determined at about 1m intervals through the bed. The procedure was developed during the early weeks of the first storage season and therefore an initial profile, at the start of warm storage, is not available for Season 1. Four profiles were sampled during each season.

Germination testing consisted of hydrogen peroxide, 4ml, 3day and 8ml, 3day tests. Samples were taken from the top (0.5m depth) at four locations adjacent to each sampling probe and from the bottom of the bed (1m height) using the three sampling tubes. Sampling was initially on a weekly and later on a monthly basis. In the second season, samples were taken more selectively on three occasions: the start and end of warm storage and just before the barley was removed from store at termination. Bagged samples of Triumph, with a low germinative energy (~20%), were also used in this work, as the selection of a dormant silo barley was not under our control. These were buried at a depth of 0.5m adjacent to the three sampling tubes. The bags were sampled every 4 days initially and less frequently when dormancy had broken. All germination counts were performed on mixed samples obtained by combining each set of 4 surface or 3 bottom samples.

All moisture contents and germination tests were performed according to the Institute of Brewing Methods of Analysis[4].

Caged insects (*S. granarius* and *O. surinamensis* adults), supplied by CSL (York)[6], were buried (0.5m) at three locations (3 x 2 species x 8 cages) adjacent to the thermocouple probes. The cages each contained 15g barley and 25 insects. The cages were sampled early due to the high temperatures, which were at levels lethal to insects. As a control, an identical set of cages were also kept in an incubator at 12°C.

Season 1

The silo was filled on the 1st September over a period of 12 hours with malting barley of the variety Alexis. The sampling pipes and thermocouple probes were inserted and a mean grain temperature of 49°C was indicated. This was above the safe temperature range for viability predicted by the computer simulation (Table I). On the 2nd September the insect cages and bags of dormant Triumph barley were buried to a depth of 0.5 m below the surface. On the 6th September the fan was switched on under manual control for the initial cooling phase. There followed a rainy period and, in accord with policy on the site, all fans were switched off manually during rainfall due to concern over rewetting. On the 17th September, when all grain was around 20°C, the fan was set to operate on a 2°C differential. Due to concern over the initial high temperature, a low differential was employed and the fan was not restricted to off-peak running. The last day of monitoring was on the 21st January, when the grain was required for malting. During the unloading of the silo, samples were taken at intervals for moisture content, germination and micro-malting analysis by the company.

Season 2

The silo was filled with malting barley of the variety Camargue over the three day period prior to the 6th September and the thermocouple probes and sampling pipes were then inserted. The thermocouple probes indicated an initial mean temperature of 46°C. Temperature control had been improved by a sensor in the grain flow down stream of the drier. However, this is again above the predicted safe temperature to maintain viability (Table I). On the 7th September the insects and bags of dormant Triumph were buried 0.5 m below the surface. On the 12th September the fan was switched on to run continuously apart from manual interruptions during rainy periods. On the 26th September, the fan differential control was set at 6°C with the timer restricting the on-time to the off-peak period (24.00 - 07.00 hours). The last day of monitoring was on the 5th January, when the grain was required for malting.

RESULTS

Fan Performance

The pressure drop across the grain bed at different flow rates can be calculated using flow resistance data for barley[3]. Matching this with the fan characteristic[5], the duty point of the fan was determined predicting a

flow, $\dot{Q}$ of $3m^3/s$ ($13.5m^3/h.tonne$), a pressure drop across the grain, Δp of 73mm H_2O and a fan efficiency, η_f of 72%. Taking the motor efficiency, η_m as 90%[5], the electrical power consumption of the fan is given by $\dot{P} = \dot{Q}\Delta p/(\eta_f\eta_m) = 3.3kW$. This is low compared with typical ratings[5], probably because it assumes no deterioration of fan performance due to long term use.

