

**Project Report No. 454**

**August 2009**

**Price: £6.00**



## **BulkDryRape – Interactive computer-based tool for oilseed rape drying**

by

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This is the final report of a fourteen-month project, which started on 1<sup>st</sup> January 2008. The work was funded by a contract for £44,514 from HGCA (Project 3432).

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## Abstract

Full scale tests were undertaken in the grain store at the Food and Environment Research Agency to provide data for validation of BulkDryRape, an interactive computer-based tool for oilseed rape drying. This data was compared with a more flexible simulation using the same mathematical calculations as BulkDryRape.

Bins 3 to 6 were each loaded with approximately 15 t of oilseed rape (OSR). Each bin was fitted with a 5.5 kW fan, which was used to dry the OSR at an average flow of 112 m<sup>3</sup>/h/t. Bins 5 and 6 had average initial moisture contents of 12.9% and 13.3% respectively and were dried successfully using continuous ventilation over 21 days. Bins 3 and 4 had average initial moisture contents of 12.0% and 11.7% respectively and were dried intermittently over 37 days so that mould was visible before drying was complete. Samples were taken at least twice weekly for assessment of moisture content, the presence of mites and moulds.

Mould was visible by microscope in all samples taken 31 days after harvest from the surface and at depth 0.5 m from bins 3 and 4. No mould was visible in the previous sample set taken two days earlier. No mould was observed in any of the samples from bins 5 and 6 and no mites were observed in any of the samples from any of the bins. The time taken for the appearance of visible mould was in line with results from the literature based on small scale tests on OSR.

Table 1 shows the storage and field mould counts for samples taken immediately after loading the bins and after the drying front had reached the surface of the OSR.

**Table 1. Storage and field moulds present at the start and end of drying**

| Bin | Time taken for drying front to reach the surface (days) | Field moulds and yeasts present at the start (log <sub>10</sub> cfu/g) | Field moulds and yeasts present at the end (log <sub>10</sub> cfu/g) | Storage moulds present at the start (log <sub>10</sub> cfu/g) | Storage moulds present at the end (log <sub>10</sub> cfu/g) |
|-----|---|--|--|---|---|
| 3   | 37  | 5.10   | 5.10   | 1.52  | 5.59  |
| 4   | 37  | 4.97   | 4.68   | 2.00  | 5.09  |
| 5   | 21  | 5.51   | 4.89   | 2.85  | 4.66  |
| 6   | 21  | 5.21   | 5.01   | 2.73  | 4.63  |

Overall, the measured drying behaviour and risk of spoilage were well predicted in both continuous and intermittent drying, giving confidence in the BulkDryRape software.

## Summary

The drying of bulk commodities such as wheat and oilseed rape (OSR) is vitally important in order to avoid the risk of mycotoxins, mould and attack by mites. Bulk storage driers can achieve quality results if run well. Decisions on loading and operating the drier need to be made with a good understanding of the basics of drying with ambient air and the effects of the many variables.

“BulkDry” is a software tool designed to enable the user to simulate a drier for wheat and to help the user to understand the factors that influence the drying process. BulkDry was well received at its launch at Cereals 2007.

There are major differences between drying requirements for oilseed rape (OSR) and wheat, such as resistance to airflow and seed cracking if OSR is overdried. This, together with that fact that oilseed rape plantings are increasing due to the expansion of the biofuels market made it timely to modify BulkDry to produce BulkDryRape, which simulates the drying of rapeseed to enable users to improve their decision making for drying of OSR.

A trial was undertaken at the Food and Environment Research Agency (formerly the Central Science Laboratory) to produce a set of good quality drying data to validate BulkDryRape. Validation was done by comparing experimental results with predictions made using Storedry, a more flexible simulation but using the same mathematical model to calculate drying and associated temperature changes, and using the same expressions for resistance to airflow, moisture equilibrium and safe time before risk of visible mould.

Four square, open-top bins of 30 tonne capacity were loaded with 15 t of OSR, cultivar ‘Castille’. Each bin was fitted with a 5.5 kW fan and each fan was connected to two parallel ducts running the length of the bin.

The OSR in Bins 5 and 6 had the higher initial moisture contents of 12.9 and 13.3% and were dried successfully in about 21 days using a continuous flow of air at an average rate of 107 m<sup>3</sup>/hour/t. The OSR in Bins 3 and 4, with the lower initial moisture contents of 12.0 and 11.7%, were dried at an average rate of 117 m<sup>3</sup>/hour/t. The drying of Bins 3 and 4 was carried out intermittently to extend the

drying time so that spoilage would be likely to occur before drying was complete, in order to check the accuracy of spoilage calculations in the model. Drying in this way took about 37 days.

The temperature and relative humidity at the surface of the OSR, in one of the aeration ducts per bin and in ambient air near to the fan inlets, were logged every hour onto a datalogger, as were the temperatures at various positions throughout the OSR.

