Project Report No. 399

August 2006

Price: £7.50

Practical strategies for minimising the production of Ochratoxin A in damp cereals

by

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This is the final report of a 24 month project which started in July 2004. The work was carried out by Silsoe Research Institute, David Bruce Consulting Ltd, JTI and the Central Science Laboratory and was funded by a contract of £151,503 from HGCA (Project No.2982).

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ABSTRACT

Ochratoxin A (OTA) is formed when grain moisture content (m.c.) exceeds 18%. EU food limits are set at 5ppb with feed limits likely to be 20-fold higher. About 20% of the British crop is harvested at above the m.c. limit for OTA formation and a similar proportion of the crop has detectable levels of OTA although less than 1% exceeds the food limit. It was considered that the highest risk of OTA formation was in the ambient air drying process when grain above the drying front may remain at its initial m.c. until the drying front passes through, after 10-14 days. This project therefore assessed the risk of OTA formation during drying using the simulation tool 'Storedry', substituting the old biodeterioration criteria of visible mould or germination loss with a new model for OTA formation and fungal growth, based on the time taken before fungal growth enters the logarithmic phase.

Initial comparison indicated shorter safe storage times using the new fungal model. For instance at 20°C and 20% mc, 10 days were available for drying based on germination loss and visible fungi while there were only 6.5 days based on OTA. Simulations were run of a 3.0 m deep, 110 m^2 bed of 250 t wheat ventilated at 0.05 m^3/s.t using the two criteria, 5 locations, 20 years, 4 m.c.s, 2 start dates and 7 drying strategies of fan and heater control. Of those treatments successfully dried using the old criteria, only 2/3 succeeded using the new spoilage model, so spoilage by OTA in near ambient drying was potentially a serious issue.

A useful measure of drying performance was the maximum bed depth which would allow drying success in all 20 years simulated. When comparing drying using the new and old criteria, a reduction in bed depth of about 1 m was required to ensure success even in the worst drying year. For instance when drying grain at 20% mc, running fans continuously and switching heat in at 80% r.h., 3.2 m depth was successful using the old criteria but only 2.3 m was permissible with the new spoilage model.

Many simulations were then run to see how far performance of existing systems could be improved by changing the fan/heater control strategies, with some success. For example, changing the r.h. at which fans were switched on and off in one of the strategies gave bed depths that were that were 112% higher, costs were 10% lower, drying times were 6% longer. A larger fan allowed an extra 0.2 m depth. Even so, a reduction from current bed depth of as much as 1 m would be needed to avoid risk of OTA in poor drying seasons.

The simulation was adapted to explore grain stirring and validated against published results. Stirring allowed considerably greater depths to be used, ranging from 0.8 m deeper at 22% initial m.c. to 2 m deeper at 20%. Drying with higher air temperatures gave further gains.

SUMMARY

This project aimed (a) to quantify the risks of Ochratoxin A being produced in wheat during drying with near ambient air, and (b) to devise practical strategies for controlling that risk. The work exploited ‘Storedry’, the well-established computer simulation model of near-ambient drying developed at Silsoe Research Institute.

1. A new model of safe storage time

The new model of safe storage time used in this study was developed within an EU-project, ‘OTA PREV’. The purpose of the model is to predict maximum safe storage time (MSST) for recently harvested moist cereal grain during aerobic conditions, based on water activity and temperature. The model was based on measurements of the respiration rate of the grain over a range of water activity and temperature. MSST was defined as the time at the minimum of the respiration curve (end of lag phase) before the exponential phase of mould growth started. The following mathematical model, which relates MSST to water activity and temperature of grain, was fitted using the least square method.

$$X = a.\exp(k1.T + k2.a_w)$$

Where X is maximum safe storage time (days), T is temperature of the grain, ^oC, a_w is water activity of the grain, decimal, and a, k1 and k2 are constants.

Comparisons with standard methods of enumeration of fungi indicated that the minimum point of the respiration curve represented an early stage of growth of storage moulds before any obvious deterioration of the grain quality took place.

According to estimation based on a few observations, the OTA level reached 5 ppb after about 1.5 times the MSST. But an underestimate by 1% m.c., often made when using an electronic meter, would be enough to wipe out this 50% safety margin.

2. Adaptation, incorporation into the simulation model of drying with ambient air, and testing of the model for safe storage time before OTA production.

Adapting the Jonsson model for practical use involved translating the water activity into a moisture content (m.c.) for wheat to which it was equivalent, using an equation for the equilibrium between moisture content and relative humidity (r.h.). The form and the parameter values of emc-erh equations have been widely studied over many years and the ‘Chung-Pfost’ equation has become widely accepted as effective. The emc-erh equation used in STOREDRY was upgraded by fitting the ‘Chung-Pfost’ equation to some high quality data for wheat from the work of Henderson (1987). The Jonsson model was then incorporated into Storedry. Comparisons made with a previous model by Fraser and Muir

(1981), based on data from Kreyger (1972) for significant germination loss or the appearance of mould, showed the new model to be more demanding, *i.e.* safe storage times were shorter.

Simulations to explore effect of grain spoilage based on OTA

Many simulations were run to find those conditions in which current recommendations for loading and running driers was still appropriate, and those which previously would have been acceptable but would not be when the risk of OTA was taken into account. A range of "current practice" in near ambient drying was simulated based on a bed 3.0 m of wheat. Airflow was near the guide value of 0.05 m^3/s.t recommended by HGCA for the design of near ambient drying systems. Each treatment was evaluated at 4 values of initial m.c. and 2 start dates during each of 20 years' weather data at 5 locations in England. Seven simple strategies were used for control of fan, and heater if present. With no heater was used, the fan was either on, or switched off when the relative humidity of the air in the duct exceeded a fixed value. With an 80 kW heater, the fan remained on and the heater was turned on when the duct air r.h. exceeded a fixed value.

In the simulations, the grain bed was modeled with 100 layers. Properties of each, including the m.c. and degree of spoilage, were calculated separately as drying proceeded. Once the m.c. of the wettest layer in the bed was below 16% wet basis, drying was considered complete. At this point the maximum degree of spoilage anywhere in the grain bed was compared with a threshold. If no layer had reached the spoilage threshold by the time the drying target was met, the treatment was considered successful, *i.e.* without risk of spoilage. The drying treatments were as follows.

Factor to be varied		**No of Levels**
Spoilage model	Jonsson, Fraser/Kreyger	2
Location	Waddington (Lincolnshire), Heathrow (Middlesex), Ringway (Manchester), Plymouth (Devon), Elmdon (Birmingham)	5
Years (1951-1970)		20
Initial moisture content, % w.b.	18, 20, 22, 24	4
Start date for drying	15/8, 15/9	2
Control policy:-	Continuous fan, Fan off if r.h. after fan >90, 80, 70 %, Heater on if r.h. after fan >90, 80, 70 %	7

Results from the 11200 simulations are summarized by control policy and overall in the following table.

Drying and spoilage outcomes for five control policies and overall. Results for the five locations are combined for all control policies.

Policy	A	B	C	D	E	Overall
Proportion of all simulated drying treatments without spoilage by current criteria, %	61	45	29	63	66	53
Proportion of treatments, successful by current criteria, spoiled by new OTA criteria, %	36	39	41	35	32	36

Key to policies:-
A Continuous fan, **B** Fan off when r.h. after fan >80%, **C** Fan off when r.h. after fan >70%, **D** Continuous fan, plus heater on when r.h. after fan >80%, **E** Continuous fan, plus heater on when r.h. after fan >70%

The most important conclusion, from the second line of the table, was that an overall 36% of treatments apparently successful by the current model were at risk of OTA. This ranged from 32% to 41% depending on control policy. The most successful policy was using heat above 70% r.h., while the least effective was turning off the fan at this r.h. setting.

Overall, 84% of treatments simulated achieved the moisture target of 16% in 2 months. Between locations, the model showed a very consistent, 34-36%, chance of OTA formation in apparently successful drying treatments, except for 41% in the case of Plymouth. Further analysis, limited to the Waddington location, showed that no treatments succeeded in avoiding risk of OTA when starting from 22 or 24% m.c. Of the treatments starting at 20% m.c., 68 out of 200 were successful. At 18% m.c., 149 of 200 succeeded.

The conclusion from these results was that a significant proportion, about 1/3, of treatments that would currently be considered successful, was predicted to lead to OTA formation, thus confirming the potentially serious scale of the problem.

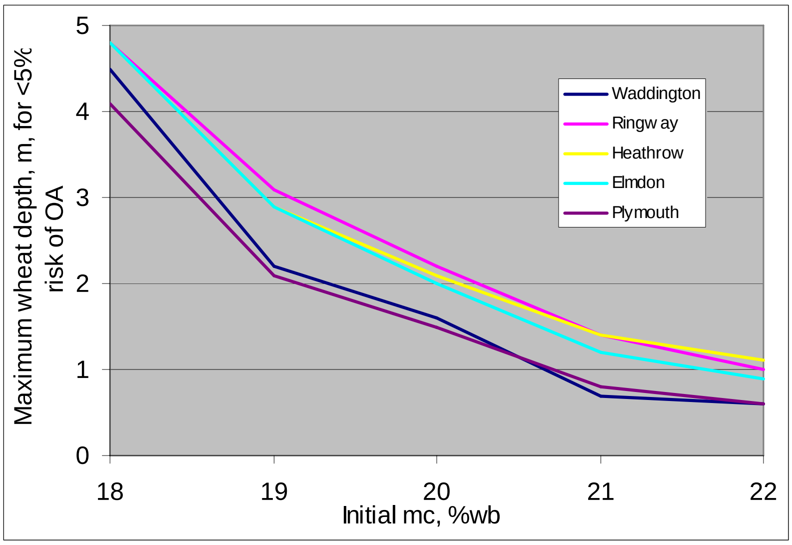
3. Use of the simulation to find how to load and run a near-ambient dryer to ensure OTA production is avoided

A measure of success of a drying treatment is the number of years out of 20 in which that treatment results in no spoilage anywhere in the grain bed when the moisture target is met. A treatment that succeeds in all 20 years with the new model of spoilage means that there is less than 1 in 20, or <5%, risk of OTA being produced. This was the criterion adopted as the basis on which treatments were selected as acceptable.

Reducing depth is a practical way of increasing drying speed and thereby reducing OTA risk. In a shallower bed, the drying front will pass through the bed in less time so the wettest grain will dry sooner. Reducing bed depth also reduces its resistance to airflow and allows more air to be delivered. Initial moisture content also, clearly, has a major influence on the probability of achieving a moisture target without spoilage so a simple graph of how maximum safe bed depth depended on initial moisture content was considered a good, practical means of summarizing the effectiveness of a drying treatment.

To produce results for such a graph, drying was simulated for a range of bed depths for each combination of other parameters to find how the number of successful years out of 20 reduced as bed depth increased. By this means the maximum bed depth was found at which there was no predicted OTA spoilage anywhere in the grain bed for any year's weather. By repeating this process, the maximum useable bed depth for spoilage risk <5% was found for each of five initial moisture contents. The graph shows results when using a heater controlled by a humidistat, but maximum depth depends on many factors some of which can be manipulated.

Effect of initial moisture content on maximum bed depth, for 20 successful years out of 20. Five locations starting drying on 15 August.



Control strategies for fan and heater

The control of fan, and heater if present, is known to be a vital aspect of near ambient drying. The following three control strategies were selected because (a) they were established approaches with simple equipment which, with parameters chosen from the exploratory work, performed reasonably well and (b) none of these strategies would require major expenditure on new equipment.

1. **Strategy 1**. Fan runs continuously and heater, controlled by humidistat, switches on when ambient air r.h. rises above setpoint. Initial results were obtained using an r.h. setpoint of 80% and a single-stage, propane heater of power 80 kW.
2. **Strategy 2**. This strategy (from HGCA Grain Storage Guide) uses no heater. The fan is switched off when the r.h. rises above a. setpoint which is progressively reduced as drying proceeds. The fan runs continuously above 20% m.c. Between 20 and 18% the fan is cut off when r.h. in the plenum rises above 83%. Between 18 and 16% it is cut off above 72%, and below 16% above 62% r.h.

3. **Strategy 3**. This strategy, for fan and heater control, again uses a stepped response to ambient r.h. depending on the progress of the drying, with the aim of avoiding rewetting. It is described by FEC Services Ltd. Initially these "steps" were used:-

r.h. %	100	83	78	73	68	62
m.c. %wb	20	18	17	16	15	

For simulations a propane heater with four stages, each of 20 kW, was used.

Comparison of results for current model (Fraser/Kreyger) and new model base on OTA (Jonsson) for safe storage time. Comparison is for Waddington location with drying started 15 Aug over 20 years.

Strategy	**Spoilage Model**	**Depth, m, at which 20 years were successful out of 20**				
Initial m.c., %w.b.		**18**	**19**	**20**	**21**	**22**
1	**Current**	>4.8	4.6	3.2	2.5	2.0
	New (OTA)	>4.8	3.2	2.3	1.6	1.2
2	**Current**	1.7	1.5	1.0	<0.4	<0.4
	New (OTA)	1.2	0.6	<0.4	<0.4	<0.4
3	**Current**	>4.8	2.7	1.7	1.3	1.1
	New (OTA)	3.9	1.5	0.7	0.4	<0.4

The performance of three strategies for fan and heater control as shown by the maximum bed depths they allowed without OTA risk rising to 5%, showed that the relatively crude use of heat in Strategy 1 allowed deepest beds. Strategy 2 was not effective at 20% m.c. or above but costs were lower by 50% compared to Strategy 1. Strategy 3 was intermediate in both maximum depths and costs. Compared with the maximum bed depths (at same risk, <5%) required by the current Fraser/Kreyger model of visible mould, the new OTA-based spoilage model required a reduction in depth of 1.1 m on average over all three strategies.

It was concluded that the 'safe envelope' graph developed for this work, of maximum bed depth for risk <5% risk of OA versus initial m.c., is a compact way of comparing drying treatments that has practical application because depth is a powerful lever to use in controlling spoilage risk. The performance of three strategies for fan and heater control showed that the relatively crude use of heat in Strategy 1 allowed deepest beds. However, compared with previous practice, a reduction in bed depth of around 1 m was needed to avoid OTA. This would have serious consequences for drier holding capacity. The next stage was to find out if it was possible to avoid OTA without having to make such a large reduction in bed depth.

4. Extending the safe envelope for the control strategies

Various parameters of the three control strategies were manipulated in attempts to improve the performance of drying when using those strategies.

Strategy 1

To explore the effect of the humidistat setting, Strategy 1 was run with r.h. setpoints of 85 to 60% in steps of 5%, for two starting dates, 15 August and 15 September, and for two locations, Waddington (the least favourable for drying) and Ringway (the most favourable). Costs generally rose, but maximum bed depths did not, as the r.h. setpoint was lowered below 80% so it was clear that the setpoint relative humidity of 80% used in initial simulations with Strategy 1 was already the best.

Strategy 1. Effect of r.h. setpoint and initial m.c. on maximum depth and cost. 80 kW propane heater.

Location and start date for drying	**Initial m.c., %w.b.**	**Depth, m, at which 20 years were successful out of 20**						**Cost, £/dried t**				
		18	**19**	**20**	**21**	**22**		**18**	**19**	**20**	**21**	**22**
RH setpoint, %												
Waddington, 15 August	**85**	4.7	3.1	2.2	1.6	1.2		3.06	3.16	3.55	3.99	4.38
	80	>4.8	3.2	2.3	1.6	1.2		3.37	3.46	3.72	3.93	4.34
	75	>4.8	3.2	2.3	1.7	1.3		4.02	3.91	4.05	4.26	4.59
	70	>4.8	3.2	2.3	1.6	1.3		4.42	4.28	4.37	4.45	4.51
	65	>4.8	3.2	2.3	1.6	1.3		4.77	4.56	4.69	4.78	4.81
	60	>4.8	3.3	2.4	1.7	1.3		5.12	4.94	5.01	5.12	5.35

As an alternative to reducing bed depth, it is possible to use a reduced area of the drying floor while maintaining the depth of grain. This concentrates the air delivered by the fan through a smaller area of grain bed and hence tends to increase the specific volume. Comparing the maximum depths where 80% of the floor was used with those for 100% floor use, the depths were increased by a mean of 16.5% Most benefit was at 22% initial mc, where a 22% increase in maximum depth was achieved. The cost penalty for reducing the floor area to 80% was a 10-11%. Less grain was dried using the original depth over 80% of the floor than with reduced depth over 100%. No significant benefit was had by reducing floor area below 80%.

Simulations were done to explore whether altering the heater power with Strategy 1 allowed the maximum bed depth to be increased. As the heater power was increased from 60 kW, the maximum bed depth increased across the range of initial moisture content. At 21 % initial mc, maximum depth increased from 1.6 m to 2.0 m. At 22 % however, the maximum depth decreased above 100 kW because the increase in drying power of the warmer air was outweighed by the increase in spoilage rate of the warmer, yet-to-be-dried grain.

Strategy 1. Effect of heater power on drying performance at Waddington, starting on 15 September.

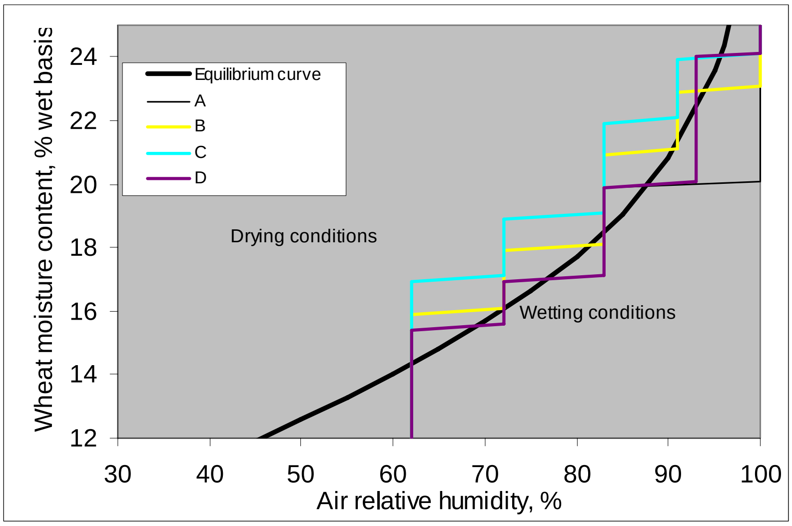
Heater power, kW	Depth, m, at which 20 years were successful out of 20					Cost, £/dried t				
Initial m.c., %w.b.	**18**	**19**	**20**	**21**	**22**	**18**	**19**	**20**	**21**	**22**
60	>4.8	3.8	2.4	1.6	1.2	3.33	3.61	3.96	4.94	5.88
80	>4.8	3.9	2.6	1.8	1.3	3.56	3.85	4.08	4.39	4.88
100	>4.8	3.9	2.7	1.9	1.4	3.96	4.24	4.36	4.64	5.09
120	>4.8	4.0	2.7	2.0	1.2	4.53	4.78	4.80	5.05	5.49

Strategy 2

Compared with using the moisture content of grain at 0.3 m depth as the value for control, using the wettest moisture of the bed for control gave increases of almost 90% in maximum bed depth while drying times were little affected.

In Strategy 2, the table of grain m.c. and corresponding r.h. setpoint aims to ensure the fan is run when the air has drying potential. The steps in the table try to follow the equilibrium relationship between air r.h. and grain m.c. Curve and the steps were plotted together (see figure). The initial steps (line A) were mostly above the equilibrium curve in their lower range but well below the curve above 20% mc.

Equilibrium curve between wheat m.c. and air r.h., with four sets of "steps" describing fan switching in Strategy 2.



Three versions of Strategy 2, which used the modified steps shown in the figure and were called 2B to 2D, were compared with the original, Strategy 2A. Strategy 2D allowed more opportunities for ventilation by allowing moister air to be used for a given moisture content of the wettest layer. Compared with maximum depths for the original Strategy 2 with the OTA-based model of safe storage life, the use of Strategy 2D and the m.c. of the wettest layer for control gave maximum depths for

Waddington and Ringway that were 112% higher, costs were 10% lower, drying times were 6 % longer. This was a major improvement.

Reductions in maximum depth were calculated, see following table, to allow growers to judge what reduction may be needed from their current practice to run no greater a risk of spoilage.

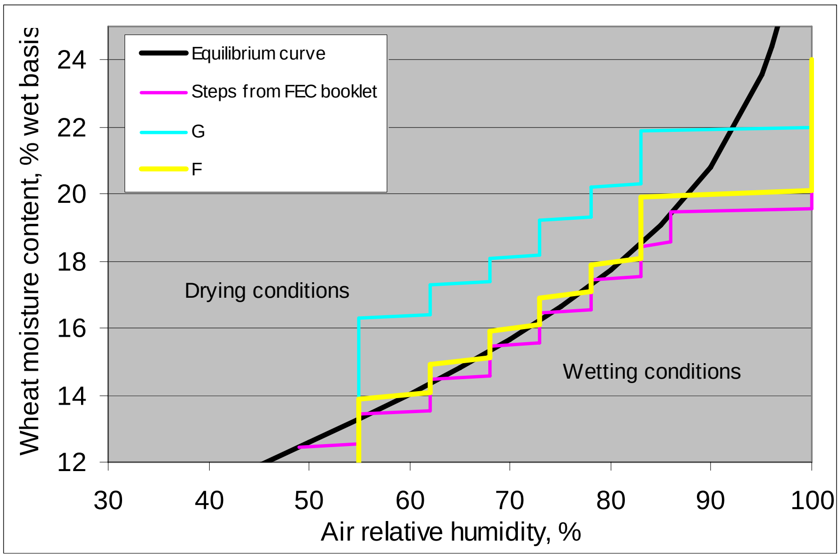
Stategy 2D. Maximum depths and depth reduction needed to maintain same risk level, <5%, using current and new models for safe storage time, at Waddington location.

Location and start date for drying		**Depth, m, at which 20 years were successful out of 20**				
	Initial m.c., % w.b.	**18**	**19**	**20**	**21**	**22**
Wad'ton, 15 Aug	**New model (OTA)**	2.2	1.2	0.6	0.4	<0.4
	Current model	3.5	2.2	1.6	1.3	1
	Depth reduction, m	1.3	1	1	0.9	>0.6

Strategy 3

Strategy 3 has more parameters to adjust than either 1 or 2. The major parameter is the set of 'steps' describing how the setpoint r.h. is reduced as drying proceeds. Between the first and second of these moisture steps, Strategy 3 cuts off ventilation when ambient air is too damp but, once the next moisture step is reached, heating is switched in until r.h. is reduced below the setpoint.

Equilibrium curve between wheat m.c. and air r.h., with three sets of "steps" describing fan switching in Strategy 3.



Strategy 3G, in which the steps were displaced above the equilibrium curve thus forcing the more frequent use of heat, provided a considerable improvement on the performance with little increase in drying time but, unfortunately, with an increase in costs per tonne. Maximum depths were 55% greater, drying costs 40% greater and drying times 8% longer.

Strategy 3. Comparison of results for current (Fraser/Kreyger) and new model based on OTA (Jonsson) for safe storage time. Waddington location with drying started 15 August.

Strategy	**Spoilage Model**	**Depth, m, at which 20 years were successful out of 20**					**Cost, £/dried t**				
Initial m.c., %w.b.		**18**	**19**	**20**	**21**	**22**	**18**	**19**	**20**	**21**	**22**
3F	**Current**	>4.8	2.7	1.7	1.3	1.1	3.44	2.52	2.73	3.55	3.92
	New (OTA)	3.9	1.5	0.7	0.4	<0.4	3.22	2.57	3.24	5.08	n/a
3G	**Current**	>4.8	4.5	3.1	1.2	0.8	3.76	3.60	4.00	3.51	4.07
	New (OTA)	4.7	3.1	2.1	0.6	0.5	3.74	3.65	4.12	4.47	4.99

From 20% initial m.c. down, Strategy 3G with the new OTA-based spoilage model (line 4 of the table) allowed a greater depth than the original Strategy 3F with the current spoilage model (line 1). This means that modifying the steps of r.h. versus m.c. with Strategy 3 more than recovered the reduction in depth (difference between line 1 and line 2) demanded by the new spoilage model at 20% m.c. and below.

In conclusion, adjusting the parameters of each strategy to improve performance proved to be a fruitful approach to recovering some of the reduction of about 1m in bed depth required to avoid OTA. Only small improvements to Strategy 1 were found. Strategy 2 was improved to allow bed depths at least 27% greater to be used for the same spoilage risk of <5% while costs were 9% greater but this still required a reduction of 0.8m to control OTA risk. Strategy 3 showed improvement in maximum depth of 55% when the steps of m.c. versus r.h. were modified. For an initial m.c. of 20% and below, this more than recovered the reduction in depth, average 1.0 m, brought about by the change to the OA-based spoilage. Costs were higher because the adjustments brought about more use of artificial air heating. Use of a larger fan increased the maximum depth by 0.2 m at the same risk level. Concentrating the air from the fan through 80% of the floor allowed an extra 0.3 m depth to be used at initial moisture contents of 20% and above.

5. Grain stirring

Grain stirring systems comprise vertical augers that reach effectively to the bottom of the bed, driven so as to draw grain upwards. This brings about a circulation of grain away from the zones that dry first, and allow damper grain from above to fall into the voids created so that any gradients in moisture are removed in about 3 days. The resistance to airflow of the grain bed is reduced which allows the fan to deliver more air and so drying progresses faster. Besides reducing the time the wettest layers wait before drying starts, stirring systems also incorporate grain that may have been overdried into the bulk.

Modelling stirring

The approach to modelling stirring was to swap some pairs of the 100 layers into which the grain bed is divided for simulation after each hourly period of drying. Two pairs of layers had to be swapped to match results from a published trial in which m.c. differences in the bed were eliminated by 72 h of stirring. A literature search revealed two reports on stirring of wheat, all from UK, two of which contained test data suitable for validating the stirring routines of the simulation, although in both trials the airflow had to be estimated based on other available evidence. In terms of drying time and moisture range at the end of drying, the results from simulating these two tests suggest the performance of the simulation was adequate for investigation of the benefits of stirring on control of OTA.

Effect of stirring during drying on avoiding OTA production

For the simulations on drying with stirring, the same approach was used as in previous chapters, *i.e.* the maximum depth of bed was found at which the risk of OTA was <5%.

Performance of drying without and with stirring. Strategy 1 at Waddington starting drying 15 Aug. 80% r.h. set point, 80 kW propane heater.

Drying treatment	**Depth, m, at which 20 years were successful out of 20**				
Initial m.c., %w.b.	**18**	**19**	**20**	**21**	**22**
No stirring	>4.8	3.2	2.3	1.6	1.2
Stirring at same OTA risk, <5%	>4.8	>4.8	4.3	2.9	2.0
	Drying time, h				
No stirring	399	271	207	159	131
Stirring at same OTA risk, <5%	309	409	443	365	297

With Strategy 1, stirring allowed considerably greater depths to be used, ranging from 0.8 m deeper at 22 % initial m.c. to 2.0 m at 20%. Stirring usually resulted in a greater drying time but at similar cost (not including capital or running costs). To seek a less costly option, Strategy 2D was simulated with stirring.

Performance with and without stirring of Strategy 2D at Waddington starting drying on 15 Aug. Grain moisture content for control was the wettest m.c. of whole bed.

Drying treatment	**Depth, m, at which 20 years were successful out of 20**						**Drying time, h**				
Initial m.c., %w.b.	**18**	**19**	**20**	**21**	**22**		**18**	**19**	**20**	**21**	**22**
No stirring	2.2	1.2	0.6	0.4	<0.4		373	240	153	128	n/a
Stirring	2.9	1.9	0.9	0.5	<0.4		444	379	220	150	n/a

Maximum depth was improved by stirring, by between 0.7 m at 18% initial m.c. to 0.1 m at 21%. This was a useful increase in depth for Strategy 2D but the range of initial m.c. with which it could reliably cope still did not extend above 20% at this location and start date. Cost per dried tonne was reduced so Strategy 2 was even more competitive. Drying time was increased in proportion to depth.

Stirring allows higher air temperatures to be used because it avoids the issue of overdrying and the accelerated fungal growth ahead of the drying zone, so this approach was modelled.

Performance of drying with Strategy 1 and with air heated to constant 25 ^{o}C, both with stirring, at Waddington starting drying on 15 Aug. Strategy 1: 80% r.h. set point, 80 kW propane heater. Constant temp: 250 kW propane heater.

Drying treatment	**Depth, m, at which 20 years were successful out of 20**						**Drying time, h**				
Initial m.c., %w.b.	**18**	**19**	**20**	**21**	**22**		**18**	**19**	**20**	**21**	**22**
Strategy 1	>4.8	>4.8	4.3	2.9	2.0		309	409	443	365	297
Air at constant temperature, 25 ^{o}C	>4.8	>4.8	>4.8	3.9	2.9		116	155	192	182	156

The use of an elevated temperature allowed increases of around 1 m in bed depth for the same level of risk of OTA, <5% between 22 and 20% initial m.c., up to the depth limit imposed by the fan. Given that stirring alone gave an increase of 0.8 to 2 m, the combination of both stirring and elevated temperature allowed an increase in maximum depth of between 1.7 m on an original depth of 1.2 m at 22 % initial m.c. and an increase of 2.5 m on 2.3 m at 20%. The drying time was reduced to 50% or less by the use of elevated temperature and the cost per dried tonne was also lower. In a higher temperature stirred system, moist air from above the bed must be removed quickly to prevent problems of condensation.

In conclusion, simulations confirmed grain stirring was beneficial in reducing the risk of OA production. All three Strategies allowed greater depths with stirring at the same risk, <5%, of OTA, the maximum increase being 2.0 m depth at 20% initial m.c. in one location. However drying time and the costs of drying were generally increased because reduced saturation of the exhaust air meant more air was needed. Drying with a constant, raised air temperature of 25 ^{o}C allowed considerably deeper beds and more rapid drying.

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TECHNICAL REPORT

INTRODUCTION

This project was necessitated by EU regulations concerning maximum permitted mycotoxin levels in food, including grain. Mycotoxins are thought to be produced by fungi to supress competition from other species or possibly even arthropods.

The fungi normally present in grain at harvest, referred to as field fungi, include species of *Alternaria*, *Cladosporium*, and *Fusarium* which generally do not develop further during storage. If storage conditions support fungal activity, species of *Aspergillus* and *Penicillium* often occur. Fungi cause a variety of deteriorative changes in grain and seeds, both before and after harvest. The effect of fungal invasion include musty or sour odours, germination decrease, visible mould, discoloration, decreased palatability, dry matter loss, heating, caking, chemical and nutritional changes, reduction in processing quality and production of mycotoxins (Christiansen and Kaufmann, 1969; Pomeranz, 1992). Occurrence of fungal spores in the grain also increases the risks of respiratory diseases and infections for exposed workers and animals (Lacey and Dutkiewicz, 1994). In the UK, the main threat is from ochratoxin A (OTA) as conditions are too cool to permit the formation of aflatoxins.

OTA causes nephrotoxicity in pigs and chickens and is a cause of Balkan endemic nephropathy in humans (Krogh, 1978). OTA is a nephrotoxic mycotoxin and a renal carcinogen (JECFA, 2001) whose level should be reduced to that lowest technically achievable (Anon, 1993).

Cereals are considered to be the main contributor (50 to 80%) to the OTA intake among European consumers (SCOOP, 2002) and OTA occurrence in blood and urine is almost universal (MAFF 1999). The European Commission has defined maximum legislative limits for OTA in unprocessed cereals at 5 ppb (Commission Regulation 472/2002 amending Regulation 466/2001). Similar maximum levels for cereals are also being discussed within the Codex Alimentarius. For unprocessed feed grain the Commission suggest a guidance value of 250 ppb OTA and for complete feedingstuffs for pigs and poultry, corresponding values are 50 ppb and 100 ppb respectively (Malm, 2006).