An alternative approach to determining electrical power input is to measure the temperature rise across the fan. The mean value observed during the first season was 2.1°C. This excluded the initial cooling period when the warm air out of the silo confounded the reading. Lammond[19] observed that no energy is released in the grain bed and therefore, in this analysis, all fan energy is considered to go to increasing air enthalpy across the fan. The steady flow energy equation, for equal velocities and heights each side of the fan, gives

$$\dot{P} = Q\rho\,(h_2 - h_1) = \dot{Q}\rho C_p\,(T_2 - T_1) \qquad (6)$$

The enthalpy, h is defined as $h = u + pv$ and describes the energy gain across the fan due to heating ($u = C_v T$, where u is internal energy) and due to the pressure rise (pv, where v is specific volume). For a perfect gas, $pv = RT$, $C_p = R + C_v$ and therefore $h = C_p T$ as in Eqn. 6.

For the measured temperature rise, $(T_2 - T_1)$ of 2.1°C, an air density[20], ρ of 1.2 kg/m³, an air specific heat[20], C_p of 1.005 kJ/kgK and flow of $3m^3/s$, the power consumption, $\dot{P}$ is 7.6kW. This value is used here in costings, in preference to the value of 3.3kW derived above and used previously[7].

Temperature and hours of aeration

Season 1

The temperature changes with time and fan running hours are shown in Figures 2, 3 and 4. Before aeration commenced, temperatures averaged 49°C for about 5-6 days. Once aeration started, temperatures at the bottom fell to around 18°C by week 3 after 300h of aeration. The temperatures then fell gradually to about 8°C by week 8 and were held at this until termination, after 630h of aeration over 20 weeks.

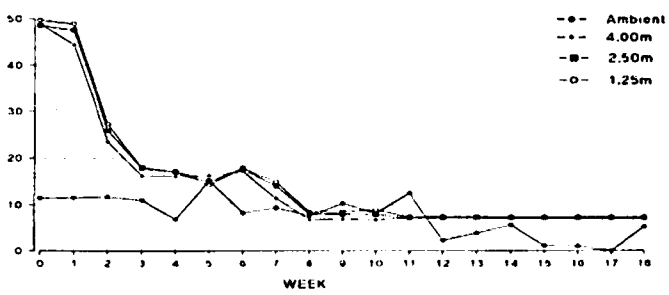

FIG. 2. Temperature at the bottom of the bin (n=4) and ambient versus time (Season 1)

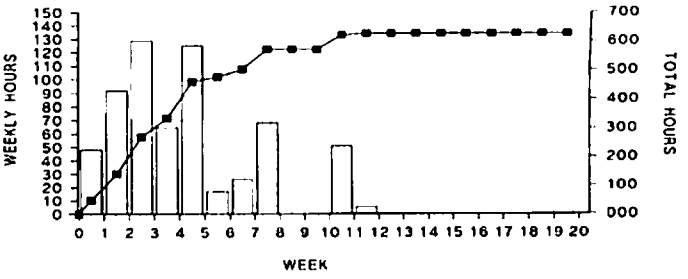

FIG. 3. Fan running hours, weekly and cumulative (Season 1)

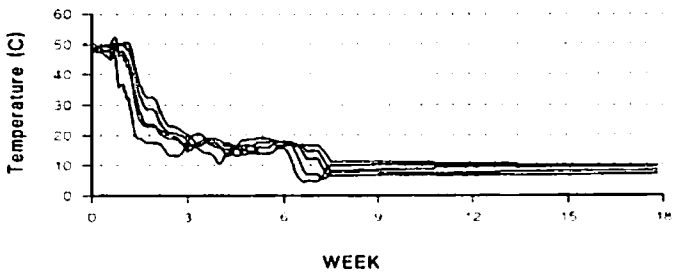

FIG. 4. Temperatures across the bed at depths of 0.5, 2.5, 4, 6 and 8m from the base (Season 1)

Season 2

These results are presented in Figures 5, 6 and 7. Before aeration commenced, temperatures averaged 46°C. Once aeration started, temperatures at the bottom fell to around 18°C by week 3 after 320h of aeration. The temperatures then fell to around 15°C by termination in week 18, requiring about 520h of aeration. Although the ambient conditions and fan running hours were similar, the long-term cooling effect was less in Season 2.