Ochratoxin A is produced by *Aspergillus ochraceous* in tropical or subtropical climates (van der Merwe, 1982) but under UK conditions it is most likely produced by *Penicillium verrucosum* (Frisvad and Filtenborg, 1989). The lowest r.h. for growth of *P. verrucosum* is 80%, while that for production of OTA is above 85% r.h. (Northolt and Bullerman, 1982). The equilibrium between relative humidity and grain moisture content is well-described so we know that the lowest m.c. for growth of *P.verrucosum* on wheat (at 25°C) is therefore about 17.2% and for production of toxins, 18.7% (Henderson, 1987). This should be regarded as authoritative even though some work has described OTA production at lower m.c.s (*e.g.*

Hetmanski, 1997). Such reports should be regarded with caution and may be attributed to inaccuracies of moisture measurement or use of different reference standards. For instance, the ISO ground grain method gives a m.c. 0.8% higher than ASAE (USA) whole grain methods (Bowden, 1984) .

In the UK, 2% of grain tested is reported as having concentrations exceeding 5ppb and 21% of samples are reported to have OTA at detectable levels (Scudamore *et al*., 1999). More recent surveys have shown less than 1% of malting barley and milling wheat exceed regulatory levels (HGCA, 2006). Since the highest m.c. for trading in most markets is 15-16%, the toxin can only be produced when the grain is still warm and wet, *i.e*.:-

1. During ambient air drying
2. Before drying by continuous driers, due to harvest backlogs
3. When surface grain absorbs moisture during the winter or during moisture translocation in uncooled grain, owing to moisture in hot air, rising from the bulk, condensing on cold surface grain.

Of these possibilities, the ambient-air drying process was deemed the area of highest risk. In this system, ambient air is forced by a fan through the grain bed, entering via ducts beneath, This causes a drying front to form and move from base to surface of a bin or flat store. The grain ahead of this front remains at or higher than the initial m.c. until the drying front passes through which can take 10 days even in the best designed systems (Armitage and Wildey, 2003). OTA was found on 4/24 farms during ambient-air drying and 8 out of 240 samples, in all cases where the m.c. was initially above 19%. No OA samples contained *P. verrucosum* and counts of *Penicillium* spp were only 200-2300 colony forming units (cfu) /g (Scudamore and Wilkin, 1999). In a Swedish field study, OTA was most common during wet years with high moisture content in the grain at harvest (> 20%) (Jonsson and Pettersson, 1999). The occurrence was attributed to insufficient or slow drying or too long a storage period before drying.

What was therefore required was an assessment to establish the conditions of initial moisture content, harvest conditions and drying strategy under which OTA would be likely to occur, and how operating conditions could be improved to avoid this risk. Fortunately, MAFF and HGCA have in the past sponsored research and development of a sophisticated engineering ambient drying model, ‘Storedry’ (Sharp, 1984) which allows a large number of simulations to be done in a short time. The missing element was a model of OTA production. It is difficult to devise a direct model since OTA is produced only by certain strains of *P. verrucosum* and even those strains that can produce it, may not always do so. Indirect measurements may also be problematic because OTA is produced during mycelial growth and is thus unrelated to colony count which rather indicates sporulation (Cahagnier *et al*., 2005). However, fungal activity is related to respiration and it was found that the start of the logarithmic phase of growth as measured by CO2 production, coincided with initiation of OTA production. A model of biodeterioration based on this observation, which had the advantage of also being applicable to fungal deterioration below the threshold for toxin production, was therefore incorporated into the engineering models and used as the criterion for biodeterioration on which the simulations of drying success and design improvements were judged.

The project was constituted with five work packages:-

1. To adapt a new model of safe storage time before OA production, depending on moisture content and temperature of grain, developed within an EU project to fit an existing, proven computer simulation of drying with ambient air.

2. To incorporate and test the safe storage time model into the simulation model of drying with ambient air.

3. To use the simulation, incorporating the new data on OA production, to find the conditions in which current recommendations for loading and running dryers are still appropriate, and those which were previously acceptable but where the risk of OA is now found to be significant based on the new data.

4. To use the simulation to find how to load and run a near-ambient dryer to ensure OA production is avoided, up to as high an initial wheat moisture as possible, over 20 years' weather data.

5. To produce material for a topic sheet and for revising the bulk storage drying pages of "The Grain Storage Guide" (see Bruce and Armitage, 2006).

The work was in two phases, a situation brought about by the closure of SRI part way through the project. At the end of phase 1 (part way through work package 3) the key member of SRI staff, David Bruce, set up David Bruce Consulting Ltd. and acquired a licence from SRI for the software, known as Storedry, and continued with phase 2 of the project under renewed funding to his company from HGCA.

1. A MODEL OF SAFE STORAGE TIME FOR CEREAL GRAIN BEFORE GROWTH OF MOULDS AND PRODUCTION OF OCHRATOXIN A

Introduction

Studies on the safe storage period for moist cereal grain are quite few, and are based on visible moulding (Kreyger, 1972), dry-matter loss (Steel *et al.*, 1969; White *et al.*, 1982) and loss of seed germination (Kreyger, 1972; White *et al*., 1982). For maize, maximum allowable storage time has been estimated, based on the time before dry matter loss exceeds 0.5% (Steel *et al.*, 1969). This loss was estimated to correspond to the loss of one US grade, which is based on visible inspection. Visible moulding may be an unreliable criterion because considerable losses can occur before moulding is visible, depending on whether or not conditions favour sporulation (Seitz *et al.*, 1979).

The new model

The new model of safe storage time used in this study was developed within the EU-project "Prevention of ochratoxin A in cereals" - Project No. QLK1-CT-1999-00433. The purpose of the model is to predict maximum safe storage time (MSST) for recently harvested moist cereal grain during aerobic conditions based on water activity and temperature, parameters that can be directly measured in the grain. The model was based on measurements of the respiration rate of the grain (winter wheat) (Lindblad *et al*, 2004). MSST was defined as the minimum point of the respiration curve (end of lag phase) before the exponential phase of mould growth starts. The data, obtained over a range of water activity and temperature, was fitted with the least square method to a mathematical model describing an exponential relationship between water activity and temperature of the grain, and maximum safe storage time:

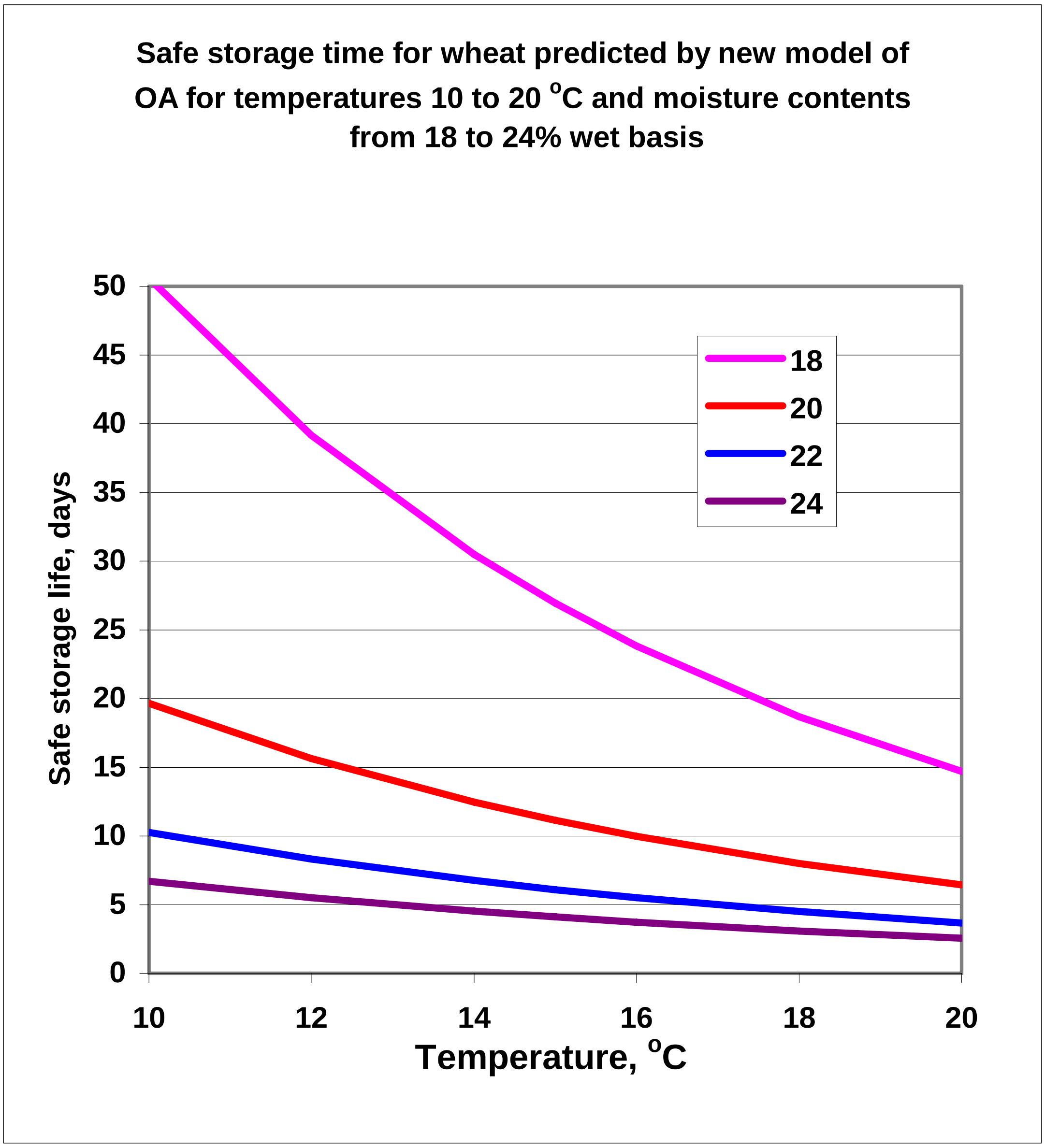
$$X=a*\exp(k1*T+k2*a_w)$$

X – maximum safe storage time (days)
T – temperature of the grain
a_w – water activity of the grain
a, k1, k2 – constants

Comparisons with standard methods of enumeration of fungi indicated that the minimum point of the respiration curve represented an early stage of growth of storage moulds before any obvious deterioration of the grain quality take place.

According to a rough estimation based on a few observations, the OTA level reached 5 ppb after about 1.5 times the MSST and 100 pbb after about 2.0 times the MSST. However, a safety margin might be needed on the farm because of difficulties concerning sampling and measurements of moisture content. Safety margins of 50% correspond to an under-estimation of the moisture content by meters of about 1.0 % at 0,85 a_w (ca 19% mc) which are the minimum usually observed at the high end of the moisture content spectrum (HGCA, 2000) Discrepancies also exist between different studies of the relationship between moisture content and relative humidity (water activity) at equilibrium in cereal grain of the same type and also between different oven methods for determining moisture content (Bowden, 1984).

The expression above is not precisely the same version of the model, which has been used in this study. That version will be released after it has been scientifically published later this year or in the beginning of next year as a part of a doctoral work.



2. ADAPTATION, INCORPORATION INTO THE SIMULATION MODEL OF DRYING WITH AMBIENT AIR, AND TESTING OF THE MODEL FOR SAFE STORAGE TIME BEFORE OA PRODUCTION.

Introduction

The simulation programme STOREDRY is based on equations that describe the tendency for air and grain to move towards an equilibrium, after which no further change takes place. In addition, equations describing the rate of transfer of heat and moisture between grain and air are used where the changes towards equilibrium are rapid. These equations operate over a wide range of conditions of grain and air temperature and moisture content, and deal with rewetting as well as drying of grain. The grain bed is represented as 100 layers, each of which has a temperature and moisture of air and grain that is recalculated every 10 min. Calculations follow the direction of air flow and, as the exchange of heat and moisture is worked out, conditions for both the air and grain are evolved over the duration of drying. The equations work both in forced convection in a packed bed *i.e.* where air is moved by a pressure generated by a fan, and also in unforced, natural convection. In addition to starting conditions of grain (m.c., temperature, depth, bulk density, etc) and of the drier (area, fan characteristics, resistance of ducts and floor to airflow) the air conditions over the period of drying can be drawn from weather records so that realistic conditions are generated in the drier. Once the temperature and moisture conditions of each layer of the grain bed have been established for each time step, the effect on the grain quality in each layer is calculated. These include progress towards spoilage by mould, reduction of viability and dry matter loss due to respiration. Drying is halted when a grain moisture target is reached, at which time the final bed conditions and various measures of performance and are calculated and output as required. The programme has not been fully described but Sharp (1984) describes the theoretical basis and many of the features as they existed then.

The model of deterioration, by Jonsson, expresses the dwell time before OA-producing fungi would begin their rapid growth phase. This dwell time is dependent on both the temperature and water activity of the grain. Adapting the expression involved translating the water activity into a moisture content (m.c.) to which it was equivalent, using an equation for the equilibrium between moisture content and relative humidity (r.h.). Such an equation, called an emc-erh equation, is also used in the simulation model of near ambient drying, and it was important for consistent results that the equation used was common to both. Because of their importance in drying, the form and the parameter values of emc-erh equations have been widely studied over many years and the ‘Chung-Pfost’ equation (Chung and Pfost, 1967) has become widely accepted as effective. This opportunity was taken to upgrade the emc-erh equation used in STOREDRY by fitting the ‘Chung-Pfost’ equation to some high quality data form wheat by Henderson (1987). Further details are given in Appendix B.

The Jonsson model, once expressed in terms of safe storage time as a function of temperature and wheat moisture content, was coded into a subroutine in the FORTRAN language, added into STOREDRY, and tested to ensure it worked as intended. The approach to calculation of progress towards spoilage, well established in previous work on loss of viability and of spoilage based on visible mould, was to calculate a “spoilage index”. For each short interval of simulated time between the drying calculations, in which the temperature and moisture of the grain were considered constant, a fraction was calculated, equal to that time interval divided by the safe storage life at those values of temperature and moisture. The spoilage index was simply the sum of these fractions. When the index reached a value of 1, the grain was defined as having reached the end of its safe storage period, and it was assumed that spoilage by OA had occurred.

Simulations to explore effect of drying conditions on grain spoilage based on OA

The objective of this work package was to use the simulation, incorporating the new data on OA production, to find those conditions in which current recommendations for loading and running dryers would be still appropriate, and those which previously would have been acceptable but would not be when the risk of OA was taken into account.

The approach taken was to run the simulation of near ambient drying to simulate conditions considered to represent a range of “current practice”, both in terms of the size and loading of the dryer and also in the control policy used during drying. Across this range of current practice, the aim was to find:-

1. if the grain dried to the target moisture,
2. if the conditions in the bed would give rise to spoilage according to the old model, by Fraser (Fraser & Muir, 1981), based on data on visible mould and significant loss of viability of Kreyger (1972), and
3. if conditions in the bed would give rise to spoilage according to the new model of Jonsson, based on OA.

In the simulations, the grain bed was considered to comprise 100 layers, and the properties of each, including the moisture content and the degree of spoilage, were calculated separately as drying proceeds. At the end of each time step of simulation, the requirement for the maximum moisture to be below a moisture threshold was applied by checking every layer in the bed. Once the m.c. of the wettest layer was below 16% wet basis, drying was considered complete. Similarly the degree of spoilage for each layer was examined to find the maximum degree of spoilage anywhere in the grain bed. If this maximum exceeded a threshold, the grain in that layer was considered to have spoiled, and the treatment was considered to have failed. If no layer had reached the spoilage threshold by the time the drying target was met, the drying treatment was considered successful, *i.e.* without risk of spoilage. This process was repeated using each of 20 years weather records in turn.

The values of certain parameters in the model were kept constant for these runs while others were altered to explore the behaviour of the dryer.

Basis of the simulations and values that were fixed for all of them.
The material dried was wheat, at initial moisture contents of 18 to 24% wet basis. (N.B. All moisture content values in this report are given on a wet basis.) Bed depth used was 3.0 m, which was towards the upper end of the normal range, but a figure commonly used for design purposes and appropriate to give a reasonably high loading of a dryer. The holding capacity of the bed being dried was about 250 t so the simulations represented a 500t dryer in which one half was being ventilated. A specific fan (Typhoon, model TC5, by Pellcroft Engineering Ltd, Coldham Road, Coningsby, Lincs, LN4 4SE) and dryer floor area of 110 m^2 were adopted because, with the characteristics of this fan, this drier area and bed depth gave a specific airflow close to the guide value of 0.05 m^3/s.t commonly recommended by ADAS (1983) for the design of near ambient drying systems. The actual airflow was calculated in the program by matching the pressure and flow characteristics of the fan and of the grain bed and ducts.

The policy for use of the fan, and heater if present, is known to be an important component of successful drying. Control policies are discussed in more detail in Chapter 2 but here seven simple strategies were used. Where no heater was used, the fan was run continuously, or switched off when the relative humidity of the air in the duct, after the heating effect of the fan, exceeded a fixed value. Values of 70%, 80% and 90% r.h. were used. When drying with a heater available (propane gas-fired, with fixed power of 80 kW), the fan remained on continuously and the heater was turned on when the duct air r.h. exceeded 70%, 80% and 90%.

Calculation of grain spoilage could only be done by one spoilage model in each simulation so duplicate simulations were done, one with the old spoilage model of Fraser/Kreyger and one with the new model of Jonsson. Loss of grain viability was calculated by the Nellist model (1981).

Weather data for 20 years from 1951 to 1970 from five locations in England were used, and drying was specified to start on two dates, 15 Aug and 15 Sept each year. The target for completion of the simulation was that the moisture content of the wettest layer in the bed should be less than 16% wet basis within two months of starting the simulation, a generous timescale. (Though this m.c. was not low enough for safe storage, test simulations confirmed that the spoilage rate predicted by the OA model was extremely low below this moisture level so it was considered a suitable point to stop the simulations in this study.)

Factors varied for the study

Factor to be varied		No of Levels
Spoilage model	Jonsson, Fraser/Kreyger	2
Location	Waddington (Lincolnshire), Heathrow (Middlesex), Ringway (Manchester), Plymouth (Devon), Elmdon (Birmingham)	5
Years (1951-1970)		20
Initial moisture content, % w.b.	18, 20, 22, 24	4
Start date for drying	15/8, 15/9	2
Control policy:-	Continuous fan, Fan off if r.h. after fan >90, 80, 70 %, Heater on if r.h. after fan >90, 80, 70 %	7

All combinations of these factors amount to 11200 individual simulations. Once simulation started it became clear that the 90% control points were not actuated because the r.h. after the fan did not drop below that value, owing to the energy input by the fan to the air. This reduced the total to 8000 simulations.

Analysis, results and discussion

"Current practice" in the work package description was taken to refer to <u>successful</u> current practice, *i.e.* all combinations of the factors that produced grain dried within the time limit and in which spoilage had not occurred according to the old, but current, model of Fraser/Kreyger. Not all combinations of the parameters would be appropriate in all locations and years, but the approach at this stage was simply to simulate all combinations and then to filter the results to identify the successful treatments.

Having combined the pairs of runs that differed only in the spoilage model that was used, results for the 4000 combinations were first analysed to find all the runs that reached the drying target (*i.e.* maximum moisture in the bed <16% wet basis). These runs, as a proportion of the total, are shown in row 1 of Tables 1 and 2. Overall success ranged from 92% at Ringway to 70% in Plymouth. Continuous ventilation was effective in only 40% of the simulations but fan control was at least 84% effective while the use of heater on a humidistat was effective in 100% of cases. 'Success' here was simply the achievement of the drying target without any consideration of the health of the grain at the end point. Success simply in terms of drying was not greatly significant because it can be argued that an experienced operator would not choose certain strategies or a depth of 3m in certain locations.

Of those runs where drying was achieved, those runs that <u>also</u> dried without spoilage were selected. Those drying without spoilage by the current spoilage model, Fraser/Kreyger, runs that would be considered successful by current practice, are shown in row 2 of the Tables 1 and 2. The proportions ranged from 44% to 57% by location, with Plymouth and Ringway again being worst and best locations. Drying strategies varied in their success in drying without spoilage by the current spoilage model, from only 29% success for a strategy of turning the fan off above an r.h. of 70% to a 66% success for a strategy of continuous ventilation with heater brought in above 70% r.h.

Finally, and most importantly, the runs in which the dried grain had <u>not</u> spoiled by the current spoilage model (Fraser/Kreyger) but <u>had</u> spoiled by the new model for OA (Jonsson) were selected. These runs showed the effective risk of OA developing during drying practices that are currently considered successful. This proportion, shown in row 3 of the Tables 1 and 2 and with an overall result of 36%, shows that, over the range of drying treatments simulated, more than one third pose a risk of OA while fully satisfying current standards for quality of dried grain. The proportion of treatments in which OA was predicted was consistent across four locations, at 34-36%, but rather worse at Plymouth at 41%. It ranged from 32 to 41% depending on drying strategy.

Effect of location

Overall, 84% of treatments achieved the moisture target in time. Four locations were similar to each other insofar as about 55% of treatments achieved drying without spoilage by the current model, while in Plymouth, with its warmer, moister climate, achieved only 44% success without spoilage. Thus, in only half the treatments was the way the dryer was loaded and operated adequate for the task. Within only those apparently successful runs, the model to predict OA showed a very consistent, 34-36%, chance of conditions occurring in which OA was predicted for four locations, with 41% in the case of Plymouth. So although the risk of OA was worst in the warmer, more moist climate of Plymouth, it was not much lower elsewhere.

Effect of control policy

The simple control policies varied widely in their success and overall were not impressively effective. Continuous ventilation was least effective, with only 42% of treatments achieving the drying target in the two month time window allowed, while both policies using heat dried the grain in time. Of those treatments that dried in time, overall only 53% avoided spoilage by the current model. The most successful was to use heat above 70% r.h. while the least effective was to turn off the fan at this setting. However, between 32 and 42% of the apparently successful treatments were at risk of OA. Bringing heat in at 70% r.h. gave the least risk while cutting off the airflow at the same r.h. had most risk. Clearly none of the strategies for fan and heater control was particularly effective at drying without risk of OA.

Effect of initial moisture content

Further analysis, limited to the Waddington location, showed that no treatments succeeded in avoiding risk of OA when starting from 22 or 24% m.c. Of the treatments starting at 20% m.c., 68 out of 200 were successful. At 18% m.c., 149 of 200 succeeded, showing that initial moisture content had a strong influence on the risk of OA.

Effect of harvest date

It might be expected that drying started on 15 August would be more successful than started on 15 September, other factors being equal, because of the likelihood of weather with better potential for drying, *i.e.* warmer and drier. However, analysis of results for Waddington showed that for a 15 August start, 109 treatments dried in time and with no risk of OA, whereas 108 did so when drying started on September 15th. (In practice, "other factors being equal" may be an oversimplification because grain moisture content at harvest would probably be lower in August.) The reason is as follows. The temperature of the air is higher and, while this does increase the drying capacity of the air, it also means that the grain at the top of the bed is warmer during the period before the drying zone reaches it and its moisture starts to fall. Hence the spoilage rate of that grain is greater.

Effect of bed depth

In the light of the main results, a few test simulations were done on the effect of reducing the bed depth from the 3.0 m used in the main work, to 2.5 and 2.0 m (Waddington weather set, 20% initial m.c., heat applied at plenum r.h. >80%.) The results were that the airflow per tonne increased, by 25 and 63% respectively, and the number of years out of 20 in which OA was predicted by the new model fell from 8 to 1 to 0. Of course, the holding and hence drying capacity of the bed were also reduced in proportion to the bed depth. These few results suggested that reducing the bed depth, or increasing airflow by other means, may be highly effective in reducing spoilage, though costs and drying speed were not considered in this brief analysis.

Conclusions

From a total of 4000 simulated drying treatments, an overall proportion of 36% of apparently successful treatments were predicted to be at risk of OA. This proportion was quite consistent across five control policies for fan and heater and across five locations in England. This result showed that:-

1. The new (Jonsson) model for spoilage is more demanding than the current one (Fraser/Kreyger).
2. None of the simple control policies, in the circumstances simulated, avoided or even much reduced the proportion of treatments in which OA was predicted.
3. The proportion of treatments in which OA was predicted was fairly similar in all five regional climates simulated, *i.e.* not confined to warmer, moister areas.

A brief study of results for the Waddington location showed that:-

4. Initial moisture content was very influential, in that all treatments that avoided OA at this location started at 20 % m.c. or below.
5. Bed depth was also very important. Reducing it from 3 to 2.5 m had a major benefit in reducing the proportion of treatments in which OA was predicted.

Table 1. Drying and spoilage outcomes for five locations and overall. Results for the five control policies are combined for all locations.

Location	Waddington	Elmdon	Heathrow	Ringway	Plymouth	Overall
1. Proportion of treatments dried within the target time, %	80	86	90	92	71	84
2. Of treatments in line 1, proportion without spoilage by current criteria (Fraser/Kreyger), %	53	55	53	57	44	53
3. Of treatments in line 2, proportion with spoilage by Jonsson model, *i.e.* risk of OA, %	36	34	35	34	41	36

Table 2. Drying and spoilage outcomes for each of the five control policies and overall. Results for the five locations are combined for all control policies.

Policy	A	B	C	D	E	Overall
1. Proportion of treatments dried within the target time, %	42	93	84	100	100	84
2. Of treatments in line 1, proportion without spoilage by current criteria (Fraser/Kreyger), %	61	45	29	63	66	53
3. Of treatments in line 2, proportion with spoilage by Jonsson model, *i.e.* risk of OA, %	36	39	41	35	32	36

Key to policies in Table 2:-

A continuous fan
B Fan off when r.h. after fan >80%
C Fan off when r.h. after fan >70%
D Continuous fan, plus heater on when r.h. after fan >80%
E Continuous fan, plus heater on when r.h. after fan >70%

3. USE OF THE SIMULATION TO FIND HOW TO LOAD AND RUN A NEAR-AMBIENT DRYER TO ENSURE OA PRODUCTION IS AVOIDED

Introduction

In the first part of the work, a range of simulations was done to determine what degree of spoilage was predicted, based on a new model of OA production in wheat as well as on a well-established model based on visible mould and germination loss. The range simulated covered normal drying practice in terms of bed depths, initial wheat moisture contents and strategies for operation of fan and heater, and the simulations were done for 20 years' weather data from five locations in England. With such a 'blunderbuss' approach, in which every combination of bed depth, control strategy, initial moisture content and location was tried irrespective of prospective suitability, one would expect many treatments to be unsuccessful and this was indeed the case. However, by selecting those treatments that were successful by the current spoilage model, a set was found that met the drying criteria of grain moisture and quality. Simulation results for the same set using the new spoilage model predicted that OA would be produced at some point in the grain bed in about one third of those apparently successful treatments. Though it confirmed that perhaps one third of apparently successful drying treatments would actually risk OA production, this finding did not give any useful insight into why certain treatments failed and how to select the combinations of parameters that would give successful drying. Thus the objective of the next part of the work was to use the power of the simulation to achieve these objectives.

Quantification of risk, and acceptable level of risk

Of course, it is the variability of the weather that provides the challenge in drying and which prevents a simple set of rules from being successful every year. The weather is variable and in difficult drying years can make drying without spoilage very difficult to achieve. For any given set of historical weather data, a particular drying treatment can be simulated and will be found either successful or not. If the same drying treatment is simulated for each of 20 years data, a good measure of success is the number of years out of 20 in which that treatment results in no spoilage anywhere in the grain bed when the moisture target is met. By this measure, 15 years without spoilage out of 20 represents 75% chance of success, or a 25% risk of failure. A treatment that succeeds in all 20 years with the Jonsson model of spoilage means that the risk of OA being produced is less than 1 in 20, or less than 5%. Given that a risk of 5% or less was the highest certainty that could be calculated using 20 weather data sets, and because it seemed to be a reasonable and practical level for dryer operators to aim at, the criterion of 20 years success out of 20 years simulated was adopted as the basis on which treatments were selected as acceptable. In a later section, possible benefits of accepting a greater risk are explored.

Determining the "envelope of safe practice"

The emphasis of the project is on devising <u>practical</u> strategies for dryer loading and operating. Bed depth is entirely within the control of the dryer operator, and it was shown in work package 3 (and is well known) that reducing the depth of the bed will achieve drying more quickly, and thus make spoilage less likely, provided the air delivered to the grain is at a suitable condition for drying. Reducing depth is effective for two reasons. First, in a shallower bed, the drying front will pass through the bed in less time so the wettest grain, near the exhaust, will dry sooner. Second, because the simulation is set up to work with a fan characteristic and resistance of the grain bed and ducts, reducing bed depth reduces its resistance to airflow and allows more air to be delivered. This speeds up the drying even more. Hence reducing the bed depth is an effective way to accelerate drying and reduce the risk of spoilage. Initial moisture content also, clearly, has a major influence on the probability of achieving a moisture target without spoilage. Therefore, a simple graph of how the maximum safe bed depth depends on initial moisture content was considered a good, practical means of summarising the effectiveness of a drying treatment.

So, in this work, the following basic approach was adopted as a means of summarising the effectiveness of a drying treatment. Drying was simulated for a range of bed depths for each combination of other parameters to find how the number of successful years out of 20 reduced as bed depth increased (Figure 1). By this means the maximum bed depth was found at which there was no predicted spoilage anywhere in the grain bed for any year's weather out of the set of 20, *i.e.* the risk of OA production was less than 1 in 20 or <5%. This is referred to hereafter simply as the "maximum depth" for the specified level of risk. In Figure 1, the maximum bed depth is 1.9m, above which the number of successful years starts to fall from 20.

By repeating this process, the maximum useable bed depth for spoilage risk <5% was found for each of five initial moisture contents, 22, 21, 20, 19 and 18% wet basis. Figure 2 shows an example in which the maximum bed depth of 1.9 m shown in Figure1 is the point for 20% moisture. The vertical bar represents the range of depth, 0.3-3.0 m, simulated for Figure 1.

Once this curve, effectively the "envelope of safe practice", was determined for a given location, start date, control strategy and other parameters, the effectiveness of a new treatments could be judged by how much they raised the curve, *i.e.* increased the maximum depth for the same <5% risk of OA. An increase in maximum depth meant that more grain could be dried for the same risk or that the margin of safety with the given bed depth was increased. Hence during the remainder of this work, there is much emphasis on the maximum depth and how much any change in drying parameters lifts the curve, either across the whole range of initial moisture content or just in part of the range.

How the simulation was set up and run

The basis of the how the simulation program 'STOREDRY' was set up and used to simulate drying treatments was explained in Chapter 1. This is also applicable to the following work but it is appropriate to explain some further aspects here. A propane heater was used, which could be specified as single-stage, multi-stage or as having a continuously variable heat output up to its maximum. The heater power specified as standard in the simulations, 80 kW, was based on achieving a temperature rise of 5 ^{o}C at the nominal airflow. This is close to the value of 6 ^{o}C suggested on p85 of McLean (1989). However as the airflow varied as a result of changing grain bed depth, floor area, and fan model, the temperature rise for a given applied heater power was not constant, but represents what would happen in practice. Weather data for 20 years from 1951 to 1970 from one of five locations in England (Waddington, Ringway, Heathrow, Elmdon and Plymouth) were used, and drying was specified to start on one of two dates, 15 August or 15 September, each year. Even if the grain had not spoiled, a time of two months was the maximum allowed in the simulation. The target for completion of drying was that the wettest layer in the bed should be less than 16% wet basis moisture. In this work, the emphasis is on the prevention of OA, and the data showed that once the moisture reached 16% wet basis or below, the safe life was very long. Hence all results for simulated drying treatments were taken when the wettest layer of wheat fell below 16%. Drying was not fully complete at this stage and drying to a final m.c. suitable for long term storage might require a change in the strategy for fan and heater control but, provided the grain is not rewetted by further ventilation, the risk of OA would have been controlled.

Costs of drying

At this stage of the simulation, the cost of drying was calculated. This comprised the cost of liquified propane gas, taken as 0.225 £/l, or electricity for air heating and for the fan (on-peak and off-peak rates taken as 8.0 and 4.5 p/kWh respectively). Added to these actual costs were the costs of lost weight for sale due to dry matter loss caused by respiration and mould activity (both very small in this work) and due to over-drying. This last was the lost value incurred by any reduction of the average moisture of the bed below the target of 14.5% wet basis at which it was assumed grain would be priced. The grain price was taken as 65 £/t. It should be noted that the drying costs presented in the report were those to reach a target of the wettest layer in the grain bed being at or below 16% m.c. So the costs are given in £/tonne but the tonne was not at a consistent m.c. It was at whatever the average m.c. was when the wettest layer reached 16%. Further costs would be incurred to achieve whatever final m.c. was required. In most of this work, grain tended to be under-dried because the average m.c. was likely to be greater than 14.5% when the wettest layer target was met.

Control strategies for fan and heater

Within “normal practice”, for which the safe envelope of depth against moisture content needs to be determined, there is a wide range of equipment and are several methods of using it. Fan, heater and humidistat are normal equipment. Control may be automatically or manually executed but in all cases setpoints (values of measured parameters, such as r.h. or grain moisture, at which control actions are taken) require to be selected at the start of drying and perhaps changed as the grain bed dries. After deciding at what grain moisture at which to harvest and to what depth to load the dryer, the choice of the control strategy setpoint is the next important determinant of drying success.

Some common strategies were simulated in Chapter 1, *i.e.* continuous running of the fan with no additional heating, taking action when values of r.h. higher than a setpoint occurred; switching the fan off (at 70 or 80% r.h.) or switching a fixed power of air heater on (ditto). Much work has been done by researchers and industry on developing improved strategies for fan and heater control but no one strategy has emerged as clearly best in all circumstances. (Work to develop novel strategies was not part of this project.) Here the emphasis was on practical steps an operator could take so a limited range of conventional strategies was explored in addition to the strategies used in Chapter 1, to determine what safe envelope they produced.

Before the strategies are described, some comment is appropriate on aspects of fan and heater control. The simplest heating arrangement is a single heater, which is either on or off. This is referred to as a single-stage heater. Electric heating is normally used in this way, but an electric heater bank may have several stages that can be switched in successively to provide levels of heat. This is a multi-stage heater. By contrast with electric heaters, propane gas heaters often have a continuously variable output and so can offer a way of altering the incoming atmospheric conditions more precisely, *e.g*. to achieve an r.h. or temperature downstream of the heater.

A humidistat is used to switch a fan or heater, based on measured relative humidity in the plenum chamber after the air has been heated a little by the fan itself. The r.h. value at which the humidistat switches may be set and left, or may be altered as drying proceeds to respond in some sense to the changing moisture in the grain bed.

Control strategies in which grain moisture is a variable require a single value of moisture to be supplied. But within the bed of grain during drying, a range of moisture is present, generally driest near the air inlet, wettest near the outlet. Some previous studies on control have used average bed moisture or moisture content of the wettest layer as the basis on which the control action is based. Because an average or wettest value requires more effort to measure, an approach was used here as recommended by McLean (1989, p83), *i.e.* to sample grain 0.3 m down into the bed from the surface and to use this for decision making in control. This location tends to be the wettest area but deep enough not to be affected by any condensation close to the bed surface. Therefore, where grain moisture is used in this work as the basis of control action, it is the moisture content 0.3 m down into the simulated bed unless otherwise specified.

A considerable number of exploratory simulations were carried out to find suitable strategies for the main part of the work. A range of strategies was programmed into the STOREDRY simulation and their performance was investigated, as detailed in Appendix E. From this work and study of the literature, the following three strategies were selected because (a) they were established approaches which, with parameters chosen from the exploratory work, performed reasonably well and (b) none of these strategies would require major expenditure on new equipment.

4. **Strategy 1**. This strategy, for heater control with continuous ventilation, used unheated ambient air when the r.h. was below a setpoint value, and switched in a fixed power of heater when ambient air r.h. rose above that setpoint. A fan, heater and humidistat would be required. In Chapter 1, this strategy produced the fewest failed years. In this strategy no account was taken of the moisture content of the grain or of the reduction in r.h. that heating achieved. Initial results, in Table 3, were obtained using an r.h. setpoint of 80% and a single-stage, propane heater of power 80 kW.

5. **Strategy 2**. This strategy, for control of a fan (with no heater), used ambient air slightly heated by the action of the fan. The fan was switched off when the r.h. of the air in the plenum chamber rose above an r.h. setpoint. A fan and humidistat would be required. The strategy aimed to ventilate the grain bed only when that would not re-wet the grain. To achieve this, the r.h. setpoint was progressively reduced, as drying proceeded, according to a series of "steps". For initial results the following steps, given in the HGCA Grain Storage Guide (Armitage and Wildey, 2003) as an example, were used. The fan was run continuously at grain moisture above 20%. Between 20 and 18% the fan was cut off when r.h. in the plenum rose above 83%. Between 18 and 16% it was cut off at r.h. values above 72%, and below 16% cut off was above 62% r.h. These steps were to some extent based on the equilibrium relationship between relative humidity and grain moisture.

6. **Strategy 3**. This strategy, for fan and heater control, again used a stepped response to ambient r.h., depending on the progress of the drying, with the aim of avoiding rewetting. It was described in a publication "Bulk grain drying and conditioning" (Anon, 1990) published by FEC Services Ltd, formerly the Farm Electric Centre. A fan, a heater with a number of stages and a humidistat would be required. Initially these "steps" were used:-

r.h. %	100	83	78	73	68	62
m.c. %wb	20	18	17	16	15	

The fan was run continuously above 20% m.c. Between grain moistures of 20 and 18% the fan was cut off when the plenum r.h. rose above 83%. Below 18% m.c., heater stages were switched in successively until the r.h. of plenum air was reduced to, or below, the setpoint r.h. value. So, for example, at a m.c. of 17.5%, the r.h. setpoint would be 78%. This setpoint was reduced in several steps ending at 62% r.h. when m.c. was below 15%. For results in Table 3 a propane heater with four stages, each of 20 kW, was used.

Safe envelope for Strategies 1, 2 and 3

This section investigates the safe envelopes produced by running simulations of drying with each of the three strategies with parameters as described above, where the safe envelope is defined by the line of initial moisture content versus maximum depth at which simulations with all 20 years weather predicted no OA in the bed. In the next chapter, this safe envelope is extended by altering the parameters of the strategies to explore how much benefit is produced, as revealed by any increase in the maximum bed depth for a given initial mc.

The three strategies were simulated for a number of locations and start dates. Initially, results for only one location, Waddington in Lincolnshire, and only one starting date, 15 August, are presented together in Table 3 for initial comparison and comment. Waddington was chosen as it gave the second lowest maximum depths, above Plymouth, and was therefore the most difficult location for drying in the main grain-producing area. Costs are considered shortly. (Note that each row of tables such as Table 3 required 100 simulations.)

Strategy 1, in which a setpoint of 80% r.h. was used to switch in a single stage, 80 kW, heater performed well across the range of initial moisture content. At 22%, a depth of 1.2 m was predicted, rising to 2.3 m at 20% and more than 4.8 m at 18%. Above 4.8 m the resistance posed by the grain bed was too great for the fan which was then close to stall conditions.

Strategy 2, in which the fan was controlled with no heating, gave poor results in comparison with Strategy 1. At 18% a maximum bed depth of 1.2 m could be used while at 19% the depth was 0.6 m. Strategy 2 was not effective at or above 20%, *i.e.* even the minimum depth of 0.4 m did not achieve drying without OA in all 20 years. (Note that at depths as shallow as 0.5 m, the accuracy of the simulation was compromised owing to effects caused by the size and spacing of individual ducts in a real dryer that were not represented in the simulation model.)

Strategy 3 was effective at 18 and 19% but at 20% the depth for 20 successful years out of 20 was only 0.7 m. It was ineffective higher m.c.s than 20%.

Costs for each case are presented in Table 4. The cost calculation took into account the reduction in saleable weight of grain if the average moisture content of the grain bed fell below 14.5% wet basis.

The drying cost of Strategy 2, with fan only, was by far the lowest but the range of moisture with which it could cope only extended up to 19%. Use of heating resulted in higher costs by both Strategies 1 and 3, costs which generally increased with initial moisture content, as would be expected because more moisture would have to be removed to reach the target. Strategy 1 had higher running costs than Strategy 3. This would be expected because, whenever the r.h. was below the setpoint, Strategy 1 used full heater power whereas Strategy 3 turned off the fan during some such periods and otherwise used only the number of heater stages needed to reduce the plenum air r.h. below the setpoint.

Drying times are presented in Table 5. To a large extent, the drying times reflect the bed depths in Table 3; times increased steeply for grain of lower initial moisture because the grain beds were deeper. The times for drying from 18 and from 19% were similar for all three strategies but, because the bed depths differed greatly, it may be helpful to express drying time in terms of hours per unit mass of grain dried. Strategy 1 took 112, Strategy 2, 428 and Strategy 3, 139 h/(t.m^2), so Strategy 1 is the fastest per tonne as well as allowing the deepest bed for the same level of risk.

Tables 3-5 have shown how a "safe envelope of practice" could be established when using one of the given strategies for fan and heater control for weather taken as typical of that location and start date. Hence a bed depth could be selected based on the initial moisture content that kept the risk of OA at below 5%. As the results were for only one location and start date, the next step was to determine if the performance of these strategies was similar at other locations, with a different climate, and at a date later in the season for the start of drying.

First, for an initial look at results from the five different locations in comparison with each other, a variant of Strategy 3 and a larger, continuously variable propane heater, was run for all five locations when starting drying on 15 August. Results (Appendix E, Table E.3.1) are shown graphically in Figure 3. The maximum depth at the five locations shows that weather at Waddington and Plymouth was most difficult for drying across the range of initial moisture content, while weather at Ringway was the most favourable. The reasons why the locations may be more or less favourable are discussed in Appendix C.

To establish if results in Tables 3-5 were generally valid, drying with Strategies 1-3 starting drying on 15 September at Waddington, and for both 15 August and 15 September at Ringway were simulated. Results for allowable depth, cost and drying time are shown in Tables 6-8 respectively.

From Table 6, the safe depth of the grain bed in weather conditions starting 15 August at Ringway was about 0.2 m greater than in Waddington. In September there was a similar difference between the locations except, for no known reason, at 19% initial moisture. The start date had a consistent effect, with the later start being better. This was because the later weather was cooler so (a) the grain bed was cooler when no heat was being used, which extended the safe storage time, and (b) air later in the season would have, generally, a higher r.h. so Strategy 1 would employ heat more often in September than in August. Drying times were longer in September than August for every case, and longer at Ringway than Waddington in all but two cases, which was a consequence of the differences in bed depth - for a given airflow, the progress of the drying front through the bed remains fairly constant, so a 10% greater bed depth would take about 10% longer to reach a target moisture. Costs per dried tonne, shown in Table 6, were influenced by initial moisture, bed depth and weather but drying at Ringway was always less costly per tonne of grain dried at the maximum allowable depth than drying at Waddington. Drying at Waddington was more expensive in September than August, but *vice versa* for Ringway.

In comparison with results for Strategy 1 in Table 6, Strategy 2 (Table 7) gave much lower allowable bed depths in both locations and with both start dates. Simply cutting off the fan when the ambient r.h. was too high resulted in a low overall drying rate so, to avoid spoilage, the grain bed had to be shallow. Strategy 2 was unsuitable for m.c.s of 20% and above at Waddington and at 21% and above at Ringway, though for 18 and 19% wheat, performance at Ringway was perhaps acceptably good. Strategy 2 used no heater and thus relied on the ambient air to provide drying opportunities, so the seasonal fall in temperature and rise in r.h. meant that maximum depths were lower in September than in August. Drying costs per tonne were lower, 50 to 70% of those from Strategy 1, because there were no air heating costs.

Table 8 shows that Strategy 3 gave reasonable results for the Ringway location but was only suitable for Waddington if the initial mc was 20% or below. There was a similar pattern of differences between locations for the same start date and between dates at each location as has already been noted for Strategy 1. These results are shown in Figure 4, which clearly shows the difference in maximum depth between the two locations.

Results for the two strategies in which air was heated, Strategies 1 and 3 (*i.e.* Tables 6 and 8) show that the maximum depth is considerably lower under Strategy 3 over the whole range of initial m.c. The maximum depths at Waddington were 2 to 4 times less under Strategy 3 than under Strategy 1, a surprisingly large difference. At Ringway the difference was smaller but was 20-50% lower under Strategy 3. The more subtle use of heating power in Strategy 3 compared to Strategy 1 might be expected to keep drying cost per tonne down and indeed this was the case at Ringway but there was no consistent cost difference at Waddington.

The results presented in Tables 6, 7 and 8 establish the "safe envelope of practice" for keeping risk of OA to less than 5% when using each of the three strategies in two contrasting locations for two start dates. It is clear from the foregoing comparisons that Strategy 1 allowed grain to be loaded to a greater depth than the other two strategies, and in some cases it was the only strategy that enabled grain above 20% moisture to be dried safely at all. The superiority of Strategy 1 was surprising, given that it was a simple system with a fixed heat power switched at a fixed r.h. setpoint, and its action was not modified according to the effect of that heat on the air r.h. or the progress of drying.

Reduction in depth required by use of new model

It was shown in Chapter 1 that the new model, based on OA, allowed shorter safe times before completion of drying than the old model, based on visible mould or significant viability loss. For grain at moisture contents higher than 18% wet basis, reducing the depth of the grain bed in the drier is one action that can be taken to reduce the risk of OA without the need for new investment. The foregoing section showed at what bed depths the risk of OA was reduced to <5% at two locations with the strategies used. To provide better guidance on how much the bed depth should be reduced, the runs from which the results in Tables 6 to 8 were obtained were repeated using the old spoilage model. This allowed the reduction in depth to be calculated.

Tables 9, 10 and 11 show results for Strategies 1, 2 and 3 respectively. Analysis of the depth reduction figures in all three tables together showed that the average reduction in depth needed was 1.1 m, and that it was not related to initial m.c. or start date of drying. There was however a significant difference between the locations, with Waddington requiring a mean depth reduction of 0.9 m and Ringway, 1.26 m. As these two locations were previously found to be the joint least and the most favourable respectively, these bed depth reductions can be taken as reductions generally required to move from depths successful in current practice to those required for the new spoilage criteria with the same level of risk. No relationship with the original depth was found, so it was not useful to express the reduction as a percentage. Drawing together results from Tables 9, 10 and 11 for the Waddington location with drying started August 15th, Figure 5 shows maximum depths for the three strategies and for both spoilage models. It illustrates that the reduction in depth required by the OA-based model was fairly constant irrespective of initial m.c.

Effect of depth on airflow, cost, drying time and spoilage

In this section, the interacting effects of depth and airflow on drying success, drying time and cost are explored.

If the maximum bed depth were to be exceeded, the risk of spoilage would rise because, in the 'worst' year, drying would not be completed before OA would be predicted. How much the risk of OA increased when a deeper bed was used is shown in Table 12 for one initial m.c., location and starting date. From Table 6, 1.2 m was the maximum depth for 20 years drying without OA at Waddington, starting 15 August at initial mc of 22%. Table 12 shows how the number of OA-free years reduced as the depth was increased above 1.2 m. Below 1.2 m, the drying was always successful in all 20 years. The relationship between risk and bed depth is considered in more detail in Chapter 3.

In general, the higher the airflow through a bed of grain, the faster the drying front reaches the top of the bed and starts to dry the grain there. Only then is the progress of that grain towards spoilage slowed. Therefore it is worth considering why the risk of spoilage increases rapidly above the maximum depth. The dryer being simulated was specified to have a fan (Pellcroft TC5) which, with the floor area of 110

m^2, ensured that the airflow provided by the installed fan was about 0.05 m^3/(s.dried t) at a bed depth of 3m. This airflow, quoted as a volume of air per unit mass of grain, is a well-established recommendation for near ambient drying (ADAS, 1983). However, even if the dryer were designed to the recommended airflow figure, the actual airflow through the grain bed might be higher or lower than the figure of 0.05 m^3/(s.t). This is because the air delivered by the fan would depend on the air resistance of the grain bed and duct system, so when the bed depth differed from 3m, the airflow would increase as the bed depth as reduced and *vice versa*. In the simulations of Table 8, for example, bed depths varied between 0.4 m and 4.8 m at which the airflows per tonne delivered by the fan were 0.55 m^3/(s.t) (<u>ten times</u> the notional design figure) and 0.032 m^3/(s.t) respectively. Of course the calculations of spoilage take full account of the effect of depth on airflow. Where the allowable bed depth was found to be low, this was <u>despite</u> the high airflow and the faster drying that the low bed depth generated.

The type of fan affects the change in airflow with bed depth. The centrifugal type of fan, of which one specific make and model is simulated here, generally has a pressure/flowrate characteristic curve that is quite steep, which is to say the air volume does not much reduce if the bed is made deeper. Conversely the volume of air delivered does not increase much if a shallower bed is used. In the two cases above, the air flowrate was 11.0 m^3/s at 4.8 m bed depth, and 15.5 m^3/s at 0.4 m depth. The difference in the airflow per tonne was mainly because the mass of grain per square metre of floor was proportional to bed depth, so grain mass per m^2 was 12 times greater at 4.8 m than at 0.4 m depth.

Table 13 illustrates the effect of depth on air delivery and shows that, when the depth of grain bed was reduced from 3.5 m to 1.6 m, the success of drying increased dramatically – the spoilage index fell and the number of successful years rose from 2 to 20. (The depth at which all 20 years were dried without spoilage was 2.2 m.) The components of this success are then presented. Mass of grain per unit floor area was in proportion to bed depth and, although the fan delivered only 16% additional air volume, the specific airflow (volume per unit mass) increased by 150% from the recommended value of 0.05 m^3/(s.t) at 3 m bed depth. The static pressure required to force air through the ducts and grain bed fell from 1550 to 1000 Pa.

If loading the dryer to the maximum depth was not required, less grain would be dried in the batch, but what advantages might there be? Table 14 shows, for an example condition at Waddington starting drying with Strategy 1 from 19% on 15 August, how the costs of drying per tonne, the time taken and the maximum spoilage index over the whole 20 years of simulated drying, were reduced as the depth of grain was reduced. In this case the drying time was in proportion to the bed depth, reflecting the steady rate of progress of the drying front through the bed. Maximum spoilage index was significantly reduced, giving a greater margin of safety, but the cost per tonne dried was reduced by less than 10% when the bed was reduced to 2/3 its original depth, so there was little economic reason for using a lower bed depth than the maximum.

Figure 6 confirms these findings for the whole range of initial m.c. It shows that drying times with Strategy 1 at Ringway from 15th August fell steadily as depth was reduced from the maximum at each value of initial moisture content. There was little difference in drying costs owing to grain depth, and the effect of initial m.c. was to raise the cost per dried tonne from just below £3/dried tonne at 18% initial m.c. to around £3.30 at 21%. Only at 22% initial m.c. did drying cost start to rise steeply for the shallowest bed. Each 0.2 m reduction in bed depth gave an extra margin of safety by significantly reducing the spoilage index.

Conclusions

1. The ‘safe envelope’ graph developed for this work, of maximum bed depth for risk <5% risk of OA versus initial m.c., is a compact way of expressing the performance of and hence of comparing drying treatments. Comparing on the basis of depth had a practical benefit because depth is a powerful lever to use in controlling spoilage risk.
2. The performance of three strategies for fan and heater control, determined in terms of the maximum bed depth they allowed without OA risk rising to 5%, showed that the relatively crude use of heat in Strategy 1 allowed deepest beds. Strategy 2 was not effective at 20% initial m.c. or above but costs were lower by 50% compared to Strategy 1. Strategy 3 was intermediate in both maximum depths and costs.
3. When additional air heating was available, drying starting in mid September allowed greater depths of bed to be used for the same initial m.c..
4. Compared with the maximum bed depths required by the previous model of visible mould, the new OA-based spoilage model required a reduction in depth on average of 1.1 m. This reduction was not related to the initial depth so it was not useful to express it as a percentage.
5. Though the additional risk of drying with beds deeper than this maximum was not investigated in detail, increasing depth by 0.5 m resulted in risk of OA rising from <5% to between 35 and 40%.
6. Using bed depths below the maximum for <5% risk resulted in an increased margin of safety from spoilage but cost per tonne dried was only reduced by some 10% for a 33 % depth reduction.
7. In general, drying time was proportional to bed depth, so treatments which allowed greater bed depths had longer drying times.

Table 3. Maximum bed depth at which drying was achieved without spoilage by the OA model in 20 years out of 20, at Waddington, Lincs, starting 15 August. (Runs 50b, 45 and 42b)

	Initial moisture content, % wet basis				
Strategy	**18**	**19**	**20**	**21**	**22**
1	>4.8	3.2	2.3	1.6	1.2
2	1.2	0.6	<0.4	<0.4	<0.4
3	3.9	1.5	0.7	0.4	<0.4

Table 4. Costs, £/dried tonne, of drying without spoilage by the OA model in 20 years out of 20, at Waddington, Lincs, starting 15 August. (Runs 50b, 45 and 42b)

	Initial moisture content, % wet basis				
Strategy	**18**	**19**	**20**	**21**	**22**
1	3.37	3.46	3.72	3.93	4.34
2	1.57	1.56	n/a	n/a	n/a
3	3.22	2.57	3.24	5.08	n/a

Table 5. Drying time, elapsed h, for drying without spoilage by the OA model in 20 years out of 20, at Waddington, Lincs, starting 15 August. (Runs 50b, 45 and 42b)

	Initial moisture content, % wet basis				
Strategy	18	19	20	21	22
1	399	271	207	159	131
2	380	236	n/a	n/a	n/a
3	401	204	115	77	n/a

Table 6. Performance of Strategy 1 at two locations (Waddington and Ringway) and two start dates for drying (15 Aug and 15 Sep). 80 kW propane heater. (from Runs 50b, 51b, 52a, 53a)

Location and start date for drying	Depth, m, at which 20 years were successful out of 20						Cost, £/dried t						Drying time, h				
Initial mc, %w.b.	**18**	**19**	**20**	**21**	**22**		**18**	**19**	**20**	**21**	**22**		**18**	**19**	**20**	**21**	**22**
Wad'ton, 15 Aug	>4.8	3.2	2.3	1.6	1.2		3.37	3.46	3.72	3.93	4.34		399	271	207	159	131
Wad'ton, 15 Sep	>4.8	3.9	2.6	1.8	1.3		3.56	3.85	4.08	4.39	4.88		425	362	255	194	156
Ringway, 15 Aug	>4.8	3.4	2.5	1.9	1.3		3.00	3.21	3.44	3.69	4.00		405	291	227	186	139
Ringway, 15 Sep	>4.8	3.7	2.8	2.0	1.5		3.04	3.26	3.45	3.70	4.03		435	344	277	213	175

Table 7. Performance of Strategy 2 at two locations (Waddington and Ringway) and two start dates for drying (15 Aug and 15 Sep). Grain moisture content for control was at 0.3m depth. (Runs 45, 162, 163, 164)

Location and start date for drying	Depth, m, at which 20 years were successful out of 20						Cost, £/dried t						Drying time, h				
Initial m.c., %w.b.	**18**	**19**	**20**	**21**	**22**		**18**	**19**	**20**	**21**	**22**		**18**	**19**	**20**	**21**	**22**
Wad'ton, 15 Aug	1.2	0.6	<0.4	<0.4	<0.4		1.57	1.56	n/a	n/a	n/a		380	236	n/a	n/a	n/a
Wad'ton, 15 Sep	<0.4	<0.4	<0.4	<0.4	<0.4		n/a	n/a	n/a	n/a	n/a		n/a	n/a	n/a	n/a	n/a
Ringway, 15 Aug	2.3	1.4	0.9	<0.4	<0.4		1.93	2.11	2.10	n/a	n/a		446	329	256	n/a	n/a
Ringway, 15 Sep	2.0	2.1	0.9	<0.4	<0.4		1.65	2.14	2.00	n/a	n/a		532	561	320	n/a	n/a

Table 8. Performance of Strategy 3 with an 80kW, 4 stage propane heater, at two locations (Waddington and Ringway) and two start dates for drying (15 Aug and 15 Sep). Grain moisture content for control was at 0.3m depth. (Runs 42b, 165, 166 and 167)

Location and start date for drying	Depth, m, at which 20 years were successful out of 20						Cost, £/dried t						Drying time, h				
Initial mc, %w.b.	**18**	**19**	**20**	**21**	**22**		**18**	**19**	**20**	**21**	**22**		**18**	**19**	**20**	**21**	**22**
Wad'ton, 15 Aug	3.9	1.5	0.7	0.4	<0.4		3.22	2.57	3.24	5.08	n/a		401	204	115	77	n/a
Wad'ton, 15 Sep	4.5	1.5	0.9	0.4	<0.4		4.31	3.34	3.71	6.49	n/a		598	261	183	100	n/a
Ringway, 15 Aug	>4.8	2.6	1.6	1.1	0.8		2.69	2.38	2.61	3.36	3.66		474	322	223	169	134
Ringway, 15 Sep	>4.8	3	1.9	1.4	0.8		3.08	2.80	2.86	3.68	4.01		540	415	278	228	146

Table 9. Maximum depths and depth reduction needed to maintain same risk level, <5%, with Strategy 1 at two locations (Waddington and Ringway) and two start dates for drying (15 Aug and 15 Sep) using new model for safe storage time (Jonsson) and old model (Fraser/Kreyger). 80 kW propane heater. (Runs 50b, 111, 51b, 196, 52a, 197, 53a, 198)

Location and start date for drying		**Depth, m, at which 20 years were successful out of 20**				
	Initial m.c., %w.b.	**18**	**19**	**20**	**21**	**22**
Wad'ton, 15 Aug	**New model**	>4.8	3.2	2.3	1.6	1.2
	Old model	>4.8	4.6	3.2	2.5	2.0
	Depth reduction, m	n/a	1.4	0.9	0.9	0.8
Wad'ton, 15 Sep	**New model**	>4.8	3.9	2.6	1.8	1.3
	Old model	>4.8	>4.8	4.2	3.2	2.4
	Depth reduction, m	n/a	>0.9	1.6	1.4	1.1
Ringway, 15 Aug	**New model**	>4.8	3.4	2.5	1.9	1.3
	Old model	>4.8	>4.8	3.5	2.7	2.2
	Depth reduction, m	n/a	>1.4	1	0.8	0.9
Ringway, 15 Sep	**New model**	>4.8	3.7	2.8	2.0	1.5
	Old model	>4.8	>4.8	4.7	3.6	2.7
	Depth reduction, m	n/a	>1.1	1.9	1.6	1.2

Table 10. Maximum depths and depth reduction needed to maintain same risk level, <5%, with Strategy 2 at two locations (Waddington and Ringway) and two start dates for drying (15 Aug and 15 Sep) using new model for safe storage time (Jonsson) and old model (Fraser/Kreyger). Grain moisture content for control was at 0.3 m. (Runs 45, 46a, 162, 199, 163, 200, 164, 201)

Location and start date for drying		**Depth, m, at which 20 years were successful out of 20**				
	Initial mc, %w.b.	**18**	**19**	**20**	**21**	**22**
Wad'ton, 15 Aug	**New model**	1.2	0.6	<0.4	<0.4	<0.4
	Old model	1.7	1.5	1	<0.4	<0.4
	Depth reduction, m	0.5	0.9	>0.6	n/a	n/a
Wad'ton, 15 Sep	**New model**	<0.4	<0.4	<0.4	<0.4	<0.4
	Old model	<0.4	<0.4	<0.4	<0.4	<0.4
	Depth reduction, m	n/a	n/a	n/a	n/a	n/a
Ringway, 15 Aug	**New model**	2.3	1.4	0.9	<0.4	<0.4
	Old model	3.8	3.3	2.2	1.9	1.5
	Depth reduction, m	1.5	1.9	1.3	>1.5	>1.1
Ringway, 15 Sep	**New model**	2.0	2.1	0.9	<0.4	<0.4
	Old model	2.1	2.1	2.1	1.7	1.5
	Depth reduction, m	0.1	0	1.2	>1.3	>1.1

Table 11. Maximum depths and depth reduction needed to maintain same risk level, <5%, with Strategy 3 at two locations (Waddington and Ringway) and two start dates for drying (15 Aug and 15 Sep) using new model for safe storage time (Jonsson) and old model (Fraser/Kreyger). 80kW, 4 stage propane heater. Grain moisture content for control was at 0.3 m. (Runs 42b, 161, 165, 215, 166, 216, 167, 217)

Location and start date for drying		**Depth, m, at which 20 years were successful out of 20**				
	Initial m.c., %w.b.	**18**	**19**	**20**	**21**	**22**
Wad'ton, 15 Aug	**New model**	3.9	1.5	0.7	0.4	<0.4
	Old model	4.8	2.7	1.7	1.3	1.1
	Depth reduction, m	0.9	1.2	1	0.9	>0.7
Wad'ton, 15 Sep	**New model**	4.5	1.5	0.9	0.4	<0.4
	Old model	4.8	3.2	1.8	1.4	0.9
	Depth reduction, m	0.3	1.7	0.9	1	>0.5
Ringway, 15 Aug	**New model**	>4.8	2.6	1.6	1.1	0.8
	Old model	4.8	4.2	2.8	2.5	2
	Depth reduction, m	>0	1.6	1.2	1.4	1.2
Ringway, 15 Sep	**New model**	>4.8	3	1.9	1.4	0.8
	Old model	4.8	4.6	3.5	2.9	2.3
	Depth reduction, m	>0	1.6	1.6	1.5	1.5

Table 12. Effect of using bed depth above the maximum calculated by simulation, on the number of years out of 20 in which OA was predicted, and on the consequent risk of OA at Waddington, starting 15 August with wheat at initial m.c. of 22% w.b. (Run 50b)

Bed depth, m	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**	**2.0**
Number of OA-free years, out of 20	20	19	18	16	13	8	4	1	0
Risk of OA, %	<5	5	10	20	35	40	80	95	100

Table 13. Effect of depth of grain bed on air flow, pressure, spoilage index and success of drying. Simulation for Plymouth, starting 15 September with initial m.c. of 20% using Strategy 1 with an 80 kW heater and 80% rh setpoint. (Run 117)

Bed depth, m	**3.5**	**3.0**	**2.5**	**2.0**	**1.6**
Successful years out of 20	2	6	18	20	20
Average over 20 yrs of maximum spoilage index	1.22	1.03	0.82	0.62	0.48
Mass of grain, kg/m^2	2830	2420	2020	1615	1290
Air volume flow, m^3/s	12.2	12.6	13.1	13.6	14.1
Specific air flow, m^3/(s.t)	0.049	0.059	0.074	0.096	0.124
Static pressure from fan, Pa	1552	1430	1293	1139	1003

Table 14. Effect of using bed depth below the maximum calculated by simulation, on the average cost, average drying time and maximum spoilage index over 20 years at Waddington, Strategy 1, 80% rh setpoint, 80 kW heater, starting 15 August at initial m.c. = 19%, drying until maximum moisture content in grain is less than 16% target. (Run 50b)

Bed depth, m	3.2	3.0	2.8	2.6	2.4	2.2
Cost, £/dried tonne	3.46	3.45	3.42	3.41	3.41	3.35
Drying time, h	271	252	235	217	198	182
Max spoilage index	0.99	0.91	0.84	0.76	0.68	0.61

Figure 1. Effect of bed depth on number of years out of 20 for which drying was achieved without OA production. Initial wheat moisture content = 20% wet basis

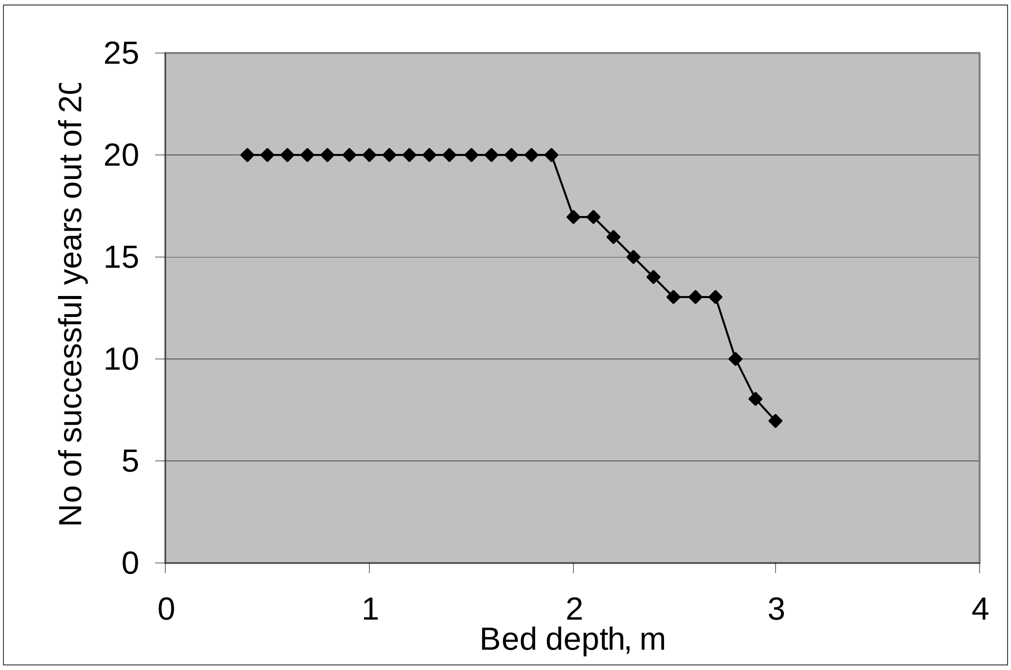


Figure 2. Effect of initial moisture content on maximum bed depth for no spoilage in 20 years simulated drying.