The major difference in operating conditions between the two seasons was in the fan control setting. The differential was increased from 2°C (no restriction to off-peak) in Season 1 to 6°C (off-peak only, 24.00 – 07.00 hours) in Season 2. The effect was to restrict fan running time in Season 2 to periods where the ambient temperature is considerably lower than the grain near the bottom of the bed. Comparing Figures 2 and 5, the increased differential appears to have prevented final cooling below 15°C, which is particularly important for *S. granarius*[6] the most cold tolerant of the common UK pests. Figures 4 and 7, which show the variation in 5 temperatures covering the whole bed depth, give further insight into the phenomenon. During the second half of the storage period, the temperature difference between the top and bottom of the bed is far greater in Season 2 than Season 1. So, although the mean temperature of the bed is falling, the critical region at the bed air exit (bottom) is not cooled as effectively. Sun and Woods[23] also observed this in their simulation of barley cooling.

Fan energy use and costs

Season 1

For the fan power of 7.6kW calculated above, the total running time of 630h and the estimated stored barley

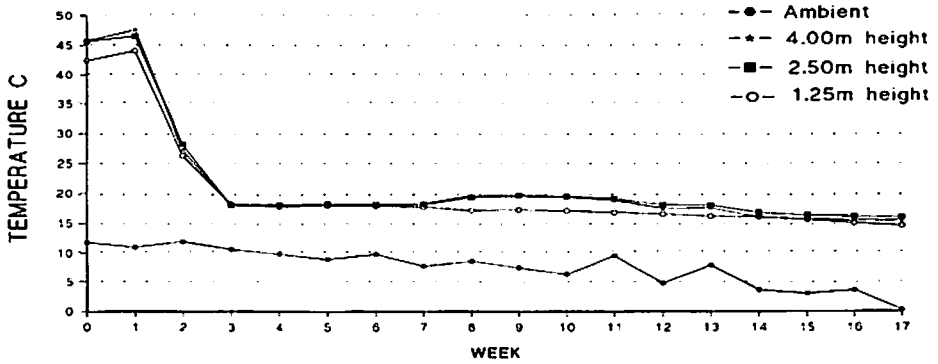

FIG. 5. Temperature at the bottom of the bin (n=4) and ambient versus time (Season 2)

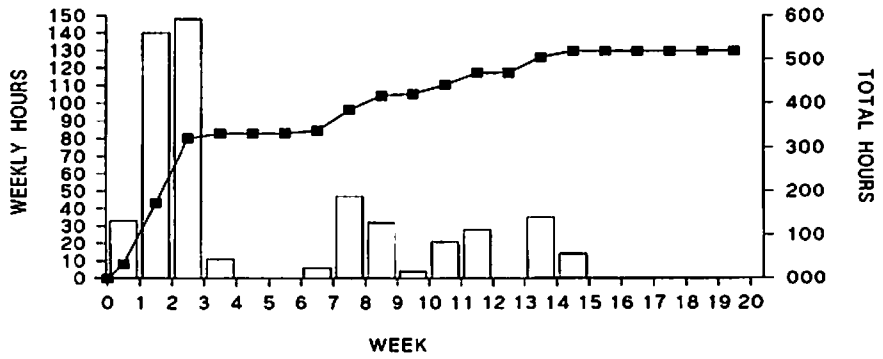

FIG. 6. Fan running hours, weekly and cumulative (Season 2).

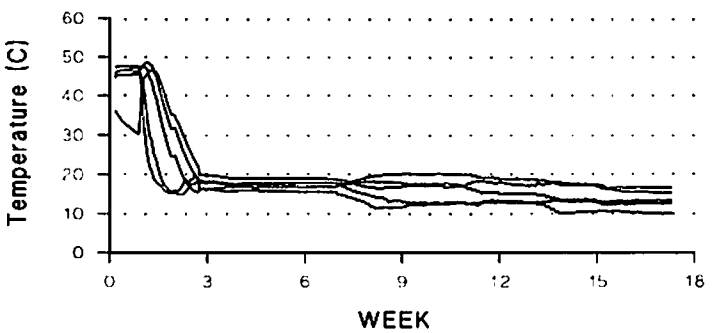

FIG. 7. Temperatures across the bed at depths of 0.5, 2.5, 4, 6 and 8m from the base (Season 2).

weight of 800tonne, the energy requirement is 6.0kWh/tonne. Based on an estimated tariff of 7.5p/kWh, the total cost would have been 45p/tonne.

Season 2

In this case, using the same fan and stored grain weight for a total of 520h gave a reduced total requirement of 4.9kWh/tonne. To cost this we divide the fan running time into 170h peak and 350h off-peak costs of an estimated 7.5p/kWh and 2.5p/kWh respectively. This gives an overall running cost of 20p/tonne.

It is interesting to compare this with a typical cost of pesticide of 35p/tonne (materials only). Although this does not include other costs like pesticide application or the differential controller, it suggests that cooling costs are comparable to pesticide treatments and potentially cheaper.

Moisture content

Season 1

The distribution of moisture content is shown in Figure 8. Although the initial moisture content distribution before cooling was not measured, assuming the grain to be originally at about 12% m.c., there was an apparent increase in moisture content of 1-4% in the top quarter of the bin. This increases the vulnerability of the upper layers to viability loss. When the bin was emptied 13 samples were taken by the company quality control laboratory. These were taken at intervals of one hour during unloading to assess germination and moisture content. Since the bin would empty from the top down, excluding the first sample which may have come from the bottom, the next six readings were taken to represent the top half of the bin and the following six to represent the bottom half. The mean moisture content for the top

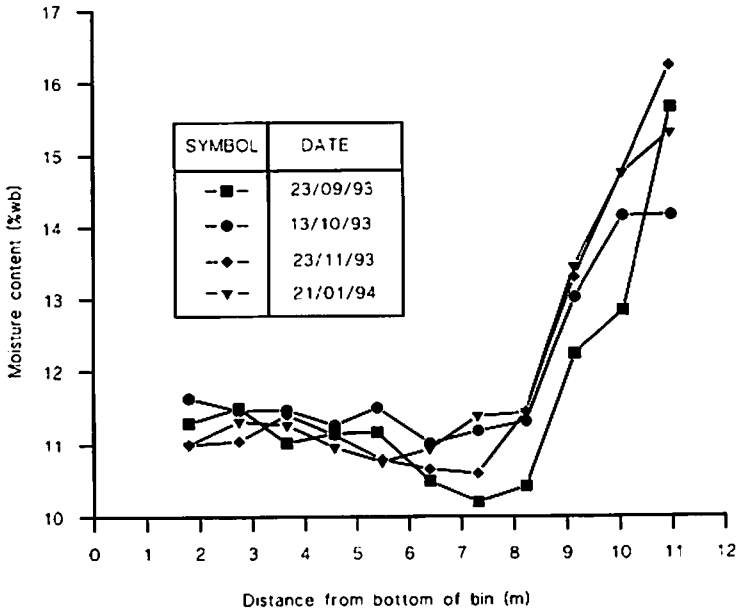

FIG. 8. Moisture content profiles through the bed at just over half radius (Season 1).

half was 13.9% (12.5 – 14.6%) and for the bottom 11.4% (11.2 – 11.5%), which corresponds reasonably well to the results in Figure 8.

Season 2

In the second season the tube raising sampling technique was available before grain cooling. In Figure 9 the moisture reduction due to the cooling process is therefore clearly shown. The mean reduction is 1.5%. In physical terms, when cool air is heated by warm grain, its relative humidity falls and it is able to dry the grain as it progresses into the bed. The process is referred to as 'dryeration' and has been applied to maize drying for some time[24]. For malting barley, there are clear benefits. The grain near the air exit is the last to cool and therefore most vulnerable to viability loss. Dryeration reduces moisture in this region and so protects the barley at highest risk.

There is little evidence of rewetting in the second season compared to the first (Figs. 8 and 9). This is attributed to changing the fan control differential from 2°C (no restriction to off-peak) in Season 1 to 6°C (off-peak only, 24.00 - 07.00 hours) in Season 2. This was the only major operating difference between seasons.