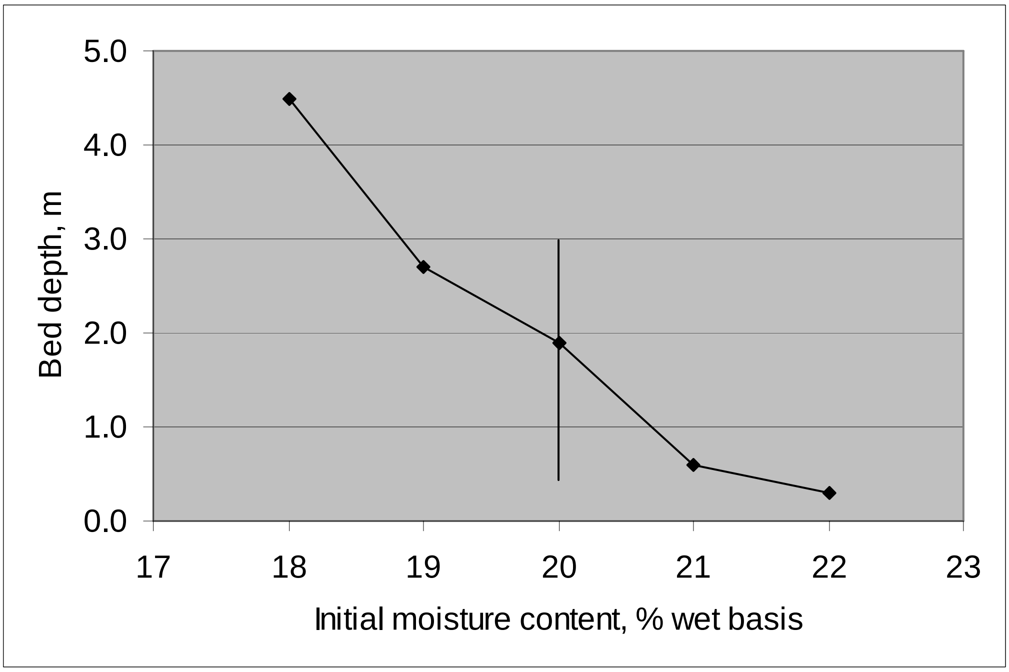


Figure 3. Effect of initial moisture content on maximum bed depth, for 20 successful years out of 20. Five locations starting drying on 15 August. (Runs 1-10, 16-22)

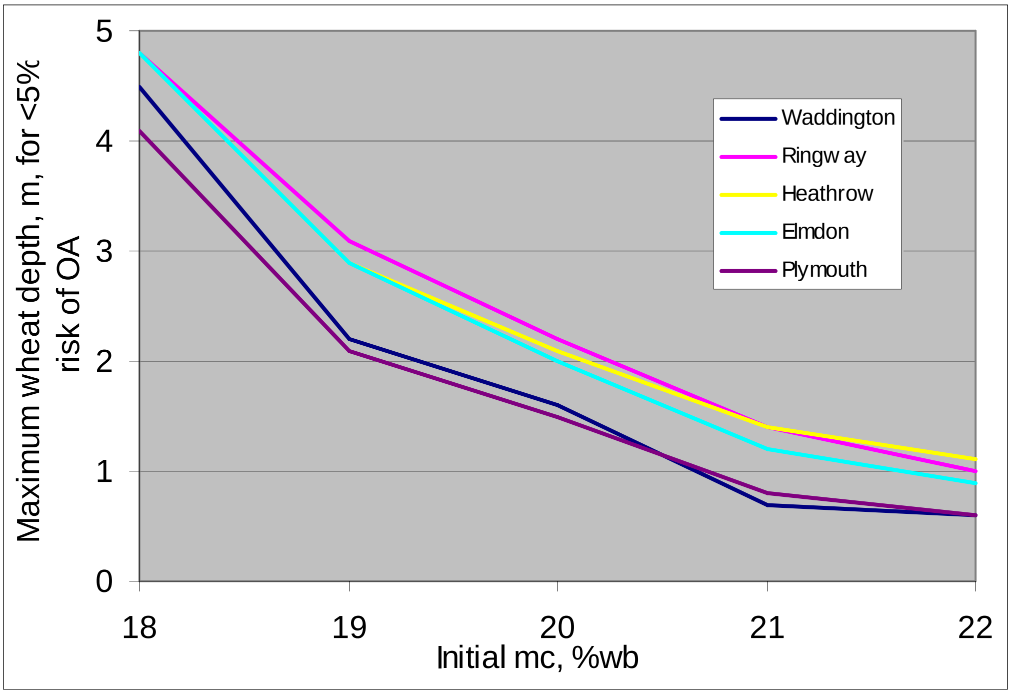


Figure 4. Effect of location and start date on maximum depth, using Strategy 3 - continuous fan, heater switched on rh that depends on mc at 0.3m.

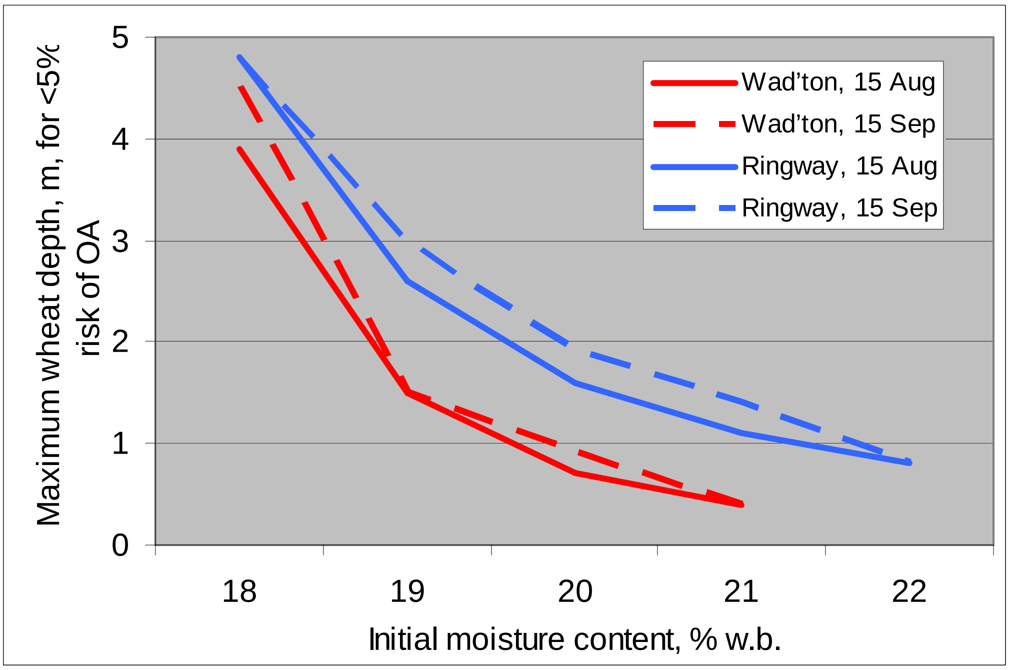


Figure 5. Maximum depths for Strategies 1 (pink), 2 (blue) and 3 (green) when the OA-based model of spoilage was used (solid lines) and the old model based on visible mould or viability loss (broken lines).

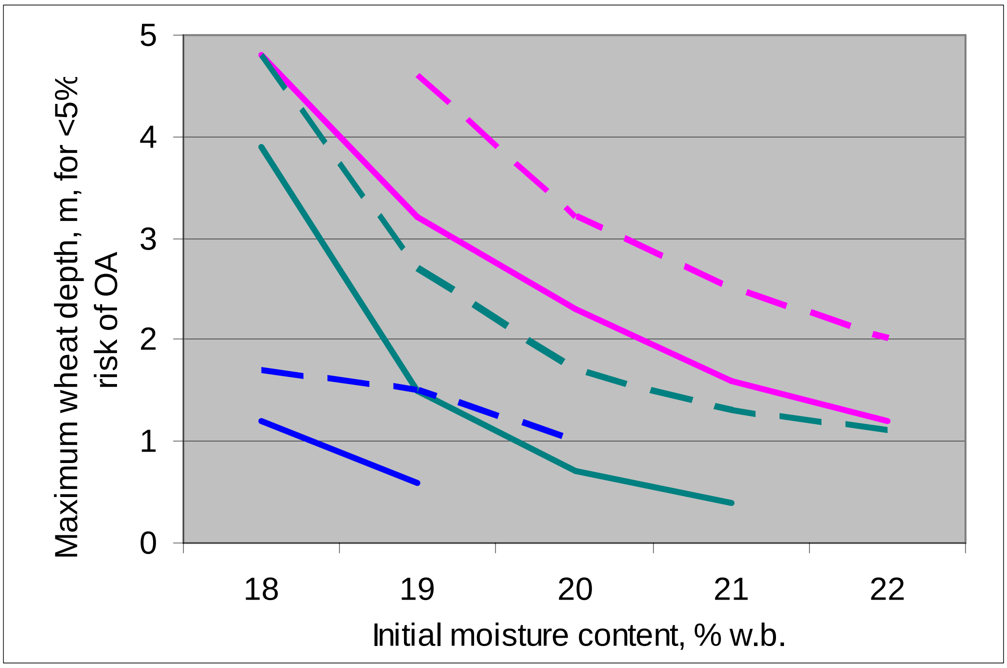
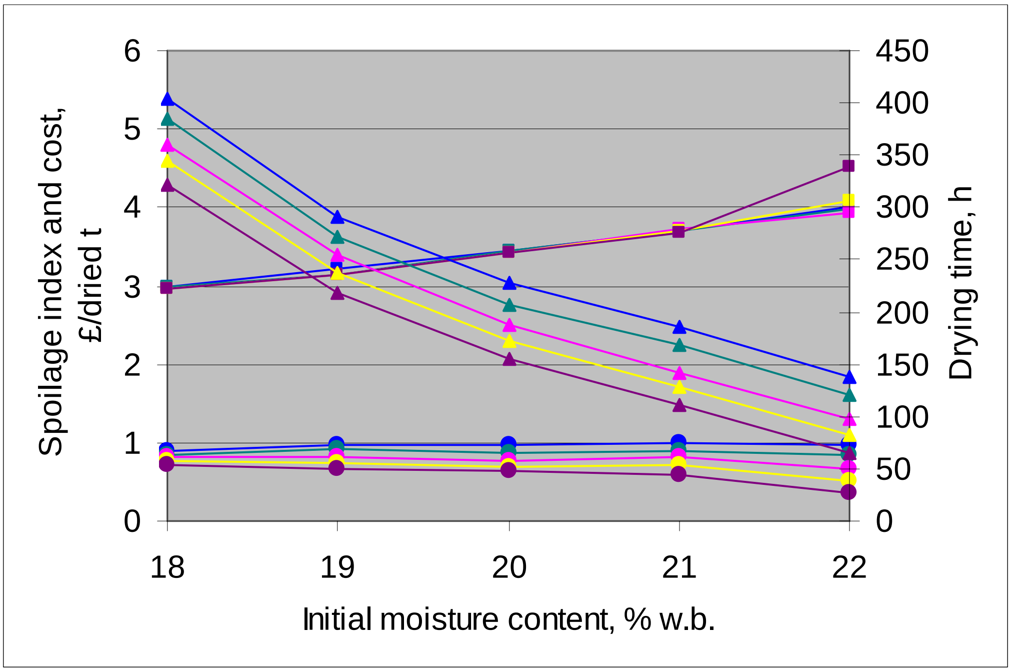


Figure 6. Effect of initial moisture content and bed depth on spoilage index, cost and drying time, for drying over 20 years at Ringway location using Strategy 1 with 80% rh setpoint and 80 kW heater, starting 15 August. Lines in blue are for maximum depth at each initial moisture content (18 - 22 % were 4.8, 3.4, 2.5, 1.9 and 1.3 m respectively), then for this depth less 0.2 m (green), less 0.4 m (pink), less 0.6 m (yellow) and less 0.8 m (violet). Triangles - drying time (right-hand axis), Squares - cost (left-hand axis), Circles - maximum spoilage index (left-hand axis). (Run 52a)



4. EXTENDING THE SAFE ENVELOPE

Introduction

Simulations using the three strategies and with both the current and the new spoilage models have shown that, if the risk of OA is to be controlled by adjusting grain bed depth, a very significant reduction is required. Such a reduction would be a serious penalty for growers because their drying equipment would have a reduced holding capacity during drying of a batch. Because of the shallower bed, each batch would be dried faster but, if there were nowhere for dried grain to be stored off the drying floor once dried, the overall drying capacity of the equipment would be reduced. In this section, we explore whether and how the maximum bed depths determined in the previous chapter can be increased. The parameters that may allow this include heater power for Strategies 1 and 3 and, for Strategies 2 and 3, the steps of grain m.c. versus r.h. used to specify the humidistat setting. Increasing the maximum bed depth would allow greater margin of safety from spoilage and so would be beneficial even if grain bed were below the maximum depth. Because the relatively crude Strategy 1 unexpectedly gave the greatest maximum depths, understanding how it achieved its performance and then refining it was a good starting point.

Extending the safe envelope for Strategy 1

Strategy 1 involves continuous ventilation and a single stage heater switched by a humidistat.

Strategy 1 - Set point relative humidity

To explore the effect of the humidistat setting, Strategy 1 was run with r.h. setpoints of 85 to 60% in steps of 5%. This was done for two starting dates, 15 August and 15 September, and for two locations, Waddington and Ringway. Table 15 shows the maximum depth and cost for 20 years success out of 20, *i.e.* risk of OA <5%.

Table 15 shows that costs generally rose as the r.h. setpoint was lowered. This was because the r.h. was above the setpoint more of the time so the heater was on for more of the time. Reducing the setpoint from 85 to 80% brought about an increase in maximum depth at and below 20% initial mc, but no change above this m.c. But from 80% downwards, however, there was no benefit for the increasing cost. It is clear that the setpoint relative humidity of 80% used in initial simulations with Strategy 1 was already the best, so there was no room for improving maximum depth using that parameter. The maximum depths obtained by simulation were for the most part not much changed by a difference in the humidistat setting of 5%, so a humidistat that was somewhat out of calibration would still be likely to result in reasonable performance in this initial stage of drying.

Further runs were then done using this 80% setpoint for the other three locations for each start date, complete results for which are shown in Table 16. The first 4 lines of Table 16 are identical to Table 6 because the setpoint of 80% r.h. was used for Table 6.

Trends in the results of Table 16 are very much in line with those noted from previous tables for Strategy 1. Drying grain with a higher initial m.c. (using the maximum depths indicated) resulted in increased costs but reduced drying time. Maximum depth was greater for starting drying on 15 September than on 15 August but the later start increased costs for the same initial m.c.

Strategy 1 - Proportion of dryer ventilated

From earlier results it was clear than reducing the bed depth is a powerful means of increasing the specific airflow and thereby increasing drying rate. As an alternative to reducing bed depth, some benefit might be had by using a reduced area of the drying floor while maintaining the depth of grain. This would concentrate the air delivered by the fan through a smaller area of grain bed and hence tend to increase the specific volume. This approach has the added advantage that the part of the drying floor not used would still be available for later drying of another batch once the initial load has been dried, without the need to move the dried grain into a deeper bed or remove it. The following work explores how much the maximum bed depth could be increased using this approach.

Table 17 shows results for the same conditions as Table 16 when directing the fan into 80% of the floor area of the drier. Table 17 shows similar effects of location and starting date as those already commented on for Table 16, but the main points of interest are in the differences between Tables 16 and 17 for the same location and date. Comparing the maximum depths where 80% of the floor was used with those for 100% floor use, the depths were increased by 0.3 m across the range of initial m.c. as a result of the increased specific volume - air flow per unit mass of grain. For example at Waddington with drying starting on 15 September, the maximum depth was 1.3 m with 100% floor area ventilated and 1.6 m when the floor area was reduced to 80%. However, even for this best improvement of depth, the mass of grain that could be dried at the improved depth over 80% of the floor was less than if it were spread out over the whole floor. Results at 19 and 18% were not meaningful because of limits to depths imposed by the fan. In Table 16 a limit of 4.8 m depth of grain was reached because of the limit to the pressure available from the fan. In the runs shown in Table 17, the air from the fan was directed through 80% of the floor area for which it was matched, and at depths exceeding 3.4 m the air delivered by the fan fell below minimum for such a fan, *i.e.* it was approaching a stall condition.

The cost penalty for reducing the floor area to 80% was a 10-11% increase, quite consistent irrespective of location or start date. Time taken to reach the drying target was little affected by the reduction in floor area - a 3% saving in time at 20% initial mc, and no difference at 22%.

Given the that reducing the floor area to 80% produced some benefits in terms of maximum depth, further runs with 60% of floor area ventilated were carried out. When connected to a much smaller outlet area than that for which it was specified, the fan was only able to run without approaching stall at bed depths appropriate to initial mc of 22%. Below this moisture, the deeper beds simulated generated enough extra resistance to stall the fan. It was concluded that reduction to 80% floor area was of some help in controlling OA risk but further reduction was not likely to be helpful.

Strategy 1 - Heater power

The size of heater selected for the initial simulations of Strategies 1 and 3 was based on a recommended temperature rise of 5-6 ^{o}C (McLean, 1989, p85). With the design air flow of the drier simulated here, an 80 kW heater fulfilled this specification. The performance of Strategy 1, in which the heat was either on or off depending on air r.h. in the plenum after the fan, would be expected to vary with heater power so simulations were done to explore whether altering the heater power allowed the maximum bed depth to be increased.

Table 18 shows results for starting drying on 15 September at Waddington, a relatively cold location and time, with heater powers 60, 80, 100 and 120 kW. Table 19 shows results for Ringway, relatively warmer and starting drying earlier, on 15 August, and using heater powers of 40, 60, 80 and 100 kW.

As the heater power was increased from 60 kW, the maximum bed depth increased across the range of initial moisture content. At 21% initial mc, maximum depth increased from 1.6 m to 2.0 m. At 22% however, the maximum depth decreased above 100 kW. This was probably because the increase in drying power of the warmer air was outweighed by the increase in spoilage rate of the yet-to-be-dried grain, the temperature of which would be increased by the applied heat. Drying costs per tonne dried rose with heater power and with initial m.c., apart from the region of 21-22% mc and 60-80 kW. In this region the costs were lower with 80 or even with 100 than with 60 kW and the maximum depths increased, so the higher power, 80 -100 kW, was justified. Drying times fell as more heater power was used.

Similar patterns were evident in Table 19. In this case, increasing heater power from 80 to 100 kW had no benefit in terms of maximum depth. Little increase in depth was obtained by additional heat above that from the 40 kW heater, and costs per tonne dried increased with heater power at low initial mc.

These results confirm that the recommended heater power of about 80 kW was reasonable for both locations, though it was lower than ideal for the cooler location of Waddington in September and higher than ideal for Ringway where a heater of 40 or 60 kW would suffice in August. The results suggest that a target plenum temperature might be a better rule of thumb than a target rise in temperature, but this has not been explored further.

Extending the safe envelope for Strategy 2

Strategy 2 involved drying with no artificial heating by switching the fan on or off with a humidistat. The humidistat was initially set at 100% rh and was reduced to 83, 72 and 62% r.h. when m.c. reached 20, 18 and 16% respectively. The performance of this strategy was disappointing in initial runs (Table 7) so improvements were sought. Parameters available for adjustment to improve the performance were the values of moisture content and corresponding values of relative humidity that determine when, and to what r.h., the humidistat must be changed as drying proceeds

Strategy 2 - Moisture content used for control

For reasons explained earlier, moisture content of grain at a depth of 0.3 m was used to measure the progress of drying, and hence as the basis of altering the humidistat setting, for the runs shown in Table 7. However, with the low bed depths produced by this strategy, a sample at 0.3 m would be a significant way down the bed, so progress of drying to that position would occur well before the bed as a whole was dried to the same extent. For this reason, simulations of Strategy 2 were run in which the wettest moisture of any grain in the bed, rather than a spot value, was used to determine when the r.h. setpoint should be changed. This enabled the two approaches to be compared. The table of r.h. and m.c. values was not altered at this stage.

Results in Table 20 compared with those in Table 7 show that using the wettest moisture of the bed as the value for control gave improved values of maximum bed depth. Assuming the values given as <0.4 were in fact =0.4, those maximum bed depths that changed all increased, by an average of 90%. The costs and drying times were little affected. Hence, for Strategy 2, performance using the wettest m.c. instead of the m.c. at 0.3 m was much improved. Although in practice measuring the wettest moisture content of the bed would require more sampling work, the improved performance justifies its recommendation.

Strategy 2 - Steps of r.h. versus m.c.

The table of grain m.c. and corresponding r.h. setpoint used with Strategy 2 aimed to ensure the fan was run when the air had drying potential, given the state of the grain bed at that time, but not when the air was too moist for drying. The steps in the table try to follow, in some sense, the equilibrium relationship between air r.h. and grain m.c. As a way of exploring how well the initial steps relate to the e.m.c.-e.r.h. curve used in the simulation, (see Appendix B) the curve and the steps were plotted together (Figure 7). The initial steps set the humidistat at 100% r.h. and reduced this setting to 83, 72 and 62% r.h. when mc reached 20, 18 and 16% respectively. These steps are shown as line A, and so the original Strategy 2 using these steps will be referred to for clarity as Strategy 2A.

As can be seen in Figure 7, the initial steps, A, were mostly above the equilibrium curve in their lower range but at 20% m.c. and above, the step was well below the curve. With these steps, air of humidity up to 100% would be blown into the grain although when the grain was approaching 20% moisture, rewetting would occur at humidities above 87%. Given that it is the wettest layer of grain that is the basis for the control, significant rewetting could occur. (In some circumstances it may be desirable to ventilate with high humidity air if it is also cold, so that a cooling benefit may be had. With Strategy 2A, high humidity air would be used, whether cool or warm.) To position the steps better to follow the upper part of the equilibrium curve, an additional step was added and the values changed. This series of steps is shown on Figure 7 as line B. Where the stepped lines are above the equilibrium curve, air that has potential to dry is excluded. Where steps project below the curve, some re-wetting would occur during ventilation. But there are two reasons why blowing in such conditions may be beneficial. First, any tendency of the damp grain to self-heat would be prevented by the airflow. Second, grain subject to re-wetting, *i.e.* that near the air inlet, may well be quite dry enough to be safe from spoilage even if a little rewetting occurs and, by absorbing some moisture from the air, this grain may give the air some potential to dry the wetter, more “at risk” layers of grain in the bed. The line C in Figure 7 repositioned the steps above the curve so all the air used to ventilate the bed had significant drying potential. The disadvantage would be that the fan would be switched off for more of the elapsed time and the grain would continue to progress towards spoilage during this time. Line D took the alternative approach to line C, of positioning the steps to allow more opportunities for ventilation by allowing moister air to be used for a given m.c. of the wettest layer. Results, in Table 21, show the performance of Strategy 2 with line D, referred to as Strategy 2D, at all five locations.

The steps of r.h. setpoint versus m.c. for Strategy 2D are detailed in Table 22.

Figures 8 and 9 show the maximum depth values from Table 21 when drying at the 5 locations from 15th August and from 15th September respectively. It is clear that the four locations (excluding Plymouth, at which Strategy 2 was unsuitable,) had a consistent ranking - Ringway was best and Waddington worst across the range of initial m.c. simulated.

Figure 10 shows results for Waddington and Ringway locations, starting drying 15 August.. Performance of Strategy 2D was considerably better than that of the original Strategy 2A, (evaluated for locations Waddington and Ringway in Table 7 when using m.c. measured at 0.3 m depth and in Table 20 when improved by using the m.c. of the wettest layer). Comparing Table 21 with Table 20, maximum depth was either maintained or increased for both locations. The average increase was 27%. This is a conservative figure in that those depths less than 0.4 m have been considered as equal to 0.4 m for the purposes of calculating the increases. Figure 10 shows the increase in maximum depth across the range of initial m.c., greatest at lowest m.c. At 18% initial m.c., the average increase in maximum depth for the two locations was 50%. From Tables 20 and 21, the cost of drying at locations Waddington and

Ringway, averaged over all the initial m.c. values, increased by 9%. Drying time was 6% longer overall, simply a consequence of the greater depths achieved.

Compared with maximum depths for Strategy 2A with the OA-based model of safe storage life, shown in Table 7, the use of Strategy 2D and the m.c. of the wettest layer gave maximum depths for Waddington and Ringway that were 112% higher, costs were 10% lower, drying times were 6% longer. It is clear that Strategy 2D gave considerable benefits.

As before, the reductions in maximum depth required by using the new, OA-based model compared with using the old model were calculated to allow a judgement to be made of what change may be needed to current practice to run no greater a risk of spoilage. Results are shown in Table 23.

The only significant difference was that the average depth reduction required in August, 1.08 m, was twice that in September, 0.54 m, but these figures were not consistent across the range of initial m.c. The average reduction in depth required by the adoption of the new model of spoilage with Strategy 2D was 0.8 m.

For ease of reference, the two series of steps are shown in Table 22.

From Figure 7 it can be seen that the effect of Strategy 2D compared with Strategy 2A would differ depending on the bed moisture. At higher moistures, between 22 and 20% for example, the new steps, line C, would only allow air at 93% and below whereas the original steps would allow any air, so fan run time would be reduced for the new steps. (Because Strategy 2D has been evaluated only up to 22% initial m.c., its performance above that value is uncertain.) But at the other end of the range, between 17 and 18% for example, the new steps would allow air of 83% r.h. or less to be used where the original steps would only allow 72 % r.h. or below. The overall time for which the fan was running, in Table 24, shows that Strategy 2D resulted in the fan running for a higher proportion of the time, the largest increase being at the lower end of the range of initial m.c. Some of the air with which the bed was ventilated would have caused rewetting of some of the grain but the overall result was to improve the maximum depth at the <5% level of risk of OA. Further improvement may well be obtainable by further refinement of the ‘steps’ used with Strategy 2. It may also be beneficial to ventilate when the air temperature is significantly lower than that of the grain bed irrespective of the ambient r.h., to cool the bed and retard progress towards spoilage.

In summary, useful improvements in performance of Strategy 2, in terms of increasing the maximum depth, were achieved by adjusting the control “steps” recommended in the HGCA Grain Storage Guide to allow the fan to run more of the time. Incorporating this adjustment, Strategy 2D was a useful and lower cost option for grain at the drier end of the range examined but at 21% mc and above, the depths needed to ensure the risk of OA was minimised depth were too low to be of practical use. It is noted that the adjusted steps were found by a very limited trial and improvement method, and further improvements would almost certainly be possible. This would require a more formal optimisation approach.

Extending the safe envelope for Strategy 3

Results already presented in Table 8 established the performance of Strategy 3 with the steps described in the booklet produced by FEC Services Ltd. (Anon., 1990) and using an 80 kW, 4-stage heater. Strategy 3 had more parameters than either 1 or 2. The first was air heating. Where Strategy 1 had only a single stage heater, Strategy 3 used a multi-stage heater in which heater stages were switched in sequentially until the air r.h. fell below the r.h. setpoint. Thus, even if the heater rated output was large it did not mean the heating cost would be high because only as much heat would be switched in as was needed. The second adjustable parameter was the set of 'steps' describing how the setpoint r.h. was reduced as drying proceeded. Between the first and second of these moisture steps, Strategy 3 cut off ventilation when ambient air is too damp but, once the next moisture step was reached, the fan was constantly on and heating was switched in to reduce the ambient r.h. to below the setpoint. From this it is clear that adjusting the steps to be above the equilibrium curve, *e.g.* line C in Figure 7, would force the more frequent use of heat. The third parameter was available if there were insufficient heater power available to reduce air to the r.h. setpoint, i.e. whether the fan was allowed to continue to run or was switched off. There was insufficient scope to investigate this parameter so the assumption was made that the fan would remain on.

Strategy 3 - Steps of r.h. versus m.c.

Figure 11 shows the equilibrium curve between air r.h. and wheat m.c. used in this work, and three sets of steps showing how the air r.h. setpoint was specified in terms of the grain m.c. at 0.3 m depth. For ease of reference, the two series of steps used for simulation in this work are shown in Table 25. Line F (yellow in Figure 11) is the basis of the results already used to establish the performance of Strategy 3 shown in Table 8. Strategy 3 with line G (turquoise in Figure 11) is the basis for the results shown in Table 26. It is noted that Strategy 3G calls for heat once m.c. reaches 20.5%, so if initial m.c. is less that 20.5%, heat will be applied immediately on starting drying.

Comparing Table 26 with Table 8, the maximum depths were greater in all cases except for Ringway, 15 Sep start, 21 and 22% initial m.c. For a 15th August start, Figure 12 shows maximum depths for both locations using Strategy 3F and Strategy 3G. The improvement in depth is particularly good at 19 and 20 % initial m.c. Overall the depths were 55% greater, but for Waddington the increase was 87%. Drying costs were higher, 40% greater averaged over both locations and drying times were 8% longer overall. Hence Strategy 3G provided a considerable improvement in performance compared with Strategy 3F with little increase in drying time, but unfortunately accompanied by an increase in costs per tonne dried.

In Table 27, a comparison is given between Strategies 3F and 3G, each using the Fraser/Kreyger and the Jonsson spoilage models, starting drying on 15 August at Waddington. Rows 1, 2 and 4 of this table are graphed in Figure 13. It is notable that, for initial m.c. of 20% and below, the Strategy 3G with the new spoilage model based on OA (broken blue line) gives greater maximum depths than were found with Strategy 3F and the old spoilage model based on visible mould and loss of viability (red line). In other words, at 20% m.c and below, modifying the steps by which Strategy 3 operated more than recovered the depth penalty, shown by the difference between the red and blue lines in Figure 13. This shows how important it is to have a strategy with good performance. At 21% m.c. and above, the depths were unavoidably lower when the OA spoilage model was used. Costs were always higher when spoilage was OA-based.