Germination

Season 1

In Table II, the results suggest a decline in germination performance at the surface and bottom of the bed. The

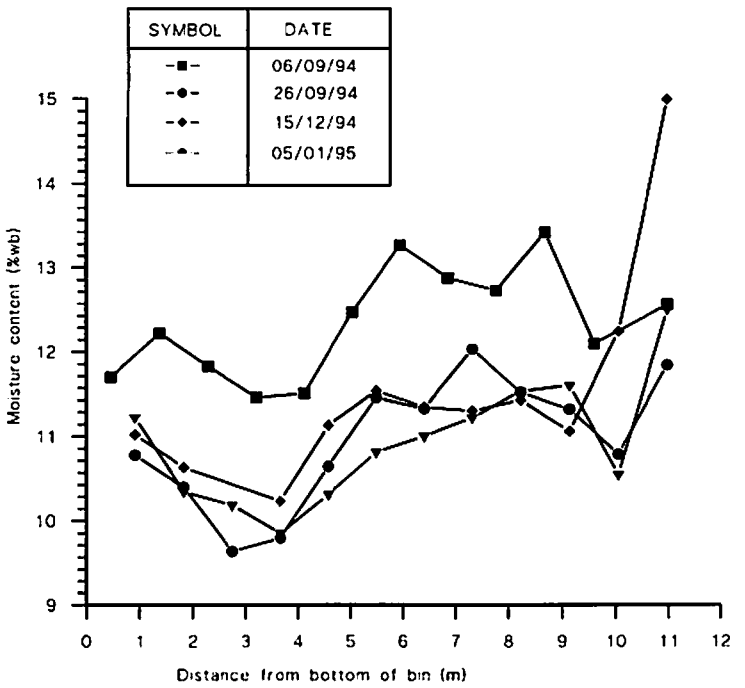

FIG. 9. Moisture content profiles through the bed at just over half radius (Season 2).

top is at a higher moisture content, whilst the bottom has the longest period of warm storage before cooling. Both of these conditions adversely affect germination. The last two samples taken from the bottom appear to recover dramatically. This coincided with the raising and lowering of the sampling tube. It is difficult to know the precise position of the tube at a depth of 11m and so these variations may depend on a change in position, either near a well cooled duct region or in a warm dead area. For example, the mean germinative energy during storage at the centre bottom, a likely dead region, was 67%, whilst the average of the samples at about half radius, probably near the vents, was 92%.

The dormant Triumph samples took some 14 days to break dormancy, which was slightly longer than expected at these temperatures. They did not quite achieve 95% germinative energy, but this may be due to loss of viability. These results are generally much better than one would expect from the model, which predicts serious viability loss above 45°C (Table I).

Season 2

Referring to Table III, the germination results for Camargue are uniformly good. The Triumph samples placed at the surface did not achieve quite such high values of germinative energy or water sensitivity. Generally,

TABLE II. Germination measurements at the top and bottom of the bin (Season 1; bulk loaded on 1/9 (day 1); fan on 6/9).