It was noted that, with the OA-based spoilage model, Strategy 3G improved the maximum depth across the whole range of initial m.c. (compare row 4 with row 2 of Table 27). When the old spoilage model was used, though the depths were greater, the use of Strategy 3G only improved the maximum depth at 20% m.c. and below. Strategy 3G appears to be quite appropriate for use with the new spoilage model.

Table 28 broadens this comparison, showing maximum depths when spoilage was calculated using the old and new models for two locations and two start dates. Reductions in depth required when the new model was adopted are shown. As expected the new model required lower depths, but the reductions did not correlate with location or start date to give any useful general guidelines for depth reduction. There is a trend for the reduction in depth to increase as initial m.c. falls, but this trend is not firm because of the limit to depth of 4.8 m owing to the fan characteristics. Simply taking the data presented in Table 28, the average reduction in depth was 1.0 m.

Strategy 3 - Moisture content used for control

A comparison was run for the two methods of obtaining a m.c. value for control, the wettest in the bed or at 0.3 m depth, both using Strategy 3G at Waddington and starting August 15th. There was very little effect on the maximum depth, but there were improvements at 21-22% m.c. and costs were similar, so sampling at 0.3 m was preferred.

Effectiveness of the strategies in completing drying

In all of the foregoing simulations, the end point for drying was when the wettest layer in the grain bed reached 16% m.c. Depths, costs and drying times are for that end point. As previously explained this approach was taken because once wheat is below 16% the development of the fungus that can produce OA has been halted. However the question needed to be addressed of whether continuing to dry using the same strategy would arrive at a reasonable average m.c. for the bed. If so, would the driest part of the bed be seriously overdried?

Using Strategies 1-3 with the best values of the various parameters, simulations of drying were done with two targets for drying - the wettest layer to be < 16% m.c and the average m.c. of the whole bed to be <14.5% m.c. – for Waddington starting drying 15 August, at the depths found by previous simulations to be the maxima for risk of OA <5%. (Even with the wettest part of the bed reduced to 16% m.c., further drying would be advisable for this part of the bed, but that stage is not investigated here.) Results, Table 29, show the number of years out of 20 for which both targets were met, and average values for the parameters for those successful years. The average and minimum m.c. show the degree of any over-drying, and the weight loss compared with that at average m.c. = 14.5%, in kg/dried tonne, is also converted to over-drying cost using the cost of dried grain of £65/t. Finally the overall cost is given.

As shown by the number of successful years, Strategy 3G was successful in reaching the average m.c. target in all 20 years, whereas the success of Strategy 1 ranged from 20/20 to 13/20. Strategy 2D was successful in all but one or two years of the 20, but always required low bed depths. The average and minimum m.c. values show that a small degree of over-drying was present, amounting to less than 3.5 kg/dried tonne in the worst case of Strategy 3G at 18% initial m.c. That case cost £0.23/tonne whereas most of the over-drying costs were less than £0.1/t. The overall costs are given for completeness but those for Strategies 1 and 3G for initial m.c. 20% and above should be treated with caution. In most of the years the second target was met soon after the first so costs were only a little higher, as expected. But in a few cases the drying continued for a long period, during which drying and rewetting took place but the target was not quite met while costs increased steadily. Eventually drying in those few cases succeeded but large costs had been accumulated, up to £25/t, which distorted the averages in the cases mentioned.

In conclusion, the three strategies were reasonably successful in completing drying, Strategy 3G being best, and none lead to significant over-drying. However, Strategy 1 failed to complete in about 1 year in 5, and both Strategies 1 and 3G led to very high costs in some circumstances. Strategy 2D behaved well across the range of initial m.c but, as already noted, had to use low bed depths and was ineffective at 21% m.c. and above.

Consideration of acceptable risk

Throughout this work, the risk level of <5% was considered to be an acceptable level. When using bed depth to control risk of OA, this assumption required that bed depths be selected to cope with the least favourable set of seasonal weather in the set of 20 years. Some operators may consider this too conservative, particularly if the season appears to be a favourable one for drying. When good weather is forecast for the medium term, operators may consider that using a deeper bed would not expose their grain to spoilage, and so would wish to use a deeper bed. This section considers what benefits and drawbacks there would be if a higher risk were considered acceptable. The modified Strategies developed in Chapter 3 allowed increased depths to be used for the same level of risk, but it was also possible that the risk of failure beyond those maximum depths was greater than found in the one case shown in Table 12, *i.e.* OA might be produced in many years if the maximum depth were exceeded. This was investigated to check the robustness of the strategies.

Figure 14, for Strategy 1, shows lines of constant risk on axes of initial m.c. versus maximum depth. The lines presented elsewhere in this report have indicated a risk of <5%, but Figure 14 also shows lines for higher risk levels, *e.g.* a risk of <25%, indicating that, at those depths and initial m.c. values, OA was predicted in 4 years of 20. The spacing apart of the lines shows how risk increased as greater depth was used. For example, at 22% initial m.c., the risk rose from <5% to <50% as a result of an increase in bed depth of 0.5 m, consistent with results in Table 12. At 19% m.c., the same increase in risk was given by an increase of about 1 m. As an illustration of how using the new spoilage model increased risk of spoilage, the line for <5% risk of spoilage under the old model is also shown. It lies beyond the 50% risk line for the new model, which indicates that if no change in practice is made, the grain bed will be at risk of OA in more than half of all drying seasons.

Performance of Strategies 2A and 2D is shown in Figures 15 and 16 respectively. The improvement in maximum depth was large at 18% initial m.c., hardly present at 20% and absent above 20%, all of which has already been noted. But it is notable that, at 18% initial m.c., the maximum depths for higher levels of risk increased in a similar pattern to that for <5%. This shows the increase in risk due to increased depth was certainly not sharper with Strategy 2D, but was instead more gradual.

Figures 17, 18, 19 and 20, in the same format, show results for Strategy 3G for August and September in Waddington and Ringway respectively. Figure 17 also shows the line of <5% risk of spoilage by the old model. As has been noted in Chapter 3, the maximum depth with Strategy 3G based on OA exceeded that based on the old spoilage criterion. For all four figures, comparing the gaps between the lines of <5%, <10% and <25% risk showed that the gaps were not very consistent and that the additional depth between <5% and <25% risk could be as little as 0.2 m (Ringway, August, 21% m.c.) and as much as 0.8 m (Ringway, August, 19% m.c.). A further similar increase of depth increased the risk to the <50% level. These increases in depth are quite small in relation to depths widely used in grain drying practice, and also small in relation to the differences in depth with location, strategy and initial m.c. A cautious approach in terms of bed depth used would be needed to avoid unwitting exposure to a relatively high risk.

One reason why the data for maximum depth and lines in figures such as Figure 17 are not very consistent lies in the use of <5% risk. If all 20 years out of a weather data set must succeed, the result is determined by the ‘worst’ year of the set at that particular location. It may be that this worst year is quite exceptional and that the depth required to cope with it is quite low. The next worst year may be similar or may be considerably better, which will result in the gap between the <5% and <10% risk lines being narrow or wide, respectively. The line of <25% risk however allows 4 years out of 20 to fail, so the worst single year will no longer dominate the result so the <25% risk line may be more consistent.

The lines of maximum depth versus initial m.c. may be of help in controlling risk if used in a different way. If extra drying capacity is available in the form of a heated air drier, how should it be used? The data presented here may be used to choose the desired bed depth for a near ambient drier, and then to read off a moisture content at which the risk is <5%. Drying the grain to this m.c. with the heated air drier and then continuing in the near ambient drier would maximise the capacity of both. For example from Figure 17, wheat at 20% m.c. harvested at Waddington could be dried under Strategy 1 at a depth of 2.1 m with a risk of <5% of OA. If a bed depth of 3 m were required, the m.c. would need to be about 19.1% so drying by heated air to remove about one percentage point of moisture would be required.

Loss of viability during drying

As has been explained earlier, two alternative spoilage models were employed in this work, the new one based on safe time before OA production, and a model which calculated the safe time before mould would be visible or until the action of the fungi would have significantly reduced the viability of the wheat. The new model, being more demanding, allows drying regimes to be specified that also avoid visible mould or viability loss through fungal action. Alongside the calculation of progress towards spoilage by OA production, a separate routine in the simulation programme calculates the loss in viability of the wheat that arises due to temperature-related effects. Though this routine is mainly for calculating the limits to higher temperature regimes of drying, it also enabled any heat damage to be monitored.

Throughout the drying runs simulated, in only two runs was the average viability of the grain bed reduced from its initial value of 99% to below 97%, and these were runs in which drying continued for 8 weeks in beds more than 1m deep with 22% initial moisture and Strategy 2 with no heating in September at Waddington. Treatments in which heat was applied did very little damage to viability because drying temperatures were moderate and drying progressed quickly. Loss of viability was not examined in detail to study the highest losses in the bed, on the assumption that the grain would be well mixed and the average viability was the important value.

The model of heat-induced viability loss is pertinent to Chapter 4 in which grain stirring is considered and higher drying temperatures may be used.

Effect of fan size

If reducing the depth of the grain bed is not considered an acceptable way of controlling the risk of OA, an alternative approach is to increase the airflow through the bed. Reducing the proportion of the drying floor ventilated by the fan has already been investigated and found to give useful increases in bed depth in certain conditions but was not effective across the range of conditions. Increasing the airflow by fitting a larger capacity fan would be another approach. This would be expected to increase drying rate and hence allow deeper beds but clearly a capital cost would be incurred and running cost would be marginally higher. It is also possible that using a larger fan would result in a more uneven air distribution for the following reasons. The lateral ducts in a drying system are generally designed to have a large enough cross sectional area that the air speed is below 10 m/s when the fan is operating at its design condition. One might hope that a larger fan would enable the drier to be operated with the bed depth for which it was designed, before OA risk required a reduced depth to be considered. A larger fan would certainly deliver more air but in so doing it would increase the air speed in the lateral ducts. This would produce larger-than-designed differences in static pressure along the lateral ducts. Airflow up through the grain bed depends on the static pressure in the duct so airflow per unit area of floor would be higher at the far end of the lateral ducts and lower in the parts of the bed near the main duct. This low airflow would give slow drying near the main duct, thus increasing risk of spoilage there. It was beyond the scope of this work to investigate the risks due this effect but clearly caution is advisable if upgrading the fan is considered and it would be advisable to seek specialist advice.

Ignoring the static pressure regain effect, the effect of fan size on performance was judged by the change in the maximum bed depth at a <5% risk level for OA, and by cost and drying time at that maximum depth. Table 30 shows results for drying with Strategy 1 at Waddington and Ringway, starting drying on the 15th of August and of September, with three models of fan. The standard fan was the "Typhoon TC5" by Pellcroft Engineering Ltd used throughout this investigation, while the small and large fans were models TC4 and TC6. To illustrate the difference, the air deliveries quoted by the manufacturer for the TC4, TC5 and TC6 at a static pressure of 100 mm w.g. were 10.8, 14.1 and 18.8 m^3/s, while at 150 mm w.g. were 9.0, 12.3 and 14.6 m^3/s. Tables 31 and 32 show results for standard and large fans for Strategies 2D and 3G respectively.

During simulated drying, the simulation converges on a static pressure and flow that matches both the characteristics of the fan and the resistance of the grain bed, plus that of the drying floor and the resistance as air is forced along the ducts. As expected, use of the larger fan gave a higher air volume flow into the drier. Heater power - 80 kW for Strategies 2 and 3 - was not altered for these simulations so the temperature rise would be lower when using the larger fan, as it would be in practice. The simulation did not include effects caused by differences in static pressure described above.

Results were quite consistent over the range of fan and heater strategy, initial m.c., location and start date. For Strategy 1, from 19 to 22% initial m.c., the use of the larger fan resulted in an average increase in depth of 0.2 m. Results were not related to depth so expressing them as a percentage was not useful. When drying with Strategy 2D (Table 31) and Strategy 3G (Table 32) the result of using the larger fan was the same as for Strategy 1, an increase in maximum depth of 0.2 m across the range of initial m.c. location and start date. For 18% initial m.c. results were limited because the fans reached their maximum bed depth before stall. For the larger fan this was at 4.4 m, while 4.8 m was the limit for the standard fan. (The limit for the smaller fan was not encountered in these simulations). When the smaller fan was used for drying with Strategy 1, the maximum depth showed an average reduction of 0.3 m, but this varied with initial m.c. in such a way that the reduction was better expressed as 13% of the maximum depth with the standard fan. Changes in cost, higher in some simulations, lower in others, were less than 5% except for values at 18% initial m.c. where the result was affected by airflow limits. Drying time ranged from 20% higher to 10% lower, with no pattern.

A check was done on drying with the larger fan using the unmodified Strategies 2A and 3F at Waddington starting 15 August. The resulting increase in depth was the same as found above, 0.2m.

Conclusions

1. Improvements in performance of the three strategies for fan and heater control were explored by adjusting the parameters of each strategy to determine the effect on the maximum depth over the range of initial m.c. This proved to be a fruitful approach and further improvements may be possible.
2. For Strategy 1, in which a constant setpoint r.h. was used throughout drying, a value of 80% was shown to be optimal. It is possible that varying this setpoint as drying proceeds would further improve performance of Strategy 1.
3. Directing all the air from the fan through 80% of the area of drying floor allowed an increase in bed depth of 0.3 m at grain moisture contents of 20% and above, though at higher cost. Although this may occasionally be useful, the mass of grain that can be dried is less than if it were spread out over the whole floor.
4. The optimum power for the single stage heater in Strategy 1 varied with the climate of the location, less heat being required in warmer locations. Too great a heater reduced maximum bed depth because spoilage was accelerated.
5. Using an adjusted set of steps of r.h. versus m.c. with Strategy 2 compared to the original steps allowed bed depths at least 27% greater to be used for the same spoilage risk of <5%. Costs were 9% greater.
6. However, compared with the performance achieved with the previous, visible mould-based spoilage model, a reduction in depth of 0.8 m was needed to maintain risk at <5%.
7. Strategy 3 also showed improvement in maximum depth of 55% when the steps of m.c. versus r.h. were modified, sufficient improvement at initial m.c. of 20% and below to more than recover the reduction in depth, average 1.0 m, brought about by the change to the OA-based spoilage. Costs were also higher because the adjustments brought about more use of artificial air heating.

8. When tested to determine their abilities to complete drying beyond the condition of wettest grain <16% used elsewhere in this work to an average bed m.c. of 14.5%, Strategy 3G was best, and none of the strategies led to significant over-drying. However, Strategy 1 failed to complete in about 1 year in 5, and both Strategies 1 and 3G resulted in very high costs in some circumstances. Strategy 2D behaved well in completing drying but it had to use low bed depths and was ineffective at 21% m.c. and above.
9. Risk rose quite quickly as depth was increased above the maximum for a <5% risk. An additional depth of between 0.2 and 0.8 m increased risk from <5% to the <25% level. A similar further increase in depth increased risk to the <50% level. Results from the simulation indicate that, if no change in bed depth were made, the grain would be at risk of OA in more than half of all drying seasons.
10. Rather than reduce depth to control OA risk, reducing m.c. using a heated air drier prior to loading the grain in the near ambient drier may be an option. The data presented can be used to calculate the moisture reduction to control risk to the level of <5%.
11. No significant loss in viability was predicted for drying treatments in which a 50% level of risk of OA was predicted.
12. Use of a larger fan increased the maximum depth. The next model in the same range allowed depth to be increased by 0.2 m at the same risk level, irrespective of initial m.c. However, forcing more air through a given duct system may give rise to uneven drying unless air speed in ducts remain within design values.

Table 15. Strategy 1. Effect of rh setpoint, location and start date on maximum depth and cost. 80kW propane heater. (Runs 50-53)

Location and start date for drying	**Initial m.c., %w.b.**	**Depth, m, at which 20 years were successful out of 20**						**Cost, £/dried t**				
		18	**19**	**20**	**21**	**22**		**18**	**19**	**20**	**21**	**22**
RH setpoint, %												
Waddington, 15 August	**85**	4.7	3.1	2.2	1.6	1.2		3.06	3.16	3.55	3.99	4.38
	80	>4.8	3.2	2.3	1.6	1.2		3.37	3.46	3.72	3.93	4.34
	75	>4.8	3.2	2.3	1.7	1.3		4.02	3.91	4.05	4.26	4.59
	70	>4.8	3.2	2.3	1.6	1.3		4.42	4.28	4.37	4.45	4.51
	65	>4.8	3.2	2.3	1.6	1.3		4.77	4.56	4.69	4.78	4.81
	60	>4.8	3.3	2.4	1.7	1.3		5.12	4.94	5.01	5.12	5.35
Waddington, 15 Sept	**85**	2.9	2.4	2.2	1.7	1.1		3.66	4.21	4.55	5.65	6.77
	80	>4.8	3.9	2.6	1.8	1.3		3.56	3.85	4.08	4.39	4.88
	75	>4.8	3.9	2.7	1.8	1.3		4.09	4.23	4.39	4.65	5.10
	70	>4.8	>4.0	2.7	1.8	1.3		4.55	4.72	4.72	4.94	5.34
	65	>4.8	>4.0	2.7	1.8	1.3		4.97	5.13	5.09	5.19	5.61
	60	>4.8	>4.0	2.7	1.8	1.3		5.27	5.42	5.34	5.47	5.81
Ringway, 15 August	**80**	>4.8	3.4	2.5	1.9	1.0		3.00	3.21	3.44	3.69	4.00
	70	>4.8	3.4	2.5	1.9	1.3		4.31	4.25	4.26	4.45	4.64
	60	>4.8	3.5	2.6	1.9	1.4		5.14	5.06	5.06	5.11	5.34
Ringway, 15 Sept	**80**	>4.8	3.7	2.8	2.0	1.5		3.04	3.26	3.45	3.70	4.03
	70	>4.8	>4.0	2.9	2.1	1.5		4.41	4.56	4.59	4.70	4.88
	60	>4.8	>4.0	2.9	2.1	1.5		5.17	5.31	5.30	5.34	5.57

Table 16. Strategy 1. Effect of location and start date on maximum depth, cost and drying time. 80kW propane heater. (Runs 50b, 51b, 52a, 53a, 112-117)

Location and start date for drying	Depth, m, at which 20 years were successful out of 20						Cost, £/dried t						Drying time, h				
Initial m.c., %w.b.	**18**	**19**	**20**	**21**	**22**		**18**	**19**	**20**	**21**	**22**		**18**	**19**	**20**	**21**	**22**
Wad'ton, 15 Aug	>4.8	3.2	2.3	1.6	1.2		3.37	3.46	3.72	3.93	4.34		399	271	207	159	131
Wad'ton, 15 Sep	>4.8	3.9	2.6	1.8	1.3		3.56	3.85	4.08	4.39	4.88		425	362	255	194	156
Ringway, 15 Aug	>4.8	3.4	2.5	1.9	1.0		3.00	3.21	3.44	3.69	4.00		405	291	227	186	111
Ringway, 15 Sep	>4.8	3.7	2.8	2.0	1.5		3.04	3.26	3.45	3.70	4.03		435	344	277	213	175
Heathrow, 15 Aug	>4.8	3.2	2.4	1.8	1.3		3.01	3.08	3.28	3.40	3.59		384	257	203	164	128
Heathrow, 15 Sep	>4.8	3.6	2.4	1.7	1.2		3.29	3.48	3.62	3.82	4.19		408	313	220	172	134
Elmdon, 15 Aug	>4.8	3.2	2.3	1.7	1.3		3.19	3.27	3.47	3.65	3.98		400	269	204	165	137
Elmdon, 15 Sep	>4.8	4.0	2.7	1.9	1.3		3.55	3.87	4.10	4.35	4.76		426	377	265	203	155
Plymouth, 15 Aug	4.5	2.9	2.0	1.4	1.0		3.48	3.73	4.01	4.41	4.88		374	250	184	142	116
Plymouth, 15 Sep	>4.8	3.4	2.2	1.5	1.1		3.76	4.07	4.32	4.65	5.14		420	135	214	162	135

Table 17. Strategy 1. Effect of location and start date on maximum depth, cost and drying time for 80% floor area ventilated. 80kW propane heater. (Runs 150-159)

Location and start date for drying	Depth, m, at which 20 years were successful out of 20						Cost, £/dried t						Drying time, h				
Initial m.c., %w.b.	**18**	**19**	**20**	**21**	**22**		**18**	**19**	**20**	**21**	**22**		**18**	**19**	**20**	**21**	**22**
Wad'ton, 15 Aug	>3.4	>3.4	2.6	1.9	1.5		3.34	3.72	4.00	4.21	4.64		228	252	200	158	135
Wad'ton, 15 Sep	>3.4	>3.4	2.9	2.1	1.6		3.59	4.00	4.35	4.64	5.10		244	269	245	190	157
Ringway, 15 Aug	>3.4	>3.4	2.8	2.1	1.5		3.10	3.38	3.73	3.99	4.28		233	256	222	177	135
Ringway, 15 Sep	>3.4	>3.4	3.1	2.3	1.7		3.03	3.39	3.68	3.94	4.25		250	275	270	209	169
Heathrow, 15 Aug	>3.4	>3.4	2.7	2.1	1.5		2.99	3.32	3.56	3.71	3.91		220	243	199	165	125
Heathrow, 15 Sep	>3.4	>3.4	2.7	1.9	1.4		3.27	3.64	3.89	4.09	4.52		234	257	213	162	129
Elmdon, 15 Aug	>3.4	>3.4	2.6	2.0	1.5		3.13	3.50	3.74	3.94	4.30		228	252	200	165	132
Elmdon, 15 Sep	>3.4	>3.4	3.0	2.2	1.6		3.62	4.03	4.36	4.59	5.03		245	270	255	198	157
Plymouth, 15 Aug	>3.4	3.2	2.3	1.6	1.2		3.59	3.96	4.30	4.69	5.15		233	240	180	135	114
Plymouth, 15 Sep	>3.4	>3.4	2.5	1.8	1.3		3.89	4.31	4.52	4.84	5.33		241	265	205	162	129

Table 18. Strategy 1. Effect of heater power on drying performance at Waddington, starting on 15 September. (Runs 183, 51b, 180-181)

Heater power, kW	**Depth, m, at which 20 years were successful out of 20**					**Cost, £/dried t**					**Drying time, h**				
Initial m.c., %w.b.	**18**	**19**	**20**	**21**	**22**	**18**	**19**	**20**	**21**	**22**	**18**	**19**	**20**	**21**	**22**
60	>4.8	3.8	2.4	1.6	1.2	3.33	3.61	3.96	4.94	5.88	459	384	261	225	203
80	>4.8	3.9	2.6	1.8	1.3	3.56	3.85	4.08	4.39	4.88	425	362	255	194	156
100	>4.8	3.9	2.7	1.9	1.4	3.96	4.24	4.36	4.64	5.09	402	340	248	188	151
120	>4.8	4.0	2.7	2.0	1.2	4.53	4.78	4.80	5.05	5.49	382	333	234	185	121

Table 19. Strategy 1. Effect of heater power on drying performance at Ringway, starting on 15 August. (Runs 186, 184, 52a, 185)

Heater power, kW	**Depth, m, at which 20 years were successful out of 20**					**Cost, £/dried t**					**Drying time, h**				
Initial m.c., %w.b.	**18**	**19**	**20**	**21**	**22**	**18**	**19**	**20**	**21**	**22**	**18**	**19**	**20**	**21**	**22**
40	>4.8	3.3	2.4	1.7	1.1	2.67	2.88	3.25	3.63	4.11	469	336	274	224	171
60	>4.8	3.4	2.5	1.8	1.2	2.76	2.96	3.19	3.48	3.97	424	307	243	191	148
80	>4.8	3.4	2.5	1.9	1.3	3.00	3.21	3.44	3.69	4.00	405	291	227	186	111
100	>4.8	3.4	2.5	1.9	1.3	3.35	3.51	3.76	4.02	4.31	388	279	216	176	130

Table 20. Strategy 2. Performance of Strategy 2 at two locations and two start dates for drying. Grain moisture content for control was the wettest m.c. in the whole bed. (Runs 100, 101, 103, 168).

Location and start date for drying	**Depth, m, at which 20 years were successful out of 20**					**Cost, £/dried t**					**Drying time, h**				
Initial m.c., %w.b.	**18**	**19**	**20**	**21**	**22**	**18**	**19**	**20**	**21**	**22**	**18**	**19**	**20**	**21**	**22**
Wad'ton, 15 Aug	1.5	1.1	0.5	<0.4	<0.4	1.52	1.74	1.75	n/a	n/a	325	239	140	n/a	n/a
Wad'ton, 15 Sep	1.6	1.1	<0.4	<0.4	<0.4	1.46	1.90	n/a	n/a	n/a	495	341	n/a	n/a	n/a
Ringway, 15 Aug	2.5	2.1	1.3	1.0	0.8	1.84	1.99	2.03	2.49	2.58	430	334	243	221	191
Ringway, 15 Sep	2.6	2.4	1.6	1.1	0.8	1.68	2.21	2.20	2.62	2.68	564	472	350	296	228

Table 21. Performance of Strategy 2D at five locations and two start dates for drying. Grain moisture content for control was the wettest m.c. of whole bed. (Runs 172-175, 187-192).

Location and start date for drying	Depth, m, at which 20 years were successful out of 20						Cost, £/dried t						Drying time, h				
Initial m.c., %w.b.	**18**	**19**	**20**	**21**	**22**		**18**	**19**	**20**	**21**	**22**		**18**	**19**	**20**	**21**	**22**
Wad'ton, 15 Aug	2.2	1.2	0.6	0.4	<0.4		1.80	1.76	1.77	2.26	n/a		373	240	153	128	n/a
Wad'ton, 15 Sep	1.6	1.1	0.7	0.4	<0.4		1.99	2.04	2.17	2.80	n/a		442	333	244	186	n/a
Ringway, 15 Aug	3.9	2.4	1.5	1.1	0.8		2.04	2.03	2.10	2.56	2.64		545	353	261	233	189
Ringway, 15 Sep	3.4	2.7	1.6	1.3	0.9		2.18	2.35	2.25	2.80	2.90		637	515	336	325	249
Heathrow, 15 Aug	2.9	1.9	1.4	1.0	0.8		1.78	1.82	1.91	2.14	2.23		339	242	202	178	154
Heathrow, 15 Sep	3.1	1.9	1.1	1.0	0.7		1.89	1.88	1.93	2.58	2.67		512	343	233	251	199
Elmdon, 15 Aug	2.9	2.0	1.2	0.8	0.6		1.87	1.93	1.98	2.39	2.46		412	299	216	182	148
Elmdon, 15 Sep	2.4	1.5	1.0	0.7	0.4		2.04	2.03	2.16	2.69	2.91		551	370	296	234	169
Plymouth, 15 Aug	0.7	0.4	<0.4	<0.4	<0.4		1.71	1.93	n/a	n/a	n/a		263	200	n/a	n/a	n/a
Plymouth, 15 Sep	<0.4	<0.4	<0.4	<0.4	<0.4		n/a	n/a	n/a	n/a	n/a		n/a	n/a	n/a	n/a	n/a

Table 22. Relationship between relative humidity set points and grain moisture content, showing ranges in which those set points were used in Strategy 2.

	Strategy 2A	**Strategy 2D**
	m.c. at 0.3 m depth	**m.c. of wettest layer**
r.h., %	**Moisture content, % wet basis**	
100	>20	>24
93	(step not used)	<24 >20
83	<20, >18	<20 >17
72	<18, >16	<17 >15.5
62	<16	<15.5

Table 23. Maximum depths and depth reduction needed to maintain same risk level, <5%, with Strategy 2D, at two locations (Waddington and Ringway) and two start dates for drying (15 Aug and 15 Sep) using new model for safe storage time (Jonsson) and old model (Fraser/Kreyger). Grain moisture content for control was at wettest layer. (Runs 172, 211, 173, 212, 174, 213, 175, 214)

Location and start date for drying		Depth, m, at which 20 years were successful out of 20				
	Initial m.c., %w.b.	18	19	20	21	22
Wad'ton, 15 Aug	New model	2.2	1.2	0.6	0.4	<0.4
	Old model	3.5	2.2	1.6	1.3	1
	Depth reduction, m	1.3	1	1	0.9	>0.6
Wad'ton, 15 Sep	New model	1.6	1.1	0.7	0.4	<0.4
	Old model	1.6	1.4	1.3	1	0.9
	Depth reduction, m	0	0.3	0.6	0.6	>0.5
Ringway, 15 Aug	New model	3.9	2.4	1.5	1.1	0.8
	Old model	4.6	3.9	2.7	2.4	2
	Depth reduction, m	0.7	1.5	1.2	1.3	1.2
Ringway, 15 Sep	New model	3.4	2.7	1.6	1.3	0.9
	Old model	3.4	3	2.7	2.3	1.9
	Depth reduction, m	0	0.3	1.1	1	1

Table 24. Comparison for two locations and two start dates of percentage of elapsed time for which fan was running when using Strategy 2A and 2D. (Runs 100, 101, 103, 168, 172-175) N.B. 'n/a' indicates that a result was not obtained for this condition.

Location and start date for drying	Percentage of elapsed time for which fan was running									
Initial m.c., %w.b.	18		19		20		21		22	
Strategy	2A	2D	2A	2D	2A	2D	2A	2D	2A	2D
Waddington, 15 Aug	30	49	43	47	43	46	n/a	53	n/a	n/a
Waddington, 15 Sep	24	38	33	39	n/a	40	n/a	47	n/a	n/a
Ringway, 15 Aug	40	68	59	66	56	62	67	70	69	72
Ringway, 15 Sep	34	57	55	61	54	58	59	65	62	67

Table 25. Relationship between relative humidity set points and grain moisture content, showing ranges in which those set points were used in Strategy 3.

Setpoint r.h., %	Strategy 3F	Strategy 3G
100	>=20	>=22
83*	<20 >=18	<22 >=20.3
78#	<18 >=17	<20.3 >=19.3
73#	<17 >=16	<19.3 >=18.2
68#	<16 >=15	<18.2 >=17.4
62#	<15 >=14	<17.4 >=16.4
55#	<14	<16.4

***** Control by switching fan off when plenum rh > 83%

Control by switching heat on when plenum rh > setpoint rh

Table 26. Performance of Strategy 3G with an 80kW, 4 stage propane heater, at two locations (Waddington and Ringway) and two start dates for drying (15 Aug and 15 Sep). Grain moisture content for control was at 0.3m depth. (Runs 105, 106, 109, 195)

Location and start date for drying	Depth, m, at which 20 years were successful out of 20						Cost, £/dried t						Drying time, h				
Initial m.c., %w.b.	**18**	**19**	**20**	**21**	**22**		**18**	**19**	**20**	**21**	**22**		**18**	**19**	**20**	**21**	**22**
Wad'ton, 15 Aug	4.7	3.1	2.1	0.6	0.5		3.74	3.65	4.12	4.47	4.99		383	276	228	85	79
Wad'ton, 15 Sep	>4.8	3.7	2.2	<0.4	0.4		3.95	4.00	4.85	n/a	6.38		416	364	269	n/a	75
Ringway, 15 Aug	>4.8	3.3	2.4	1.2	0.8		3.52	3.39	3.77	3.55	3.84		394	297	255	164	119
Ringway, 15 Sep	>4.8	4.3	2.7	1.1	0.6		3.43	3.49	3.84	3.37	3.64		415	431	323	181	119

Table 27. Performance of Strategy 3F and 3G with old model (Fraser/Kreyger) and new model (Jonsson) for safe storage time. Comparison is for Waddington location with drying started 15 August. 80 kW, 4 stage propane heater, grain moisture content for control was from 0.3m depth. (Runs 161, 42b, 110, 105).

Strategy	Spoilage Model	Depth, m, at which 20 years were successful out of 20						Cost, £/dried t						Drying time, h				
Initial m.c., %w.b.		**18**	**19**	**20**	**21**	**22**		**18**	**19**	**20**	**21**	**22**		**18**	**19**	**20**	**21**	**22**
3F	**Old**	>4.8	2.7	1.7	1.3	1.1		3.44	2.52	2.73	3.55	3.92		540	377	259	222	202
	New	3.9	1.5	0.7	0.4	<0.4		3.22	2.57	3.24	5.08	n/a		401	204	115	77	n/a
3G	**Old**	>4.8	4.5	3.1	1.2	0.8		3.76	3.60	4.00	3.51	4.07		394	430	342	181	131
	New	4.7	3.1	2.1	0.6	0.5		3.74	3.65	4.12	4.47	4.99		383	276	228	85	79

Table 28. Maximum depths and depth reduction needed to maintain same risk level, <5%, with Strategy 3G, at two locations (Waddington and Ringway) and two start dates for drying (15 Aug and 15 Sep) using new model for safe storage time (Jonsson) and old model (Fraser/Kreyger). 80kW, 4 stage propane heater. Grain moisture content for control was at 0.3 m. (Runs 105, 110, 106, 218, 109, 219, 195, 220)

Location and start date for drying		**Depth, m, at which 20 years were successful out of 20**				
	Initial m.c., %w.b.	**18**	**19**	**20**	**21**	**22**
Wad'ton, 15 Aug	**New model**	4.7	3.1	2.1	0.6	0.5
	Old model	>4.8	4.5	3.1	1.2	0.8
	Depth reduction, m	>0.1	1.4	1	0.6	0.3
Wad'ton, 15 Sep	**New model**	>4.8	3.7	2.2	<0.4	0.4
	Old model	>4.8	>4.8	3.9	1.2	1
	Depth reduction, m	n/a	>1.1	1.7	>0.8	0.6
Ringway, 15 Aug	**New model**	>4.8	3.3	2.4	1.2	0.8
	Old model	>4.8	>4.8	3.4	2.1	1.6
	Depth reduction, m	n/a	>1.5	1	0.9	0.8
Ringway, 15 Sep	**New model**	>4.8	4.3	2.7	1.1	0.6
	Old model	>4.8	>4.8	4.5	2.6	1.9
	Depth reduction, m	n/a	>0.5	1.8	1.5	1.3

Table 29. Results for simulating drying until both moisture targets (wettest layer <16%, average <14.5%) were met. Waddington, starting 15 August. (Runs 450, 451, 452). * see comment in text.

Strategy etc.	**Strategy 1, 80 kW heater, 80% r.h. setpoint**					**Strategy 2D**					Strategy 3G				
Initial m.c., %w.b.	**18**	**19**	**20**	**21**	**22**	**18**	**19**	**20**	**21**	**22**	**18**	**19**	**20**	**21**	**22**
Maximum depth for risk of OA <5%, m	4.8	3.2	2.3	1.6	1.2	2.2	1.2	0.6	0.4	n/a	4.7	3.1	2.1	0.6	0.5
No of years of 20 when second target met	20	14	14	13	16	18	19	19	20		20	20	20	20	20
Elapsed time when both m.c. targets met, h	466	345	330	281	269	519	330	202	174		387	303	250	108	97
Average m.c. when both targets met, %w.b.	14.3	14.4	14.4	14.4	14.4	14.3	14.4	14.4	14.4		14.2	14.4	14.4	14.4	14.3
Min m.c. when both targets met, %w.b.	13.8	13.6	13.3	13.4	13.1	13.1	13.5	13.4	13.5		13.0	13.0	13.4	13.5	13.6
Overdrying when both targets met, kg/t	2.06	1.17	1.19	0.73	0.82	1.82	1.31	1.36	1.28		3.46	1.23	1.18	1.72	2.26
Overdrying cost when both targets met, £/dried t	0.13	0.08	0.08	0.05	0.05	0.12	0.08	0.09	0.08		0.23	0.08	0.08	0.11	0.15
Total cost when both targets met, £/dried t	3.99	4.34	5.84*	6.88*	8.78*	2.05	1.99	2.03	2.56		3.78	4.17	4.74	6.57 *	6.96*

Table 30. Strategy 1. Effect of fan size in two locations with two starting dates. 80 kW propane heater. (Runs 400, 50b, 420, 401, 51b, 421, 402, 52a, 422, 403, 53a, 423).

Location and start date	Fan size	Depth, m, at which 20 years were successful out of 20						Cost, £/dried t						Drying time, h				
Initial m.c., %w.b.		18	19	20	21	22		18	19	20	21	22		18	19	20	21	22
Wad'ton, 15 Aug	Small	4.2	2.7	1.9	1.4	1.0		3.53	3.51	3.66	3.96	4.31		387	258	197	158	126
	Standard	>4.8	3.2	2.3	1.6	1.2		3.37	3.46	3.72	3.93	4.34		399	271	207	159	131
	Large	>4.8	3.3	2.4	1.8	1.4		3.36	3.38	3.63	3.86	4.41		396	269	203	165	141
Wad'ton, 15 Sep	Small	5.6	3.5	2.2	1.6	1.1		3.94	3.83	4.04	4.35	4.76		580	356	243	192	148
	Standard	>4.8	3.9	2.6	1.8	1.3		3.56	3.85	4.08	4.39	4.88		425	362	255	194	156
	Large	>4.4	4.0	2.8	2.0	1.4		3.50	3.80	4.01	4.37	5.10		377	376	261	202	161
Ringway, 15 Aug	Small	4.7	2.9	2.1	1.5	1.1		3.19	3.22	3.40	3.69	3.93		447	280	218	168	136
	Standard	>4.8	3.4	2.5	1.9	1.3		3.00	3.21	3.44	3.69	4.00		405	291	227	186	139
	Large	>4.4	3.5	2.7	2.1	1.5		2.95	3.14	3.37	3.58	3.91		358	290	230	190	142
Ringway, 15 Sep	Small	5.8	3.7	2.4	1.7	1.2		3.33	3.27	3.47	3.67	3.93		626	400	269	206	161
	Standard	>4.8	3.7	2.8	2.0	1.5		3.04	3.26	3.45	3.70	4.03		435	344	277	213	175
	Large	>4.4	4.3	2.9	2.2	1.6		2.97	3.29	3.37	3.62	3.91		387	412	272	217	169

Table 31. Strategy 2D. Effect of fan size in two locations with two starting dates. Grain moisture content for control was the wettest m.c. of whole bed. (Runs 172, 425, 173, 426, 174, 427, 175, 428).

Location and start date	Fan size	Depth, m, at which 20 years were successful out of 20						Cost, £/dried t						Drying time, h				
Initial m.c., %w.b.		18	19	20	21	22		18	19	20	21	22		18	19	20	21	22
Wad'ton, 15 Aug	Standard	2.2	1.2	0.6	0.4	n/a		1.80	1.76	1.77	2.26	n/a		373	240	153	128	n/a
	Large	2.4	1.5	0.8	0.6	0.4		1.78	1.87	2.06	2.78	3.04		376	253	155	138	109
Wad'ton, 15 Sep	Standard	1.6	1.1	0.7	0.4	n/a		1.99	2.04	2.17	2.80	n/a		442	333	244	186	n/a
	Large	1.8	1.4	0.9	0.6	n/a		2.01	2.17	2.45	3.42	n/a		436	345	246	199	n/a
Ringway, 15 Aug	Standard	3.9	2.4	1.5	1.1	0.8		2.04	2.03	2.10	2.56	2.64		545	353	261	233	189
	Large	4.0	2.5	1.6	1.3	1.0		2.02	1.97	2.15	2.67	2.84		547	339	251	225	188
Ringway, 15 Sep	Standard	3.4	2.7	1.6	1.3	0.9		2.18	2.35	2.25	2.80	2.90		637	515	336	325	249
	Large	3.5	2.8	1.9	1.5	1.1		2.13	2.33	2.26	2.92	3.07		625	511	343	320	241

Table 32. Strategy 3G. Effect of fan size in two locations with two starting dates. Grain moisture content for control was at 0.3 m. (Runs 105, 430, 106, 431, 109, 432, 195, 433).

Location and start date	Fan size	Depth, m, at which 20 years were successful out of 20					Cost, £/dried t					Drying time, h				
Initial m.c., %w.b.		**18**	**19**	**20**	**21**	**22**	**18**	**19**	**20**	**21**	**22**	**18**	**19**	**20**	**21**	**22**
Wad'ton, 15 Aug	**Standard**	4.7	3.1	2.1	0.6	0.5	3.74	3.65	4.12	4.47	4.99	383	276	228	85	79
	Large	>4.4	3.2	2.4	0.8	0.6	3.67	3.61	4.05	4.52	5.37	346	272	242	103	87
Wad'ton, 15 Sep	**Standard**	>4.8	3.7	2.2	<0.4	0.4	3.95	4.00	4.85	n/a	6.38	416	364	269	n/a	75
	Large	>4.4	3.8	2.5	0.4	0.4	3.87	3.95	4.80	8.48	8.22	366	363	286	75	78
Ringway, 15 Aug	**Standard**	>4.8	3.3	2.4	1.2	0.8	3.52	3.39	3.77	3.55	3.84	394	297	255	164	119
	Large	>4.4	3.5	2.6	1.4	0.9	3.48	3.32	3.68	3.42	3.79	346	302	259	165	113
Ringway, 15 Sep	**Standard**	>4.8	4.3	2.7	1.1	0.6	3.43	3.49	3.84	3.37	3.64	415	431	323	181	119
	Large	>4.4	>4.4	2.9	1.4	0.9	3.52	3.47	3.88	3.70	4.10	363	434	317	176	119

Figure 7. Equilibrium curve between wheat mc and air rh, with four sets of "steps" describing fan switching in Strategy 2.

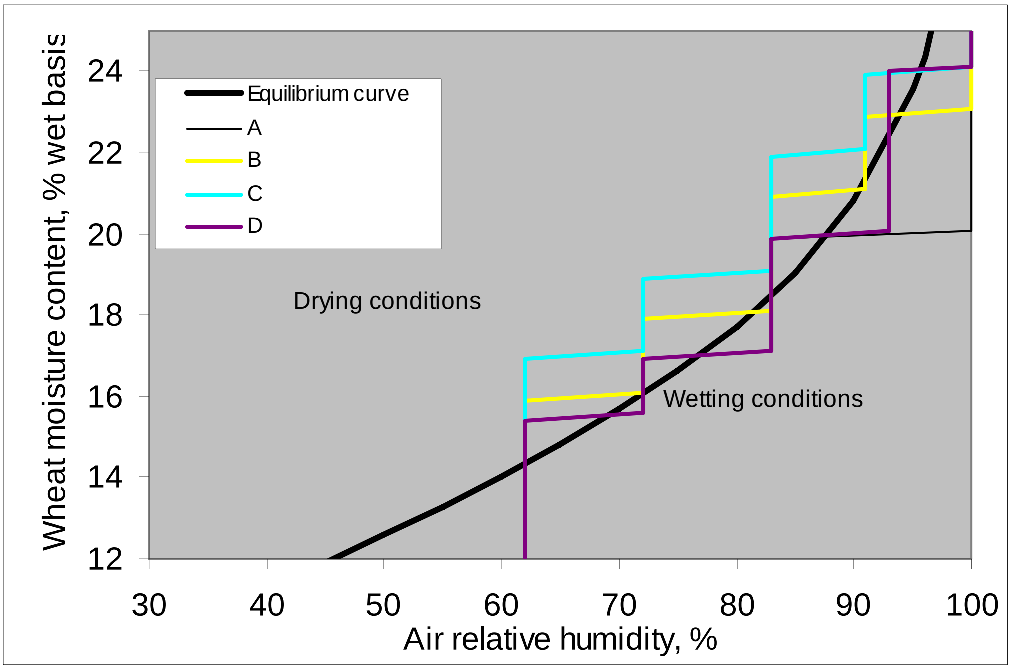


Figure 8. Effect of initial moisture on maximum depth with Strategy 2D for the five locations when starting drying on 15th August in each of 20 years, 1951-1970.

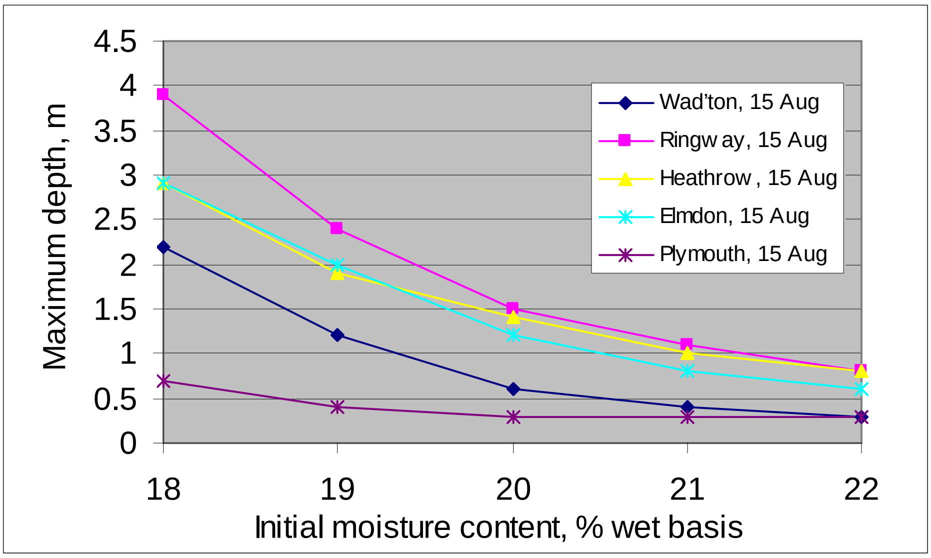


Figure 9. Effect of initial moisture on maximum depth with Strategy 2D for the five locations when starting drying on 15th September in each of 20 years, 1951-1970.

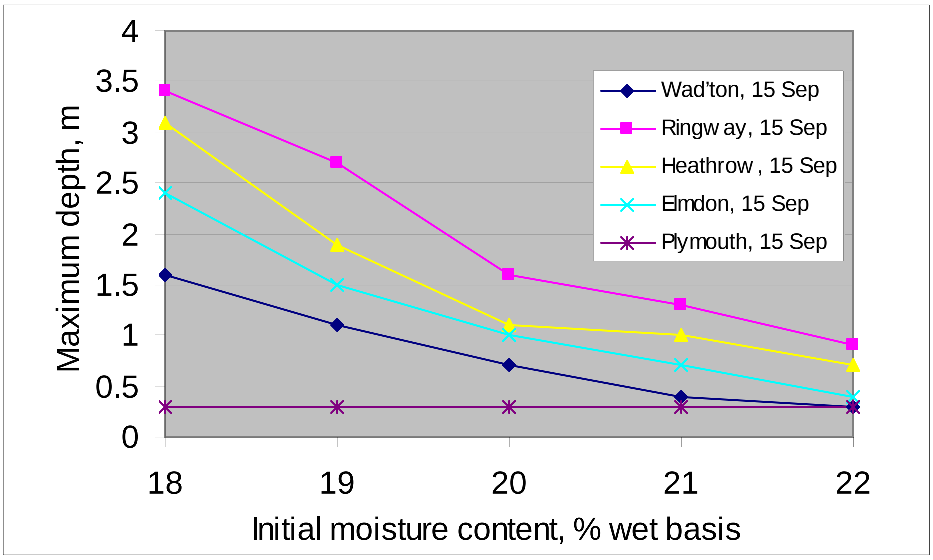


Figure 10. Effect of Steps of r.h. vs m.c., and of location on maximum depth, using Strategy 2 - fan switched on r.h. that depends on highest bed m.c. Drying started 15 August.

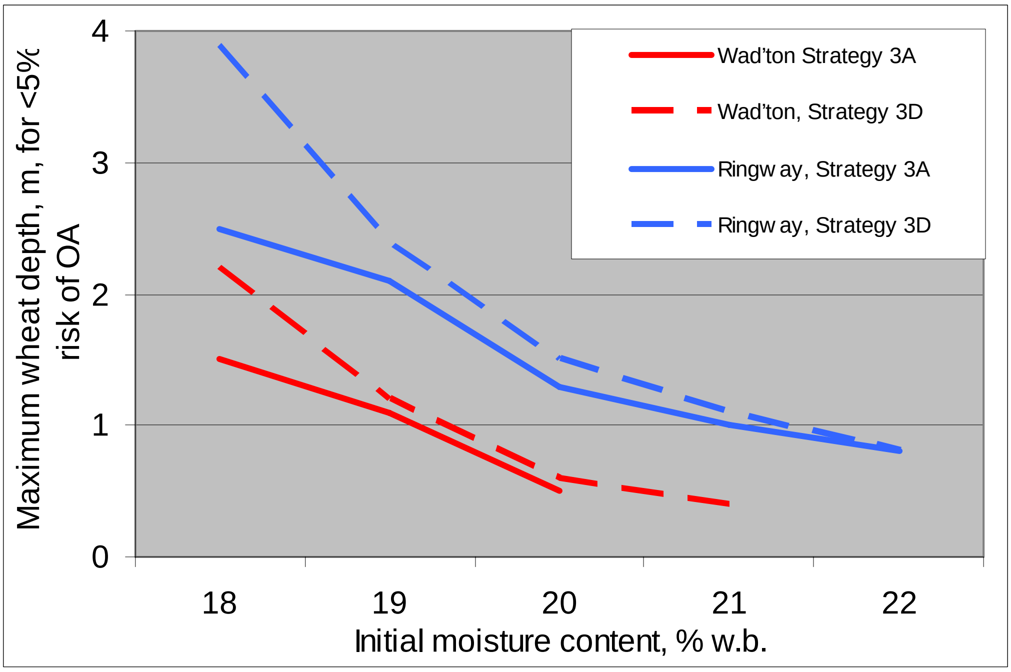


Figure 11. Equilibrium curve between wheat mc and air rh, with three sets of "steps" describing fan switching in Strategy 3.

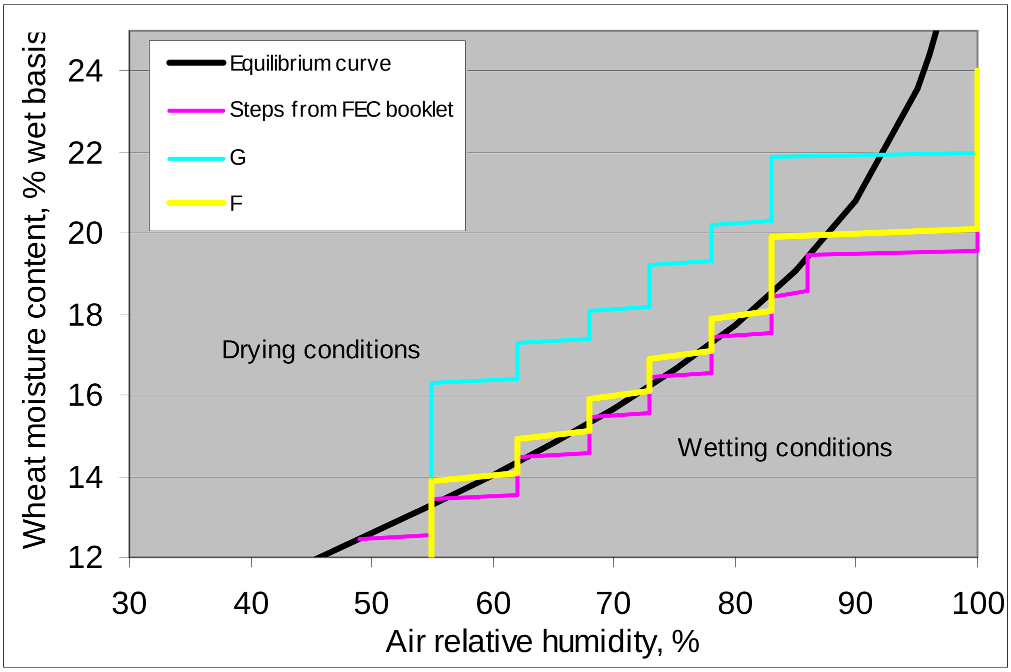


Figure 12. Effect of Steps of r.h. vs m.c., and of location on maximum depth, using Strategy 3 - fan switched off, and heater switched on, using r.h. setpoint that depends on bed m.c. at 0.3 m. Drying started 15 August.

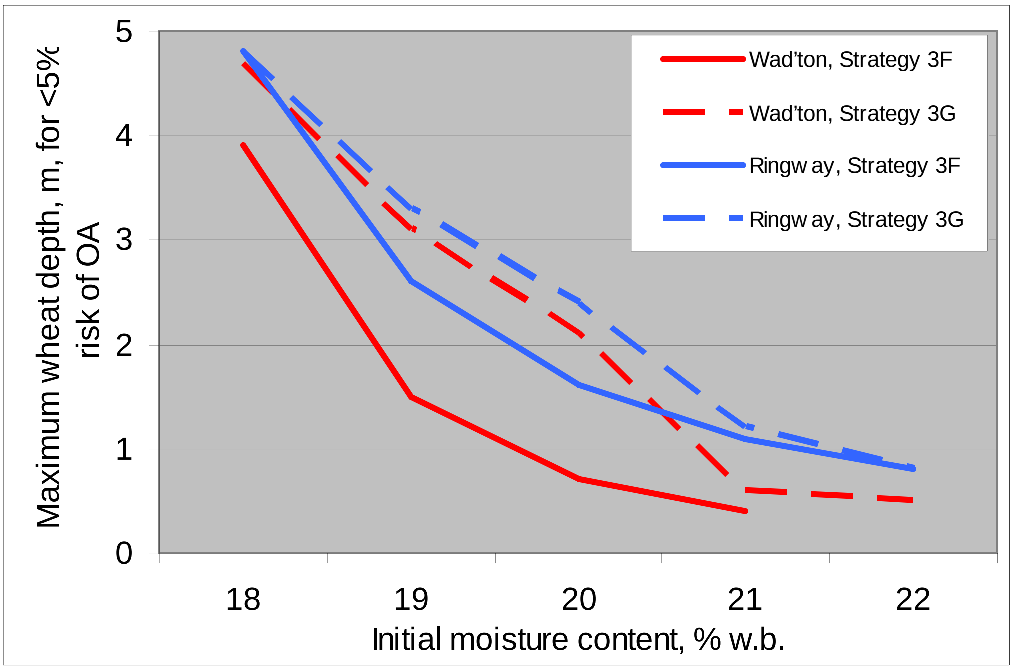


Figure 13. Maximum depths for Waddington, starting 15th August. Strategy 3A with Fraser/Kreyger spoilage based on visible mould (red line), with Jonsson model based on OA (blue line). Strategy 3D and Jonsson model (broken blue line).

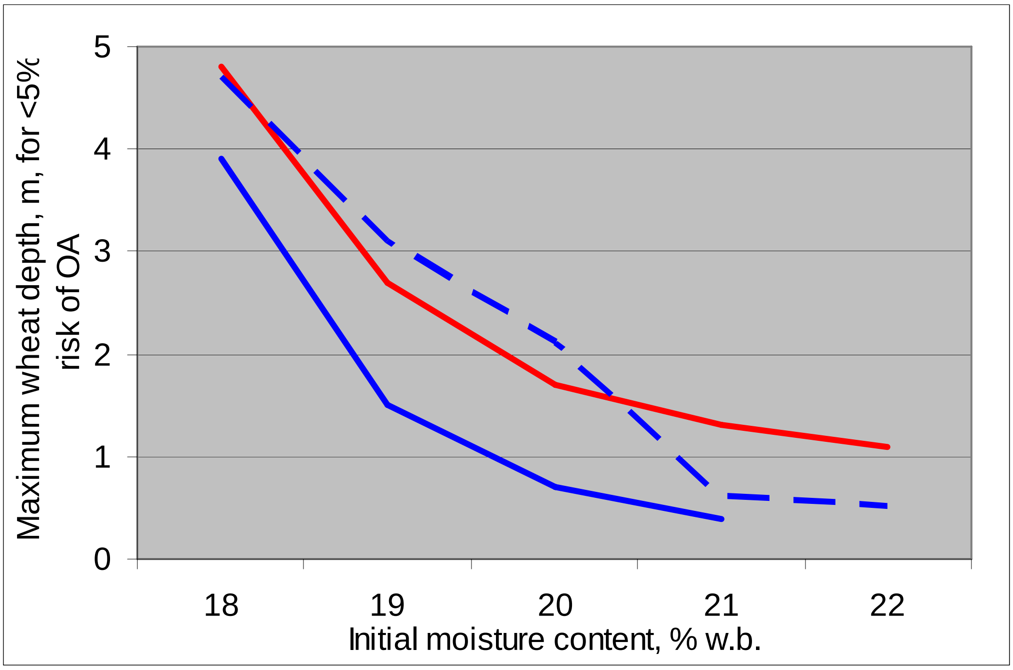


Figure 14. Effect of accepting an increased risk of OA on the maximum depth and comparison with risk by old spoilage model under same conditions. Strategy 1, Waddington, starting 15 August. (Runs 50b and 111)

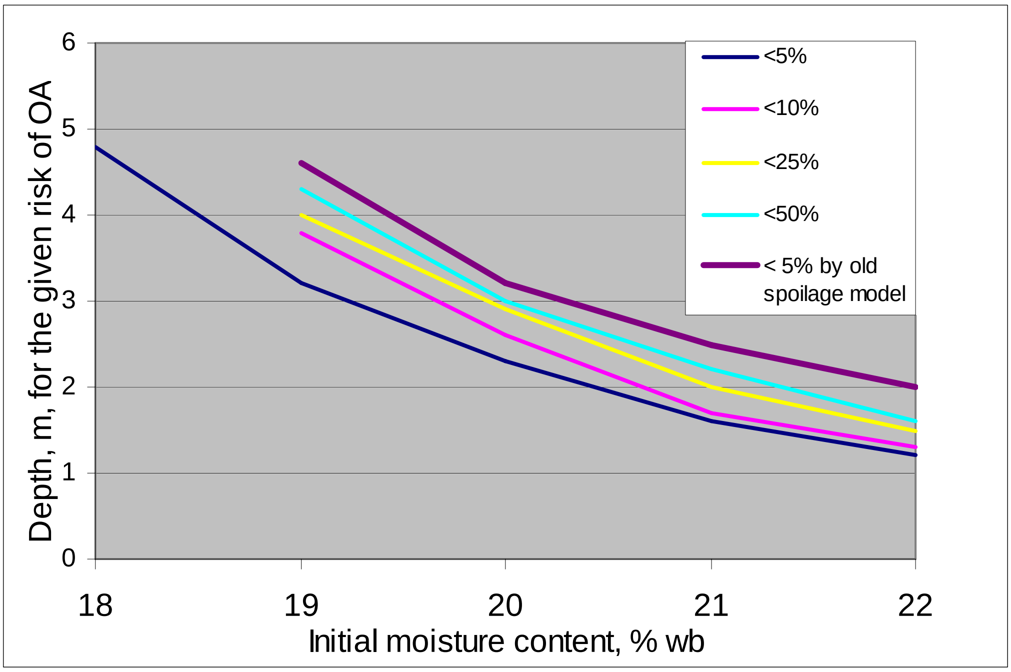


Figure 15. Effect of accepting an increased risk of OA on the maximum depth. Strategy 3A, Waddington, starting 15 August. (Run 100)

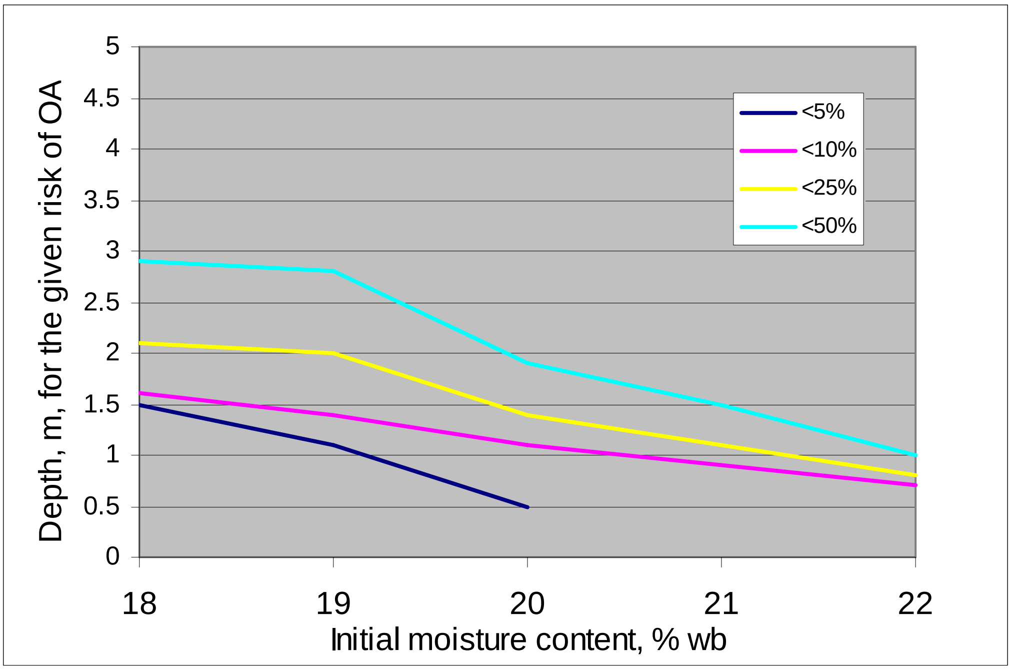


Figure 16. Effect of accepting an increased risk of OA on the maximum depth. Strategy 3D, Waddington, starting 15 August. (Run 172)

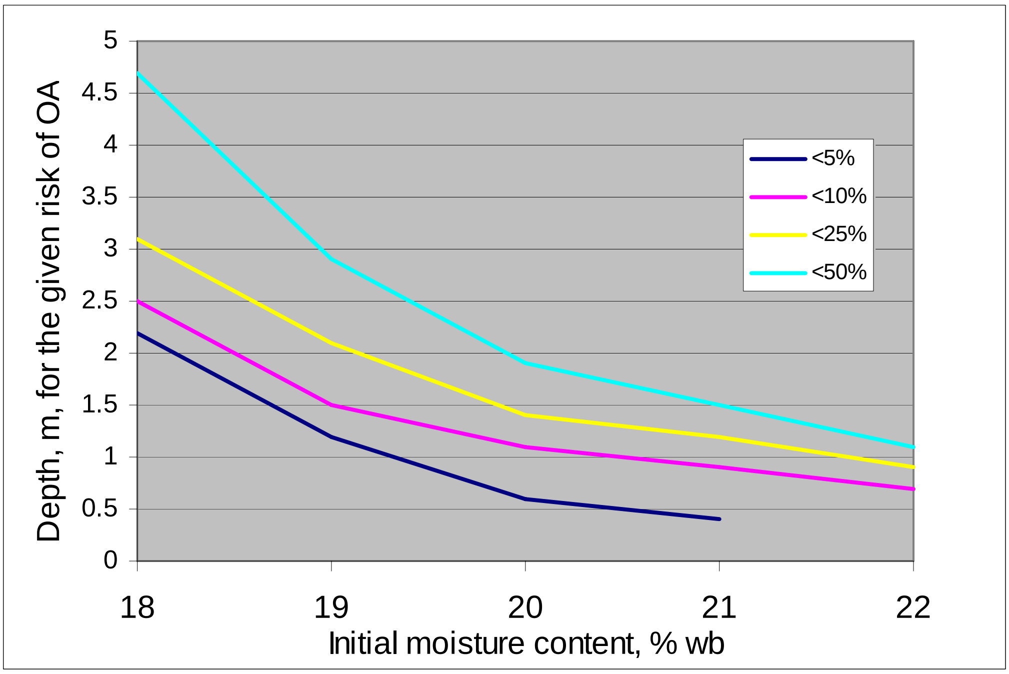


Figure 17. Effect of accepting an increased risk of OA on the maximum depth with Strategy 3D and comparison with risk by old spoilage model and Strategy 3A. Waddington, starting 15 August. (Runs 105 and 161)