Date	Day	H_2O_2	4 ml, 3day	8 ml, 3day
Surface samples (0.5m, n = 4) from the bulk (variety Alexis)				
06.09.93	6	95.8 (94-98)+	94.3 (93-97)	66.0 (60-70)
14.09.93	14	96.0 (93-98)	94.0 (92-96)	68.8 (65-76)
*23.09.93	23	95.8 (95-98)	93.0 (90-96)	68.8 (62-76)
01.10.93	31	95.3 (90-99)	90.8 (87-92)	59.0 (30-78)
*13.10.93	43	95.5 (94-97)	87.8 (85-94)	39.8 (27-52)
28.10.93	58	93.8 (92-96)	88.3 (85-94)	37.0 (27-54)
* 23.11.93	84	92.3 (88-99)	87.3 (81-92)	47.0 (24-70)
20.12.93	111	96.0 (96-96)	91.5 (91-92)	37.5 (34-41)
* 21.01.94	143	95.0 (94-96)	87.5 (86-88)	36.5 (35-38)
Bottom samples (1m, n = 3) from the bulk (variety Alexis)				
06.09.93	6	97.7 (96-99)	97.0 (94-99)	86.0 (78-96)
14.09.93	14	94.5 (94-95)	85.5 (85-86)	31.0 (25-37)
*23.09.93	23	90.3 (81-96)	78.0 (56-96)	46.7 (25-70)
01.10.93	31	86.3 (75-97)	80.0 (63-94)	34.7 (20-58)
*13.10.93	43	86.3 (78-94)	76.3 (52-89)	23.7 (10-37)
28.10.93	58	82.7 (61-94)	77.3 (55-91)	33.3 (16-48)
*23.11.93	84	86.0 (73-90)	75.0 (55-86)	31.0 (20-42)
20.12.93	111	97.5 (97-98)	98.5 (97-100)	72.5 (50-95)
*21.01.94	143	98.0 (97-99)	99.0 (98-100)	71.5 (62-81)
Surface samples (0.5m, n = 3), inserted bags (variety Triumph)				
06.09.93	6	98.7 (98-99)	28.0 (28-28)	10.0 (10-10)
10.09.93	10	98.0 (98-98)	89.0 (87-91)	34.7 (27-48)
14.09.93	14	97.0 (95-98)	94.7 (94-96)	57.7 (46-64)
21.09.93	21	97.3 (97-98)	94.7 (93-96)	52.7 (46-62)
27.09.93	27	95.5 (95-96)	93.5 (92-95)	56.5 (50-63)
21.01.94	143	97.3 (95-100)	94.7 (91-98)	56.0 (51-62)

+ range of values in brackets.
* dates on which sampling tubes raised and lowered.

These top and bottom areas are the most vulnerable extremities of the grain. Sampling the grain during bin emptying gives more averaged values. Applying the procedure described above under *Moisture Content*, the average H_2O_2; 4ml, 3 day and 8ml, 3 day for the top half of the bed were 98.2% (97–99%), 99.5% (98–100%) and 91.2% (79–96%) respectively, which suggests that the extent of the high moisture surface damage was limited. Similarly, the values for the bottom half were 97.5% (97–99%), 95.7% (93–99%), and 56.7% (51–67%), suggesting that the adverse effect of high temperature at the bed bottom was more widespread.

the changes to fan operation and reduction in initial storage temperature in Season 2 gave more uniformly high germination results, particularly at the bottom of the bed. The results were again better than would be expected from the simulation at 45°C (Table I).

Insects

S. granarius and *O. surinamensis* adults were all killed in samples taken after 1 day and 4 days exposure in Season 1 and 6 days and 10 days exposure in Season 2. There was less than a 1% mortality in any of the controls.

TABLE III. Germination measurements at the top and bottom of the bin (Season 2; bulk loaded on 6/9 (day 1); fan on 12/9).

Date	Day	H_2O_2	4 ml, 3day	8 ml, 3day
Surface samples (0.5m, n = 4) from the bulk (variety Camargue)				
07.09.94	2	97.5 (97-98)+	96.3 (93-98)	69.3 (63-75)
12.09.94	7	97.8 (97-99)	97.3 (96-99)	85.3 (82-90)
05.01.95	122	98.0 (97-99)	97.3 (96-99)	89.3 (86-92)
Bottom samples (1m, n = 3) from the bulk (variety Camargue)				
07.09.94	2	98.3 (98-99)	96.0 (94-98)	82.3 (79-85)
12.09.94	7	98.7 (98-99)	97.7 (97-98)	88.7 (85-90)
05.01.95	122	98.3 (98-99)	98.0 (97-99)	92.3 (89-94)
Surface samples (0.5m, n = 3), inserted bags (variety Triumph)				
12.09.94	7	96.3 (95-98)	92.3 (89-94)	27.0 (24-30)
16.09.94	11	96.7 (96-97)	94.3 (93-96)	24.3 (18-30)
20.09.94	15	97.0 (97-97)	95.7 (94-98)	21.7 (20-25)
06.10.94	31	97.7 (97-98)	94.7 (94-95)	21.0 (17-23)
14.12.94	100	97.0 (96-98)	94.3 (94-95)	31.0 (22-37)
05.01.95	122	97.0 (96-98)	93.0 (93-93)	29.3 (26-31)

+ range of values in brackets.

DISCUSSION AND CONCLUSION

Commercial storage temperatures, above those that the computer simulation indicated feasible, were employed successfully. This suggests that the worst case scenario assumptions in the simulation may be too severe. In the light of current work, the value of K_i appears low and further data is required. Given that insects die off rapidly at around 40°C[6], then the use of this temperature to break dormancy deserves further investigation.

There is also the process of 'dryeration' taking place, which reduces the moisture content of the grain and so gives protection. In its application to maize[24], it involves placing the grain into store warm off the drier, allowing it to stand until moisture returns to the grain surface and finally cooling with the removal of a few moisture points. For maize, it is seen as a method of increasing drier throughput and reducing both energy consumption and stress cracking. This process is also of potential advantage to the malting industry and its benefits need to be appreciated. As described in the RESULTS section, 'dryeration' protects the barley that is the last to be cooled by reducing its moisture content. This explains, to some extent, why temperatures higher than those predicted safe by the simulation model have been shown to be effective in producing maltable barley. As shown by Gupta and Woods[18] in their work on dryeration of barley, the effect is to some extent self-compensating. The higher the temperature the greater is the moisture reduction, particularly at the bed exit, and so the barley most vulnerable to viability loss is best protected. The industry needs to be aware of this phenomenon to take more direct advantage.

There was some difficulty in cooling barley below 15°C, when a 6°C differential was used for fan control as compared with 2°C. This could also have been influenced by the restriction of fan running to off-peak times. However, there was a clear benefit in reduced grain rewetting. Cook *et al.*[14] operated grain stores (wheat and barley, 15% m.c.) with 4 and 6°C differentials at off-peak times with similar flow rates per tonne to this work. Although 6°C gave slower cooling, the difference was not great. Wilkin *et al.*[25] compared 2°C and 4°C differentials (no restriction to off-peak, wheat, 15% m.c.) and observed a drop in fan running time by a factor of three at 4°C with little reduction in cooling effect. Based on the above, a 4°C differential would be a well tried compromise between completing cooling, lessening rewetting and reduced fan running costs. The optimum fan control strategy will depend on local climate and could involve adaptive programmable control. This needs further work.

The need for downward flow is demontrated by calculating the humidity of air exiting the bin from the equilibrium isotherm for barley[21] at a given temperature and then determining the dew point from psychrometric data. At barley temperatures of 30 and 40°C the dew points are 18 and 27°C, which would almost always give condensation during cooling after harvest in the UK. When upward aeration was first tried by the company, condensation was so severe that germination over the grain surface restricted the fan, leaving little option but downward aeration for warm / cool storage. Downward aeration also has the advantage of avoiding a typical 2°C temperature rise across the fan, which would reduce cooling, although there may be some advantage in reducing rewetting. In downward flow, there is the disadvantage of the dead areas between the floor vents being the last to cool and therefore vulnerable to viability loss. This does not affect large volumes of the bed and is less significant in tall silos or more uniformly ventilated floors. Overall, downward flow appears to be justified to ovecome the severe condensation problems due to warm initial storage temperatures.

The maltsters see the cooling of the barley to below ~15°C as a posible problem for two reasons. Firstly, they are concerned that secondary dormancy may be induced.

Previous work on the chilling of barley (Woods and McCallum[27], Baxter *et al.*[8]) has not been able to detect this effect. Secondly, there is a concern over the reheating costs prior to steeping. Based on the specific heat of barley (Disney[15]), the energy to heat the crop from 5°C to 15°C is 4.4kWh/tonne, which at an estimated 1.5p/kWh (natural gas) would cost 6.6p/tonne. This is substantially less than cooling costs and would only be necessary in winter. Given the potential benefits of cooling below 15°C in winter for insect control through into spring[6], the industry needs to give serious consideration to the more extensive use of cooling with fan control.

The choice of fan control algorithm requires further testing at a wide range of conditions. Given the cost of full scale monitoring, the use of computer simulation, as in Sun and Woods[22,23], may be the best option and the simulation could first be verified against the data presented here.

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