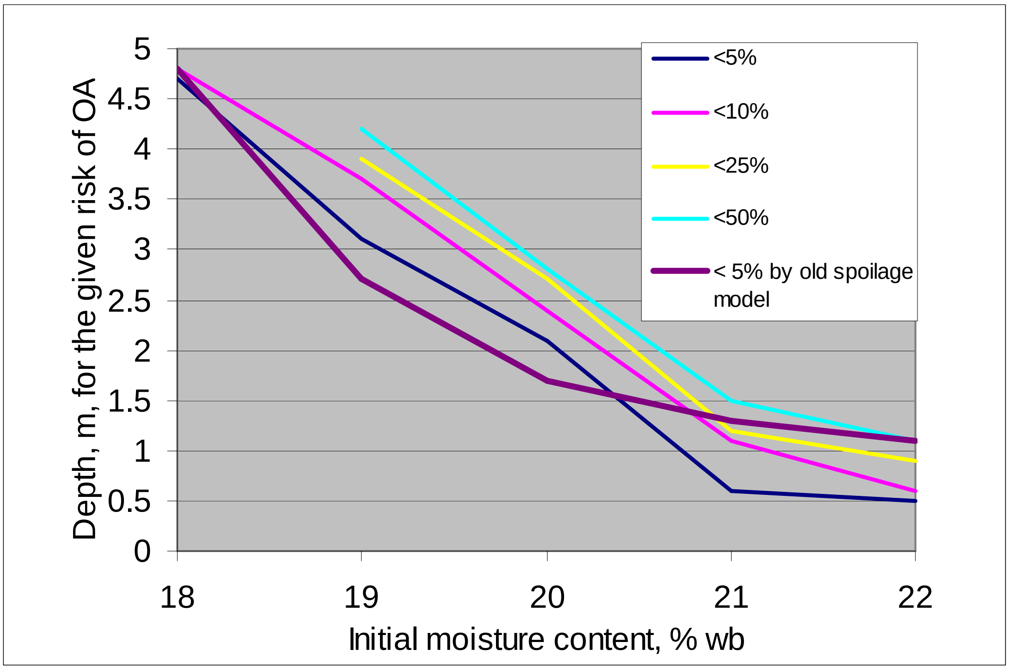


Figure 18. Effect of accepting an increased risk of OA on the maximum depth. Strategy 3D, Waddington, starting 15 September. (Run 106)

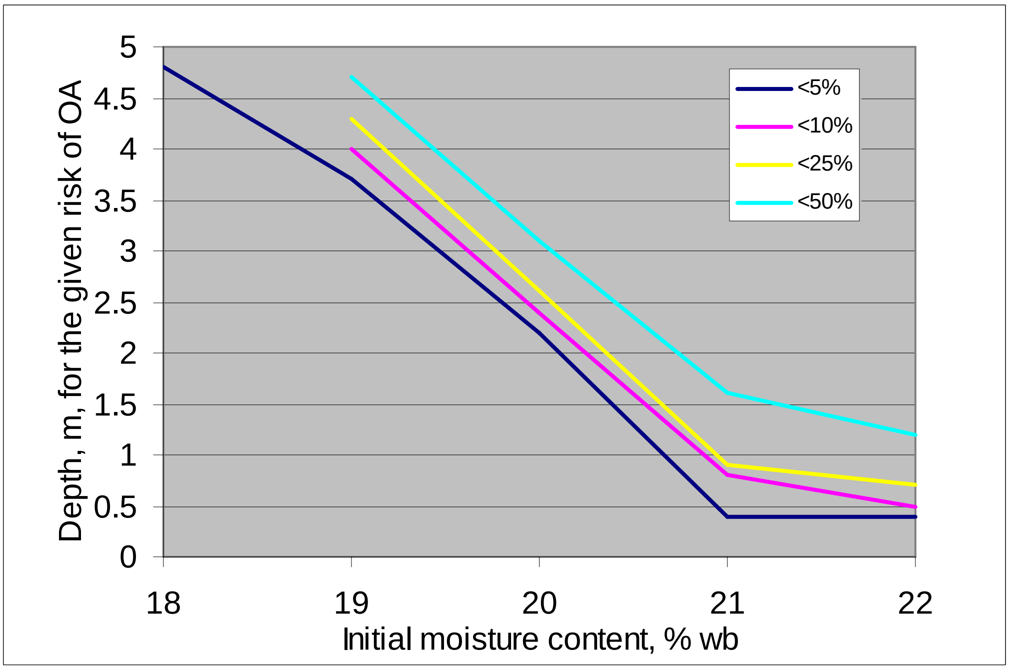


Figure 19. Effect of accepting an increased risk of OA on the maximum depth. Strategy 3D, Ringway, starting 15 August. (Run 109)

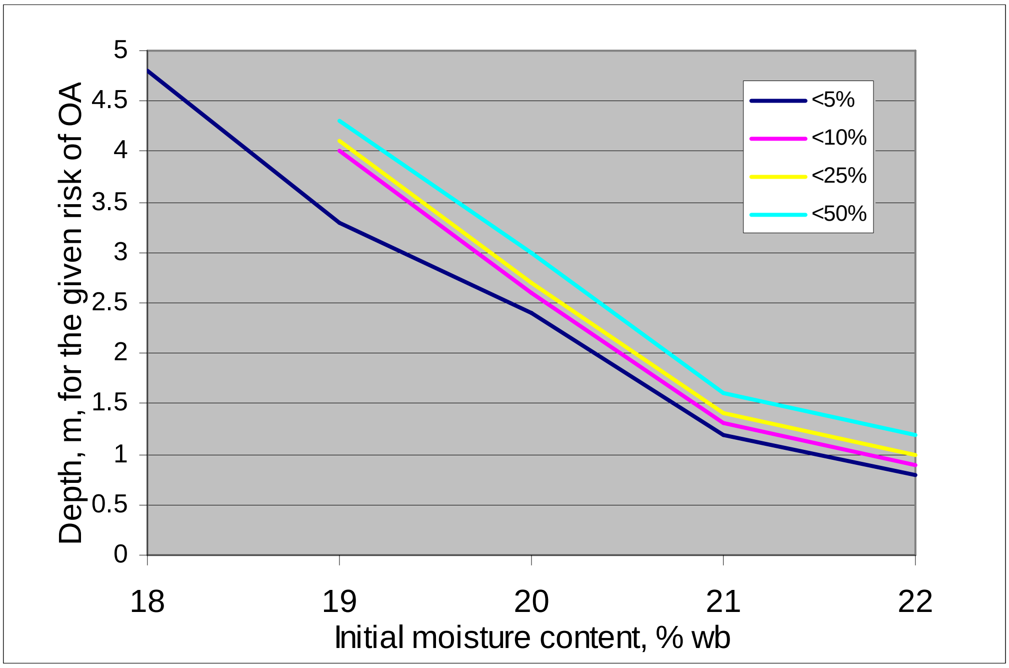
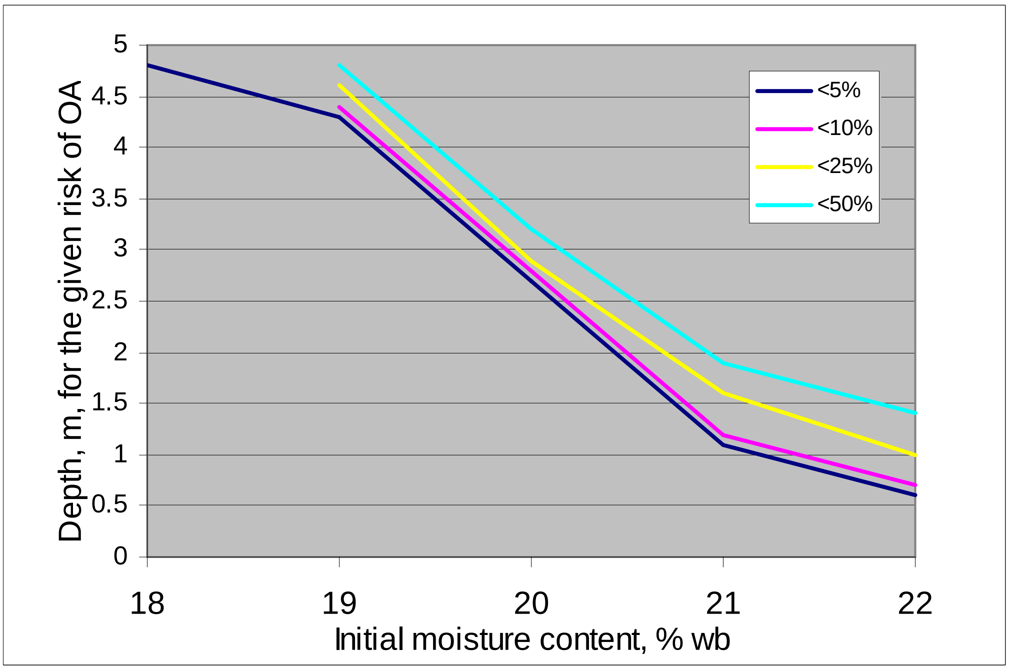


Figure 20. Effect of accepting an increased risk of OA on the maximum depth. Strategy 3D, Ringway, starting 15 September. (Run 195)



5. GRAIN STIRRING

How stirring works and why it may help avoid spoilage

Grain can be mixed by manual methods involving for example, bucket loader in a floor store or by moving from one bin to another. This might be done before or after drying to even out moisture differences or to blend two batches. Moving the grain during drying also has attractions. In the context of this report, there would be appear to be a benefit from mixing moist grains at the top of the bed, where the air surrounding them will be unable to remove more moisture from them, with dried grains from the bottom. When mixed, the moist grains will dry faster because the surrounding air is not as saturated. This faster drying may ensure the fungi that can produce OA do not reach their rapid growth stage so OA production is avoided. The already dry grains will absorb moisture but they may not reach a high enough moisture to put them at risk. Such mixing during drying requires automatic equipment, and several such systems are available in the UK for floor stores and bins. Grain stirring systems comprise vertical augers that reach effectively to the bottom of the bed, rotated so as to draw grain upwards. This brings about a circulation of grain away from the zones that dry first, and allow damper grain from above to fall into the voids created. In most systems a number of augers operate in the grain bed, suspended from a gantry that moves slowly over the section of the store to be mixed, so that over a period of some hours, every part of the bed is stirred. The circulation pattern from each auger is complex but overall the effect of several augers moved through the bed is to mix sufficiently thoroughly that any gradients in moisture are removed in about 3 days (Anon., 1994).

Besides reducing the time the wettest layers wait before drying starts, stirring systems also incorporate grain that may be overdried into the bulk. This is helpful if drying air r.h. is very low simply due to low ambient r.h. or if the drying air has been heated excessively. It is clear from the foregoing that a stirred bed no longer works by a drying front moving through the bed from air inlet to outlet, and needing to reach the surface before spoilage has occurred there. This also removes constraints on the temperature of the drying air normally imposed by the drying front method, *i.e.* too high an air temperature giving rise to high grain temperatures and rapid spoilage in the damp region ahead of a drying front. With stirred grain and effectively no drying front, higher air temperatures may be usable before spoilage occurs. Stirred wheat systems have been tested at air temperatures of up to 35-40 ^{o}C (Anon., 1997a, Anon., 1997b, McLean, 1993), without obvious spoilage. However, drying with higher temperatures generates high humidity conditions above the grain bed, and significant condensation may occur if measures are not taken to remove the air rapidly.

Another advantage of stirring is that the resistance to airflow of the grain bed is reduced, which allows the fan to deliver more air and so drying to progress faster. The amount of reduction, which is not consistent, depends among other factors on the condition of the grain. Some damage to the grain may result from the mechanical action of the augers.

Modelling stirring

Mixing action

In some previous work on modelling of the effect of stirring on grain beds during drying (Bridges *et al*., 1983, Williams *et al*., 1978), mixing of corn was modelled by simply averaging the conditions in the bed. This means that, when stirring is carried out, every part of the bed is set to the average temperature, moisture and condition of pre-spoilage. Stirring is activated every few hours and then the bed is undisturbed until the next time point when conditions are averaged. Averaging of the state of the grain in respect of progress towards spoilage seemed to be unrealistic, in that mixing a layer of grain on which the fungi is about to undergo rapid growth with a layer of grain having little fungi is not likely to produce a population of fungi half way to the point of rapid growth. Instead, the fungi present would probably continue as fast as moisture and temperature of the grain allowed, so the best approach to modelling progress towards spoilage seemed to be to allow the OA-based model of Jonsson to continue to work, with the conditions applicable to each layer of grain, while the grain dried, or wetted, through normal exchange processes.

So the approach to modelling stirring taken here was to “shuffle” some of the 100 layers into which the grain bed was divided for simulation. Stirring was carried out after each hour. A number of pairs of layers were selected, using a random process, and their positions in the bed swapped so that all layers were re-ordered over time. All the layers were then moved down the bed one place. The temperature and moisture of each layer and the measures of its quality were not changed during this re-ordering. The number of pairs of layers to swap each hour was then determined by simulating a trial reported in by FEC Services Ltd. (Anon, 1994). In that trial, a gradient of moisture was set up by drying for two days and then stirring was started and heating of the air stopped. The moisture samples from the bed showed that the differences in moisture content with position down the bed were eliminated by between 48 and 72 h of stirring. In the simulation, it was found two pairs of layers needed to be swapped each hour achieved the same effect.

Effect of stirring on airflow and bed resistance

Evidence from published experiments showed that stirring reduced resistance to airflow but did not measurably reduce density. So, rather than introducing a density change to model the change in air resistance (resistance depends on density in the simulation), the resistance of the grain bed per unit depth was multiplied by an empirical factor, less than unity. This factor was altered to find what value gave reduction in duct static pressure similar to that reported in an experiment on wheat by McLean (1993). A “resistance reduction” multiplier of 0.85 was found appropriate.

Constant temperature control strategy

Several experiments reported in the literature use a more powerful heater than normally fitted to near-ambient driers to enable higher temperatures to be achieved, and also use a control system that seeks to maintain a constant temperature of drying air. This differs from all of the three Strategies used earlier in this work in which control was based on r.h. A new control strategy was developed for this part of the work that added heat to the ambient air, after heating by action of the fan, to achieve either the set temperature or the maximum possible temperature, if lower.

Validation using published data

Method

A literature search revealed only 13 reports on stirring, of which five were on wheat, all from UK, the rest being North American work on corn. In these five, all of which report on tests of driers fitted with grain stirring systems, some data is presented that was potentially suitable for validating the simulation with its stirring routine. A paper by McLean (1993) reports results from a constant air temperature trial at 40 ^{o}C for which enough details are given for simulation. Kneeshaw and Cragg (1997) describe two trials at a drying temperature of 25 ^{o}C and, though few data are given, one trial was a candidate for simulation. However, in neither trial was any analysis done of grain quality, *e.g*. viability, so only the drying performance and energy use could be compared. Simulations were set up of the two above mentioned trials and run for the time needed to achieve the reported mean final moisture content, at which time the values of various parameters were noted for comparison.

Results

An analysis of the two trials and the work done to simulate them is presented in Appendix D. Results are summarised in Table 33 below. As explained in Appendix D, data in both reports had shortcomings that made them less than ideal as the basis for validating results from the simulation. In particular, in both trials the airflow had to be estimated based on other available evidence.

Discussion and conclusions

The trial by McLean was the better described and recorded data were more suitable for the purpose here. Simulation gave a drying time some 15% greater than measured. Fan energy values were very similar while simulated heater energy was 6% greater. Final moisture range was realistic. The pressure in the duct was much greater according to the simulation. There were difficulties over the airflow reported in the test so pressure and flow results may not be reliable. Simulation of the trial by Kneeshaw and Cragg also required adjustment of airflow via the duct pressure. Drying time by simulation was lower for this trial, by 7.8%. Fan energy was not separable from overall electrical energy, but heater energy use was underestimated by 38% despite the shorter run time. As explained in Appendix D, the data showed significant gas use on days when no moisture reduction was achieved, so energy results were subject to uncertainty.

A high quality set of data is needed with which to compare the simulation to fully validate its calculations, but in terms of drying time and moisture range at the end of drying, the results suggest the performance of the simulation is at least adequate for investigation of the benefits of stirring on control of OA.

Effect of stirring during drying on avoiding OA production

For the simulations on drying with stirring, the same approach was used as in previous chapters, *i.e.* the maximum depth of bed was found at which the risk of OA was <5%. Table 34 shows a simple comparison of drying at Waddington, starting 15 August, using Strategy 1 with heater switched in above 80% r.h. The comparison is first for the same depth of bed without and with stirring, then the maximum depth was determined that the stirred treatment would allow. The progress towards spoilage is shown in the form of the spoilage index. Once this index reaches 1, the grain is deemed to have reached the time limit for safe storage, and so the amount by which the index is below 1 indicates the margin of safety. For depths that were selected as maximum depths, the spoilage index was of course close to 1.

Comparing the treatments at the same depth (the first two lines of Table 34), stirring resulted in a much reduced maximum spoilage index. This is the maximum value found anywhere in the drying bed over the whole 20 years of drying. It is clear that stirring produced a considerable margin of safety at the depth at which there was no remaining margin without stirring.

Drying time was greater with stirring except at 18% initial m.c. This is because, in an unstirred bed, air leaving the grain is as humid as it can be, having last been in contact with the wettest grain near in the surface layers. Therefore the drying potential of the air is well used and so drying is both as fast and as energy-efficient as possible – advantages that have made near-ambient drying a popular method. When the bed is well-stirred, the air leaving the bed has been in contact with grain of average m.c. so the air is less humid and so carries away less moisture per m^3 than in the stirred case. Even though the reduced bed resistance allows a small increase in airflow, this is not enough to compensate, so drying is slower.

For the same reasons drying is less efficient in terms of evaporation achieved per unit of heat added, confirmed by the costs per dried tonne in Table 34 which show all stirred treatments except that at 18% initial m.c. have higher cost than the unstirred equivalents. (This cost, as before, is to achieve a target moisture for the wettest part of the bed of less than 16% w.b. so fungi that can produce OA are no longer active, not the cost to complete drying to a m.c. suitable for longer term storage.) Also the cost of the energy used by the stirring system was not been included.

In rows 1 and 3 of Table 34, the depths given are the maximum depths for which the risk of OA was <5% or that the fan could operate against. In this comparison, use of stirring allowed considerably greater depths to be used, ranging from 0.8 m deeper at 22 % initial m.c. to 2 m deeper at 20%. At depths not limited by the fan, spoilage index was close to 1, as would be expected at the limit to safe depth. At 18 and 19% maximum depth was limited by the fan. Costs were very similar to those in row 2. Drying times were greater in proportion to depth because the rate of water removal from the bed was more or less constant.

It is clear that a stirred bed with Strategy 1 gave advantages of increased maximum depth (or margin of safety) but at a penalty of increased drying cost. To seek a less costly option, Strategy 2D, in which a fan with no heater is controlled using ambient r.h., was simulated with stirring to find out how far stirring the bed improved its performance. Results for Waddington location starting drying on 15 August over 20 years are given in Table 35.

Maximum depth was improved, by between 0.7 m at 18% initial m.c. and 0.1 m at 21%. This was a useful increase in depth for Strategy 2D but the range of initial m.c. with which it could reliably cope still did not extend above 20% at this location and start date. Drying time was increased in proportion to depth. Cost per dried tonne was reduced so Strategy 2D was even more competitive with stirring. This strategy, whether stirred or not, is very dependent on the weather, so there would be periods of drying and rewetting for the lower part of the bed and periods when the fan is turned off. But the main difference between the treatments was that in this strategy the r.h. setpoint at which fan switching occurred was set on the basis of the m.c of the wettest layer in the bed. This m.c. would have been quite different in a stirred and a non-stirred bed.

A stirring system opens up the possibility of using a higher air temperature for drying than has been possible with a static (unstirred) bed. In drying a static bed, the use of too high a temperature results in grain ahead of the drying zone becoming warmed so fungal growth is accelerated, leading to more rapid spoilage in the upper layers. Also, grain may be overdried in the lower parts of the bed. Stirring helps to overcome these issues. Table 36 compares two drying treatments in a stirred bed; Strategy 1 and air at a constant temperature of 25 ^{o}C. For comparison, the air temperature in the plenum when using Strategy 1 (first line of Table 34) was between 18 and 19 ^{o}C.

Compared with Strategy 1, the use of a constant temperature of 25 ^{o}C allowed an increase of around 1 m in bed depth for the same level of risk of OA, <5% between 22 and 20% initial m.c., up to the depth limit imposed by the fan. Given that stirring alone gave an increase (Table 34) of 0.8 to 2 m, the combination of both stirring and higher temperature allowed an increase in maximum depth of between 1.7 m on an original depth of 1.2 m at 22 % initial m.c. and an increase of 2.5 m on 2.3 m at 20%. Table 36 also shows that the drying time was reduced to 50% or less by the use of elevated temperature and the cost per dried tonne was also lower. The cost for grain at 20% or more was lower when drying in a stirred bed with constant 25 ^{o}C than in an unstirred bed using Strategy 1. Below 20% it became cheaper to use an unstirred bed and Strategy 1.

Conclusions

1. Simulations confirmed the expected benefit of grain stirring in reducing the risk of OA production. By incorporating the upper layers of the bed, which in an unstirred bed would remain at the initial m.c., into the mass and thereby drying them more quickly, stirring greatly reduced OA risk for a given bed depth, and so allowed greater depths to be used for the same level of risk.
2. Strategy 1 was very again effective when used with grain bed stirring, allowing an additional 2 m depth at 20% initial m.c. in one location. However drying time and the costs of drying were generally increased because reduced saturation of the exhaust air meant more air was needed. Compared with its use on a static bed, Strategy 2D combined with stirring gave a useful increase in maximum depth and reduced drying cost at 20% initial m.c. and below.
3. Drying with a constant, raised air temperature of 25 ^{o}C was highly effective, allowing considerably deeper beds and more rapid drying. At initial m.c. values of 20% and above, costs were also lower.

Table 33. Results of two trials of wheat drying with stirring from the literature, comparing reported and simulated values.

Parameter	McLean		Kneeshaw & Cragg	
	Reported	Simulated	Reported	Simulated
Drying time, h	73	84	102	94
Duct static pressure, Pa	1504	2235	1200	(adjusted to agree)
Final moisture range, % w.b.	4.6	5.8	(not reported)	2.6
Fan energy, MJ	2904	2929	10820 (includes stirring system)	5640 (fan only)
Heater energy, MJ	19379	20503	45240	27900

Table 34. Performance of drying without and with stirring. Strategy 1 at Waddington starting drying 15 Aug. 80% r.h. set point, 80 kW propane heater. (Runs 50b, 306, 303)

Drying treatment	Depth, m, at which 20 years were successful out of 20						Cost, £/dried t, not including energy used by stirrers				
Initial m.c., %w.b.	**18**	**19**	**20**	**21**	**22**		**18**	**19**	**20**	**21**	**22**
No stirring	>4.8	3.2	2.3	1.6	1.2		3.37	3.46	3.72	3.93	4.34
Stirring at same depth	>4.8	3.2	2.3	1.6	1.2		2.54	3.64	4.56	5.27	5.84
Stirring at same OA risk, <5%	>4.8	>4.8	4.3	2.9	2.0		2.54	3.39	4.21	5.15	5.91
	Drying time, h						**Bed maximum spoilage index**				
No stirring	399	271	207	159	131		0.99	0.99	1.00	0.94	0.95
Stirring at same depth	309	291	262	212	181		0.47	0.55	0.62	0.62	0.63
Stirring at same OA risk, <5%	309	409	443	365	297		0.47	0.47	0.99	1.00	0.98

Table 35. Performance with and without stirring of Strategy 2D at Waddington starting drying on 15 Aug. Grain moisture content for control was the wettest m.c. of whole bed. (Runs 172 and 304)

Drying treatment	Depth, m, at which 20 years were successful out of 20						Cost, £/dried t, not including energy used by stirrers						Drying time, h		
Initial m.c., %w.b.	**18**	**19**	**20**	**21**	**22**		**18**	**19**	**20**	**21**	**22**		**18**	**19**	**20**
No stirring	2.2	1.2	0.6	0.4	<0.4		1.80	1.76	1.77	2.26	n/a		373	240	153
Stirring	2.9	1.9	0.9	0.5	<0.4		1.35	1.69	1.76	2.06	n/a		444	379	220

Table 36. Performance of drying with Strategy 1 and with air heated to 25 °C, both with stirring, at Waddington starting drying on 15 Aug. Strategy 1: 80% r.h. set point, 80 kW propane heater. Constant temp: 250 kW propane heater. (Runs 303 and 305)

Drying treatment	Depth, m, at which 20 years were successful out of 20						Cost, £/dried t, not including energy used by stirrers						Drying time, h		
Initial m.c., %w.b.	**18**	**19**	**20**	**21**	**22**		**18**	**19**	**20**	**21**	**22**		**18**	**19**	**20**
Strategy 1	>4.8	>4.8	4.3	2.9	2.0		2.54	3.39	4.21	5.15	5.91		309	409	443
Air at constant temperature, 25 °C	>4.8	>4.8	>4.8	3.9	2.9		2.24	2.98	3.72	4.58	5.59		116	155	192

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APPENDIX A

CHECKS AND MODIFICATIONS TO SIMULATION CODE

The main items are briefly described.

1. Running the program using a batch approach so several input files can be run in succession.
2. Processing weather files into the format needed for Storedry to read.
3. Identifying missing values in weather data and repairing.
4. Conversion of simulated heating from electric to propane, which adds water of combustion to the drying air.
5. Investigating aspects of the calculation of air conditions before and after fan and heater are calculated. Recalculating the efficiency of conversion of fan power to air temperature rise.
6. Investigating how shrinkage is modelled and modifying the code for shrinkage and wet density equations.
7. Checking problem with natural convection calculations.
8. Developing a condensed output, one line for each year of simulation, that can be read easily into MS Excel, and advanced filtering can be used for results specific to specific success criteria.
9. Effect of leaving fan on versus stopping it if the target r.h. can't be reached
10. Developing an Macro in MS Excel to speed up processing of large files from a group of simulations.
11. Investigation of equilibrium equations, fitting of Henderson's data to Chung-Pfost form of equation and checking effect of using this. (See Appendix B).
12. Developing the concept of the line on axes of initial m.c. versus maximum depth, that defined a condition of risk <5%.
13. Checking the several versions of STOREDRY and assembling the most appropriate version for this project.
14. Checking which equilibrium equations were operational with which crops.
15. Checking what control policies were available in the code, how they worked, which were suitable for this project, checking if they worked as declared, and implementing certain of them.
16. Modelling the characteristics of the fans based on data from Pellcroft Engineering Ltd., generic fan curves for centrifugal fans for agricultural use, and setting stall limits to air volume flow. Putting three models of fan into the various parts of the code.
17. Reviewing the pressure drop equations for the grain bed and for system of ducts and selecting and checking the most appropriate one. Adding the effect on resistance of non-linear airflow near floor owing to discrete ducts.
18. Checking Kreyger's (1972) data, Fraser and Muir's (1981) extension of it, the equilibrium equation used by Kreyger, and working out whether to use an existing subroutine based on the data or the equation.

19. Development of a new fan and heater control policy with iteration to find the heat power needed to achieve a target r.h.
20. Checking that progress towards spoilage at moisture contents lower than 16% is a suitably low for OA risk to be considered eliminated by that stage.
21. Modifying the cost calculations to calculate correctly for over-drying.

APPENDIX B

EQUILIBRIUM MOISTURE EQUATION

Several equations are present in STOREDRY to describe the equilibrium relationship between air and wheat. The need to convert data provided by Jonsson (private communication) on safe storage time without risk of OA prompted a reconsideration and revision of the equilibrium equation used. The form of the equation selected, presented by Chung and Pfost (1967), has been widely used because its shape follows well that of experimental data.

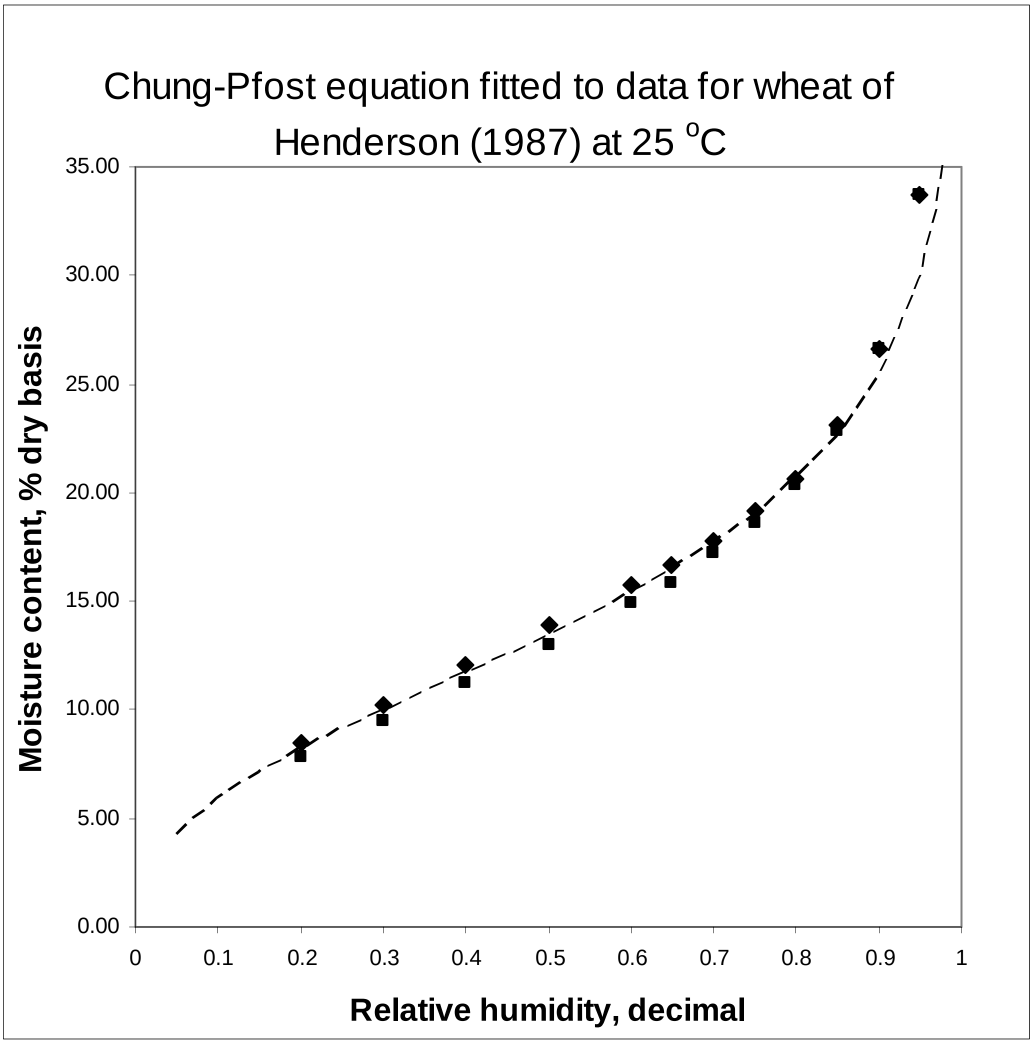
The equation can be written as

$$M=-a.\ln(-R.(T+c).\ln(rh))/b)$$

Where M is moisture content, % dry basis, T is grain temperature, ^{o}C, and rh is relative humidity, decimal. R is the universal gas constant, with value 1.987. The values used for coefficients a, b and c were 6.3, 840 and 47.0 respectively. Natural logarithm is denoted by ln.

High quality data were available from Henderson (1987) but only for one temperature, 25 ^{o}C. Nellist and Dumont (1979) fitted the Chung-Pfost equation to a large body of published data and derived its three coefficients, including the coefficient that describes the effect of temperature. This coefficient was accepted and used at 25 ^{o}C, to achieve the best fit of the other two coefficients to all of Henderson's data, *i.e.* adsorption and desorption. The coefficients were adjusted to achieve the best fit over the range of interest in UK drying, with an emphasis on the range 13-17% wet basis. The data and fitted curve are shown in Figure B1. Various checks were then done to ensure the equation predicted values satisfactorily and that these were close to values from equilibrium equations published by other workers. Specifically, the effect of the under-prediction of the chosen equation at moistures above 25% wet basis was investigated. Results, in terms of maximum depths, were found to be unchanged from those predicted when other equilibrium equations were used that fitted better at this upper region (but less well elsewhere).

Figure B1. Chung-Pfost equilibrium moisture curve, with coefficients fitted to data of Henderson (1987) at 25 ^{o}C. Squares – adsorption, diamonds – desorption.



APPENDIX C

WEATHER DATA ANALYSIS

The weather data used in this work is from five sites in England, all sites of airports or airfields:

Waddington:- RAF Waddington, Lincs
Ringway:- now Manchester International Airport
Heathrow:- Heathrow International Airport, Middlesex
Elmdon:- close to Birmingam International Airport, West Midlands
Plymouth:- Plymouth City Airport, Devon

The data includes dry bulb temperature, relative humidity and atmospheric pressure, the three values used in this study. Data are available as hourly values at each location, though in the case of barometric pressure data were only recorded every 3 hours so hourly values were obtained by linear interpolation. The suitability of the weather for drying depends on its “saturation deficit”, *i.e.* how much capacity the ambient air has for absorbing moisture by an adiabatic process such as drying before it becomes saturated. (An adiabatic process, of which grain drying is an example, is one in which the air must supply the energy in order to evaporate water, so that the air cools as it gains humidity.) Accurate calculation can be done only when the grain moisture content is brought into the calculation because complete saturation will not occur when air passes through partly dried grain, but the saturation deficit is nonetheless a useful way of combining temperature humidity and pressure into one measure that is pertinent to drying. It is expressed in terms of mass of water per unit mass of dry air, in this case in g/kg.

Higher temperature of air would lead to higher grain bed temperature once drying was underway, and so spoilage would be more rapid. For this reason, a warmer location would not necessarily be better, nor a cooler one worse, for drying.

Objectives

For each location, the data were analysed by calculating average values over nine, one-week periods, starting on 15th August in each of 20 years. The objectives were (a) by comparing locations, to understand why differences in drying performance arose, (b) to examine how the conditions differed between the first period used for simulating drying, starting 15th August, and the second period, starting 15th September, and (c) to enable the operator of a dryer in any location to apply the results of the study to that location.

Figure C1. Dry bulb temperature of ambient air, averaged for nine, one-week periods, starting 15th August in each of 20 years from 1951 to 1970, for each of five locations.

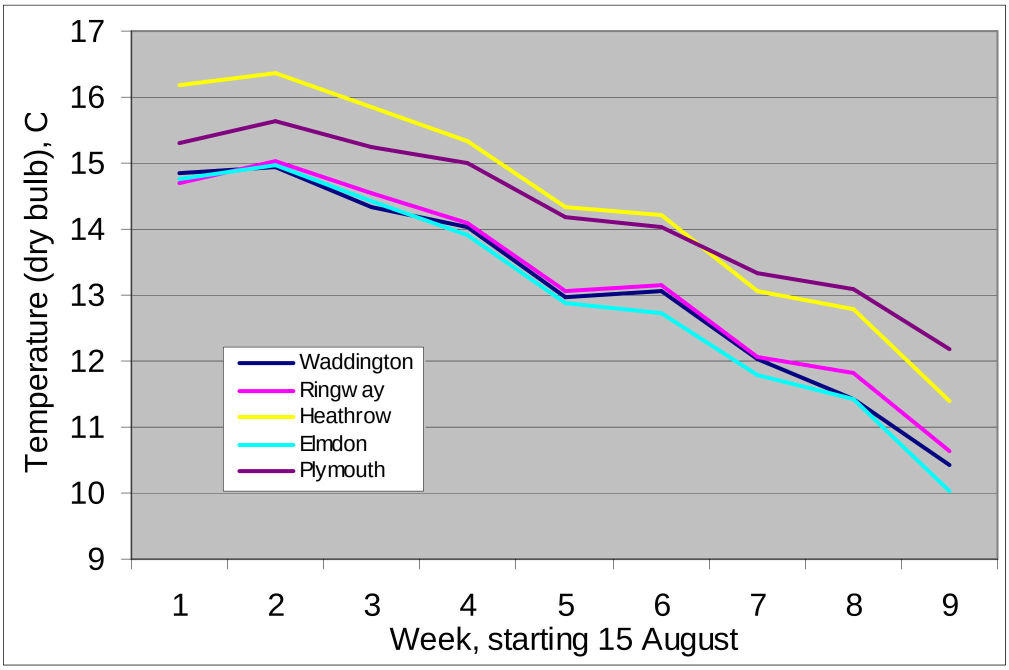


Figure C1 shows the general decline in temperature as the drying season progresses. Heathrow was warmest in August and September. Plymouth, though less warm than Heathrow in August, declined less quickly and so was warmest in October. The other locations had very similar records.

Figure C2. Relative humidity of ambient air, averaged for nine, one-week periods, starting 15th August in each of 20 years from 1951 to 1970, for each of five locations.

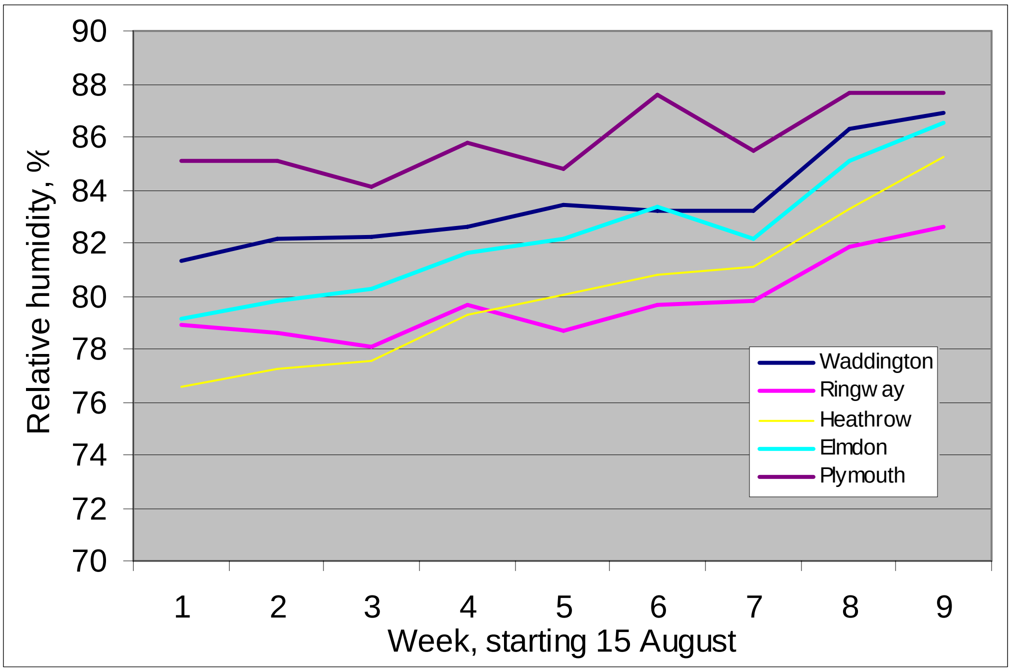


Figure C2 shows that relative humidity rose steadily at all locations over the nine week period, was consistently highest at Plymouth and next highest at Waddington. In August it was lowest at Heathrow but in September and October, Ringway was lowest.

Figure C3. Saturation deficit of ambient air, averaged for nine, one-week periods, starting 15th August in each of 20 years from 1951 to 1970, for each of five locations.

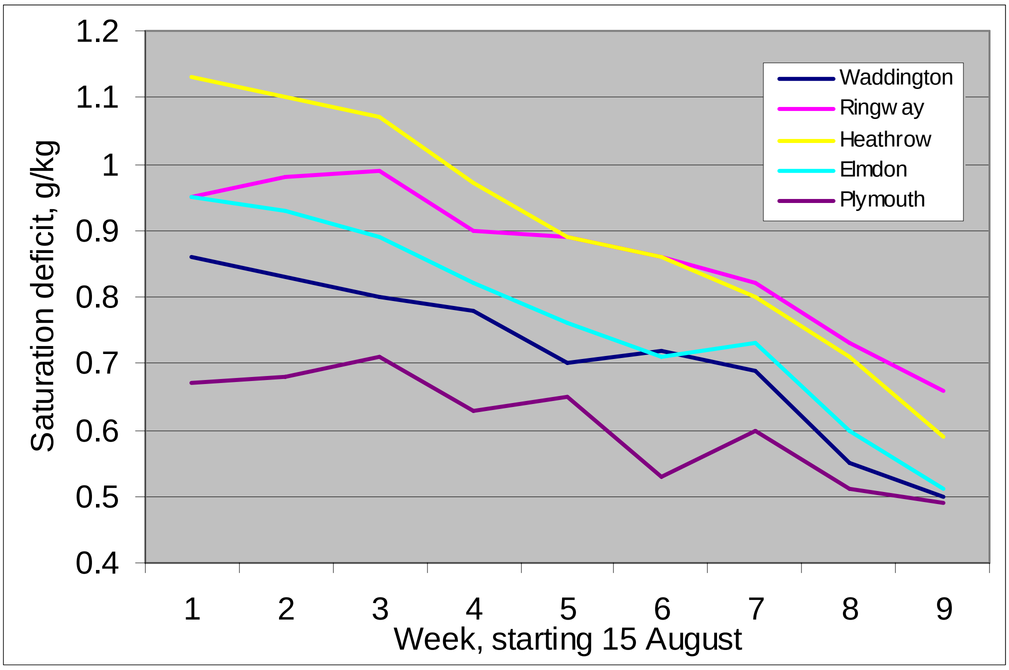


Figure C3 shows that the differences in saturation deficit between locations were more marked than the differences in relative humidity of Figure C2. The saturation deficit decreased over the 9 week period, steadily for three locations but after rising until early September at Ringway and Plymouth. The deficit was, throughout, lowest at Plymouth and second lowest at Waddington. Heathrow was highest in August and the first half of September but thereafter Ringway had the highest deficit.

Effectiveness of Strategy 2in relation to weather

Because Strategy 2 is effectively "filtered weather" with no additional heating, it should be possible to explain the variation in performance of this strategy with location by analysing the weather records. Figures 8 and 9 show the grain depth for 20 years out of 20 with no spoilage at each of five locations, using data from Table 21. By comparing Figures 8 and 9 with the analysed weather r.h. data (Figure C2), it is clear that for a 15 September start, the ranking of the r.h. values of the weather records aligned with the ranking of the maximum depths as produced by Strategy 2. The situation was similar for the saturation deficit values, shown in Figure C3. For a 15 August start, the ranking of the weather r.h. and saturation deficit values were again predictors of ranking of maximum depth, with one exception. Grain depths for Heathrow were lower than at Ringway, though the r.h. and saturation deficit values suggested they would be higher. The likely explanation is that, as shown in Figure C1, the average temperature at Heathrow was more than a degree Celsius higher than at Ringway, which would lead to higher grain temperature and hence accelerated rate of spoilage. This would necessitate a lower maximum bed depth to achieve drying before the top layers of the bed spoiled. The maximum depth to avoid spoilage at Heathrow with an August 15th start was therefore lower than at the cooler but slightly more humid Ringway location. For a 15th September start, temperature difference between Heathrow and Ringway was less but humidity at Heathrow had risen above that at Ringway. Hence Ringway was still a more favourable site than Heathrow but more for usual reasons of lower humidity air having good drying potential than because of accelerated spoilage. Validation of this explanation would require work beyond the scope of this study.

At present, no simple way has been formulated of meeting objective c) above *i.e.* of generalising the results to any region of the UK.

APPENDIX D
ANALYSIS AND SIMULATION OF GRAIN STIRRING TRIALS

D.1. Test reported by McLean (1993)

In a paper by K A McLean (1993), test results are given for a circular bin fitted with a stirring system, and used to dry a batch of 86 tonnes of wheat using air temperature controlled to a constant 38 ^{o}C. Air was heated by a propane gas burner. Drying starting on 24 August 1991 in a location in Herts, finishing after 73 h.
Bin was 5.49 m diameter, 5.49 m high, and of nominal 100 t capacity. A 7.5 kW centrifugal fan was used. Clearance between the ends of the two stirring augers and the perforated drying floor was 40 mm. The wheat was pre-cleaned and had an average m.c. before drying of 18.6% w.b.
After drying the moisture content range was 11.1-15.7% w.b., average 14.4% w.b. (16.8% d.b.) Specific weight was 79.85 kg/hl at final m.c. Calculated dried weight of the batch was 86.4 t at final m.c.
Ventilation rate is given as 0.049 m^3/s.tonne and static pressure in plenum was 1504 Pa.
Mean drying air temperature and relative humidity were 38.1 ^{o}C and 22.7 %. Mean ambient air temperature and relative humidity were 17.2 ^{o}C and 78.1 %.

Grain bed volume was 108.2 m^3, area of bed was 23.67 m^2 so bed depth was 4.57m.

In the test, ambient conditions varied but no details are given so the constant ambient conditions were used. A heater of nominal 150 kW was used in the simulation, adequate to maintain the mean air temperature.

Results of simulation

At the specified airflow of 0.049 m^3/s/t, assumed to refer to per tonne at final m.c., (0.057 m^3/s/t dry matter), the simulated drying time was 58 h, significantly shorted than the 73h reported. One common reason for differences is airflow, because it is both a very influential parameter in the drying and also it is difficult to measure accurately. Given other similar fan curves, it seemed doubtful whether a fan with an electrical power of 7.5 kW could deliver the airflow quoted, 0.049 m^3/s.tonne. No mention is made in the paper of how the airflow was measured, so it may be that it was calculated, probably using the measured static pressure and the fan curve. The fan curve would be for STP, *i.e.* 15 ^{o}C. The heater was reported to have been situated before the fan, so the fan was pumping air at temperature 35.5 ^{o}C, (*i.e.* 38.1 ^{o}C less fan temp rise of 2.6 ^{o}C). Air density at 35.5 ^{o}C is 1.13 kg/m^3, while at 15 ^{o}C it is 1.20 kg/m^3 so the mass flow pumped would be lower by 6%. It may be that this was allowed for but it was not adequate to explain the difference in drying time.

The performance of a range of similar centrifugal fans for agricultural drying was considered. A "Typhoon TC1" fan (Pellcroft Engineering Ltd.) has a 5.5 kW rating and will deliver approx 2.0 m^3/s at 1500 Pa, obtained by projecting the quoted curve. The TC2 fan has a rating of 11.25 kW and delivers 4.1 m^3/s at 1500 Pa. Both therefore give 0.36 m^3/s.kW. The fan in the test, at 7.5 kW, was intermediate between these two so it should have delivered 2.73 m^3/s into the bed of 86.4 t, *i.e.* 0.032 m^3/s.tonne. This is considerably less than the quoted 0.049 m^3/s.tonne. In the terms used by the simulation, the specific airflow rate calculated by this interpolation was 0.037 m^3/s.tonne dry matter.

The airflow required to achieve the temperature rise and energy use reported in the test was then considered. From the psychrometric chart, enthalpy of ambient air is 41.5 kJ/kg, the enthalpy of the heated air is 63.5 kJ/kg so added enthalpy, all in form of heat, was 22 kJ/kg. The run was 73 h or 262800 s and energy content of propane used was 19379 MJ so the average heat power was 73.7 kW. Hence the air mass used was 880900 kg. At specific volume of 0.83 m^3/kg (from psychrometric chart at ambient condition), air volume was 731100 m^3. So the air volume flow rate was 2.78 m^3/s which, through a mass of 86.4 tonnes, gave 0.033 m^3/s.t dried. Through 73.96 tonnes dry matter, this air volume flow was 0.0376 m^3/s/tdm.

These two calculated values of specific airflow were very close to each other and were significantly lower than the reported figure. Supported by this, simulation was re-run using 0.037 m^3/s/t d.m.

Drying time was 84 h. This is longer than the reported time of 73 h.

Given the uncertainty over the airflow, simulation was re-run to find the airflow at which the drying time was equalled. This was found to be 0.044 m^3/s/t d.m, or 0.0377 m^3/s/t dried, 14.2 % higher than the initial value used. Accepting that this estimate of airflow is the best that could be made, the performance at the airflow of 0.0377 m^3/s/t dried was compared with the reported results in other respects than the drying time.

Simulated fan energy and heater energy were 33.9 and 237.3 MJ/dried tonne respectively. Over 86.4 dried tonnes this equates to fan and heater energy of 2929 and 20503 MJ respectively. Energy recorded on test for fan and heater was 2904 and 19379 MJ respectively. Hence the simulated energy values for fan and heater were 0.9% and 5.8% high respectively.

Airflow may also be compared indirectly by comparing fan power. Measured fan power was 11.05 kW against a simulated fan power at the corrected airflow of 10.77 kW, lower by only 2.5%. As the fan power was measured directly during the test, this close agreement suggests that adjusting the airflow to 0.0377 m^3/s/t dried in the simulation to achieve the correct drying time, rather than using the quoted but unsupported figure of 0.049 m^3/s/t dried, was justified.

Mean r.h. of drying air was reported as 22.7% where simulation gave 24.5%.

Static pressure over grain bed and drying floor is given as 1504 Pa. The pressure given by the simulation was 2235 Pa, much higher. It is noted that, if an alternative equation, due to Spencer, for resistance to airflow of the grain bed was used, pressure across the grain bed and drying floor given by the simulation was 1863 Pa, which is much closer.

Moisture difference within the grain bed is reported as 11.1 - 15.7% w.b. The simulation gives 9.8 - 15.6% w.b. The maximum m.c. values agree well but the values of minimum m.c. differ by 1.3 percentage points. It is noted that grain next to the air inlet was dries in the simulation, as would be expected. This is stirred into the bed but in the test, the bottom 40 mm is not positively stirred into the bed. This would increase the minimum m.c. measured.

D.2. Test reported by Kneeshaw and Cragg (1997)

A paper by Kneeshaw and Cragg (1997) reports details of two trials with a notional air temperature of 25 ^{o}C, of which trial 1 is appropriate for simulation. In trial 2 filling of the drier continued during the first period of drying so it is very difficult to model. However there are several aspects in which the data is less than ideal. Insufficient details are available of what area was being ventilated or what the airflow was. In Trial 1 a mean m.c. for the incoming grain is given but the m.c. varied widely (13.8-20% w.b.). There is a break in ventilation of 2h but this is not a serious problem as the total drying time is given. Few details are given of ambient conditions of r.h. and temperature – only half a day is shown – and it's not clear whether the ventilation was continuous or whether the target air temperature was achieved. There were problems with the gas-fired heater but the point during drying when these were overcome is not given. It is clear from the paper and the FEC report from the same site (Anon, 1997a) that airflow was not measured though static pressure in the ducts was measured.

Initial and final m.c. of wheat given as 17.2 % and 14.1 % w.b. respectively. Floor width given as 9m, length given as 8.22m, so area ventilated was 74 m^2. Mass of grain given as 170 t (probably wet weight because it would be weighed coming into store). Depth not given so it must be estimated. In test 2 the depth is given as 3.65m, so in test 1 it was probably similar, particularly if the same equipment and stirrers were used. Assuming 3.65 m depth over entire area being ventilated, grain bed volume was 270 m^3. This gives density of grain as 0.630 t/m^3. This is very low but the grain in the bed is being stirred, this density is possible.

From Figure 1 of the paper by Kneeshaw and Cragg, it's not clear if the system was run for 24h/day. The total drying time is given as 100.2 h, *i.e.* 4 d, whereas the records show Test 1 results over 8 d. This suggests only about 12 h running per day, and this agrees with their Figure 1, where heating is shown as being switched on at 13:00 and off at 24:00. The moisture content results in their Figure 1 show no reduction between day 3 and day 5, and again between day 6 and day 7 but no explanation is given as to whether drying was interrupted, ineffective, or some other cause. Moisture was reduced only between days 1-2, 2-3, 5-6 and 7-8. However, as simulation was done using constant ambient conditions, the elapsed time should be comparable.

A fan from the "Typhoon" range by Pellcroft Engineering Ltd was used. Power is given as 30 kW, so from the manufacturer's literature, it is likely to be the model TC5. However the fan is specified as delivering 17.9 m^3/s at 75mm wg. This is mid-way between the TC6 and TC5. So at 1200 Pa, the likely flow, similarly mid-way, is about 15 m^3/s from this fan, but I shall assume the TC5 characteristics apply.

Duct pressure given as 1200 Pa. Some of this is generated by the drive-on floor, some by the duct system and the rest by the grain bed. The pressure of 1200 Pa suggests a flow of 13.4 m^3/s from the fan curve for TC5.

Specific airflow rate is given as 0.079 $m^3/s.t$, which equates to 0.0954 $m^3/s.t$ dry matter. This may well be a notional figure calculated from the airflow from the fan curve. At this specific flow through 170 t, the flow delivered by fan was 13.4 m^3/s. This agrees with the estimated airflow given as 13.5 m^3/s, but it is likely that the 13.5 was the starting point, and 0.079 was calculated.

For 13.4 m^3/s over a ventilated area of 74 m^2, velocity was 0.18 m/s, which is relatively high, as expected from the 0.079 $m^3/s.t$ figure, but reasonable. (A commonly used value for design of near ambient driers is 0.05 $m^3/s.t$ which gives an air velocity of about 0.1 m/s with a 3 m bed depth.)

One can assume that, of the static pressure in the duct given as 1200 Pa, the floor itself required 200 Pa and the grain bed 1000 Pa. A pressure drop of 1000 Pa for a velocity of 0.18 m/s in a bed 3.65 m deep requires a resistance per meter depth of 275 Pa/m, which is a very low resistance, and does raise a question about the accuracy of the airflow estimate.

Constant ambient temperature and r.h. conditions of 16 ^oC and 75% and pressure of 101 kPa were assumed.

The drier may not have been run at constant drying air temperature. This was the aim but the description of the initial problems with the burner suggests the heater power limited the temperature rise. This is supported by the energy data of their Figure 2, which shows a lot more energy used for the final three days. The reason for this is not given but it could be variation in the ambient temperature, or the problem of burner output, which was apparently limited to 100 kW initially and uprated to 263 kW at some unspecified point in the test. This problem meant that the target temp of 25 ^oC was not achievable throughout. The temperature record in Figure 1 of the paper for day 3 of the test shows duct temp of 25 ^{o}C in the afternoon but ambient would have been higher then it is not certain that the burner output was fully operational by then. On day 4 the energy use was low so the weather may well be the reason. The effect of this would be to change the fuel use, and the simulation will not be able to match it because the weather records are not available. Full heater power will be assumed to check if air temperature of 25 ^{o}C is reached.

No details of the stirring system, e.g. speed or number of augers, clearance between auger ends and drying floor.

Results

A simulation was run using a 100 kW heater, *i.e.* the 'worst case' assumption that the burner was not uprated until after test 1 and a specific airflow rate of 0.079 m^3/s.t. Temperature was maintained at 24.4 C in the simulation, less than 1 C below target so 100 kW heater is almost enough for the average temp, but would not have been enough at night. Simulation gave a drying time of 60 h to reach the target average m.c. of 14.1% w.b.

This drying time was far less than the reported time of 100.2 h, suggesting there was a major difference between the test situation and the situation simulated. Some information is available from the results for trial 2 in the paper. One possibility was depth. Depth is also vital for accurate simulation. It given as 3.65 m for trial 2 but not given for trial 1. The floor area for trial 2 is given as 219.6 m^2 so the volume of grain was 801.5 m^3 giving a density of 717 kg/m^3. Assuming the same density applied to trial 1, 170 t over 74 m^2 must have been 3.2 m deep, less than the values used in the initial simulation. Using the modified depth, the bulk density of dry matter was recalculated as 598 kg dry matter/ m^3. These values were used for a second simulation run. The drying time increased but only to 62 h, so the airflow values must be examined critically.

In trial 2 the moisture reduction graph shows steady progress for the 8 days of the test, during which 3.1 % points of moisture were lost, the same as lost in trial 1. The estimated air volume for trial 2 is the same as for test 1, *i.e*. 13.5 m^3/s. The grain mass dried in trial 2, given as 575 t, was dried in 187 h, *i.e.* 7.8 d. The drying in trial 2 must have been continuous based on the dates shown in Figure 4 of the paper. So in trial 2, 3.4 times the mass of grain was dried in only 1.87 times the time, apparently with the same total airflow. This suggests the airflow estimated in the paper for trial 1 may have been too high, and it is possible that some of the air being delivered by the fan was being directed elsewhere in the drier.

In test 2, airflow was estimated at 0.026 m^3/s.t. It is noted that airflows were in the same proportions as the ventilated floor areas, *i.e.* the ratio of 0.026 to 0.079 m^3/s.t was same ratio as 219.6 to 74 m^2. If the grain bed were the same depth, the It may be that the airflow notionally delivered by the fan, 13.5 m^3/s, was simply used in both cases.

A duct pressure of 630 Pa was reported for trial 2, far lower than the 1200 Pa reported for trial 1. Using the equation for pressure vs flow employed in STOREDRY simulation, the air velocity required to generate this static pressure was 0.0655 m/s. From values in trial 2 of 0.026 m^3/s.t., 219.6 m^2 and 575 t, air velocity through the grain bed in trial 2 equates to 0.068 m/s, in reasonable agreement with the value from the equation, so it is also an approach to improve the estimate of airflow for trial 1. The same equation gave an air velocity of 0.108 m/s to generate a pressure of 1200 Pa, as reported in trial 1. Over 74 m^2 and 170 t, it equates to 0.047 m^3/s.t. In terms used by the simulation, it equates to 0.059 m^3/s.t dry matter.

A third simulation run, carried out using these values, gave a drying time of 94h. This was in reasonable agreement with the reported drying time of 102 h, being only 7.8% lower.

Electrical energy consumption was reported as 3006 kWh, 10820 MJ for fan and stirring system combined. Gas energy was 12567 kWh, 45240 MJ. Simulation gave fan and heater energy use as 34.4 and 170.0 MJ/t at final m.c. Final dried weight was 164 t so simulated energy use was 5642 and 27880 MJ. These are much lower than reported. The reason for this difference must in part lie in the observation that during some days of the trial, energy was used but no drying was achieved, though this is not analysed in the published paper.

In conclusion, the reported data have some inconsistencies and missing measurements that require estimates to be made based on the data from both tests. Using such estimates, particularly of the depth and the airflow achieved during the test, simulated drying was faster than that measured by 8%.

APPENDIX E
EXPLORATORY WORK

E1. Condensation calculations

In Chapter 2 of the report where the effectiveness of Strategy 1 is examined and in Chapter 3, where the effect of altering Strategy 3 is explored, the improvements predicted by the simulation are dependent on heating the drying air. The use of heating when wheat is wetter than 20-22% and the use of too high a rise in temperature, have both has been cautioned against, e.g. ADAS (1983). This is because the former accelerates spoilage of undried grain ahead of the drying front, and the latter carries the additional risk of causing condensation at or near the surface. High humidity air in the bed cools by contact with cooler grain and water may condense. Grain at the bed surface may be cooled by heat loss by radiation at night to the cold surfaces of the roof.

To ensure that the calculations of the model reflected reality as closely as possible, a new routine to calculate radiation heat loss was added, and various aspects of the simulation model that come into play close to saturation conditions were checked carefully.

The radiation heat loss was based on the temperatures of the uppermost layer of grain, the ambient temperature (assuming the roof followed ambient temperature changes) and using an emissivity of 1.0 for grain. Switching in this routine was found to have an effect of less than 0.1 ^{o}C on the temperature of the uppermost grain layer. Even when the effect was multiplied by a factor of 10 there was no change in the predicted maximum depth. Cooling of the grain by radiation loss also had the effect of slowing the rate of spoilage.

The simulation did not include any calculations of the fate of the air after it had left the bed and entered the airspace above the grain. Poor ventilation of that space would be likely to result in condensation on cold parts of the structure. This would be particularly the case for a stirred bed using an elevated temperature, when very high levels of exhaust air humidity would be encountered.

A parameter in the simulation limits the exhaust r.h. from any grain layer. This is designed to prevent numerical problems when equations are used which predict values of m.c. tending to infinity as r.h. approaches 100%. This parameter is usually set at 98%, but exploratory runs with values of 99 ad 99.5% were done to check whether it was artificially limiting conditions that would otherwise lead to condensation. No additional condensation was found, so the r.h. limit was left at 98%.

In conclusion, no aspect of the drying calculations could be found that cast any doubt on the results from the simulation when using heat.

E.2. Control strategies.

In initial work, Strategy 1 and simpler versions of Strategies 2 and 3 above were used to explore the effects of the following. Results were used to select equipment and actions for the main study.

- using moisture sampled from 0.3m depth instead of an average bed moisture
- the decision, if the target rh could not be reached with full heater power, whether the fan should be turned off or allowed to continue to run
- effect of using a higher power of heater, noting from literature that propane heaters were often more powerful than electric ones.
- Effect of using more steps of heat power or fewer coarser ones.

E.3. Exploratory simulations with a variable heating control strategy.

Table E.3.1. Policy 19. Effect of initial moisture content on maximum bed depth for 20 successful years out of 20, and cost, £/dried tonne, for five locations and two start dates. Moisture content and relative humidity steps: 20, 18, 16, 10% mc with 100, 83, 72, 62% rh, 158kW heater. (Runs 1-10, 16-22)

		Depth, m, at which 20 years were successful out of 20						Cost, £/dried t				
		Initial moisture content, % wet basis						Initial moisture content, % wet basis				
Location	**Start date**	**18**	**19**	**20**	**21**	**22**		**18**	**19**	**20**	**21**	**22**
Waddington	**15-Aug**	4.5	2.2	1.6	0.7	0.6		3.37	3.52	3.5	3.28	3.40
	15-Sep	4.5	2.7	1.9	0.6	0.3		3.66	4.68	4.35	3.95	3.38
Ringway	**15-Aug**	4.8	3.1	2.2	1.4	1.0		3.03	3.31	3.24	3.32	3.26
	15-Sep	4.8	3.5	2.5	1.5	1.0		3.04	3.81	3.6	3.27	3.3
Heathrow	**15-Aug**	4.8	2.9	2.1	1.4	1.1		3.04	2.72	2.84	2.89	2.93
	15-Sep	4.8	2.8	1.9	1.2	0.9		3.25	3.61	3.41	3.36	3.25
Elmdon	**15-Aug**	4.8	2.9	2.0	1.2	0.9		3.25	3.25	3.24	3.22	3.25
	15-Sep	4.8	3.0	1.9	1.1	0.7		3.58	4.63	4.17	4.01	3.77
Plymouth	**15-Aug**	4.1	2.1	1.5	0.8	0.6		3.50	4.58	4.56	3.91	3.76
	15-Sep	4.8	1.5	1.0	0.6	0.4		3.99	4.73	4.66	4.19	3.77