Each bulk was sampled at least twice weekly and the sampled OSR was sieved to check for mites, examined under a microscope for the presence of visible moulds and analysed by air oven for moisture content. Additional samples were taken before drying began and as the drying front reached the surface. These samples were analysed for storage and field moulds.

Mould was observed in all samples taken 31 days after harvest from the bins that were dried intermittently. The samples were taken from the surface and at a depth of 0.5 m, from 5 positions. No visible mould was observed in the previous sample set, taken two days earlier. No visible mould was observed in any of the samples from bins that had been dried continuously and no mites were observed in any of the samples from any of the bins.

The time taken for the appearance of visible mould was in line with results from the literature based on small scale tests.

Table 1 shows the storage and field mould counts for samples taken immediately after loading the bins and after the drying front had reached the surface of the OSR. It was found that mould was visible when the mould count reached the order of  $10^5$  cfu/g.

**Table 1. Storage and field moulds present at the start and end of drying**

| Bin | Time taken for drying front to reach the surface (days) | Field moulds and yeasts present at the start ( $\log_{10}$ cfu/g) | Field moulds and yeasts present at the end ( $\log_{10}$ cfu/g) | Storage moulds present at the start ( $\log_{10}$ cfu/g) | Storage moulds present at the end ( $\log_{10}$ cfu/g) |
|-----|---|---|---|--|--|
| 3   | 37  | 5.10  | 5.10  | 1.52   | 5.59   |
| 4   | 37  | 4.97  | 4.68  | 2.00   | 5.09   |
| 5   | 21  | 5.51  | 4.89  | 2.85   | 4.66   |
| 6   | 21  | 5.21  | 5.01  | 2.73   | 4.63   |

The data were compared with the output of a simulation program, 'Storedry', which had been adapted to use the same mathematical expressions as 'BulkDryRape' to calculate drying, but allowed more flexibility in the validation. Simulation of continuous drying of Bin 5 and the intermittent drying of Bin 3 accurately predicted the measured time for the bed to dry to the average moisture content. The drying fronts were steeper than measured so the uppermost layers of the simulated beds remained moist for 3 to 4 days longer than measured.

Temperatures of the OSR before and after the drying front passed were predicted accurately and, at the side of Bin 5, the time at which the OSR temperatures rose as the drying front passed was also well predicted. At Bin 5 centre, the front moved faster than predicted, probably because airflow was greater at the bin centre. For Bin 3, temperatures at the centre were better predicted than at the edge. Predicted relative humidity of the exhaust air was lower than measured in Bin 3. Re-absorption of moisture by the surface is a possible cause.

The simulation calculated a spoilage index, which predicted the risk of spoilage in the OSR. Visible mould would be expected where the spoilage index was greater than 1. For Bin 5 the spoilage index was 0.68 after the 17.5 days drying, which suggests the OSR was well within its safe storage life. This agreed with the experiment in which no mould was observed. Bin 3 had mould visible after 31 days. The simulation predicted a spoilage index of 0.95 at that time, and a final index of 1.06, in good agreement with the observation of mould.

Overall, the simulation predicted well the measured drying behaviour in both continuous and intermittent drying, and so it can be confidently used as the basis of the BulkDryRape software.

## Introduction

Bulk storage driers can achieve quality results if run well. Decisions on loading and operating the drier need to be made with a good understanding of the basics of drying with ambient air and the effect of the many variables.

The software tool, "BulkDry" (Bruce *et al.* 2006).enables the user to simulate drying of wheat, simply and quickly, and to understand how the progress of drying is influenced by bed depth, equipment, control actions, weather and the limitations imposed by growth of fungi. BulkDry was well received at its launch at Cereals 2007 and the positive response shows it has potential to allow users to develop their understanding of drying with near-ambient air and improve their decisions on bulk drying. This is expected to help growers produce better and more consistent quality of dried grain, in particular avoiding mycotoxins.

Given that oilseed rape (OSR) plantings are increasing due to the expansion of the biofuels market, it was timely to modify BulkDry to produce a version for OSR, 'BulkDryRape', to simulate the drying of rapeseed and thus enable users to improve their decision making for drying of OSR. However the major differences between drying requirements for OSR and wheat required a major revision of many aspects of BulkDry to covert it for OSR. The most important were resistance to airflow, equilibrium moisture relationship between seed and air and calculation of risk of spoilage by fungi. Safe time before risk of spoilage was calculated from the time taken for mould to become visible on OSR held at constant temperature and moisture conditions (Burrell *et al.* 1980). The output of BulkDryRape includes values of minimum moisture content so that users are alerted to any overdrying, which may, if excessive, result in seed cracking.

Validation was required to give confidence in the predicted drying results. For wheat the output of BulkDry was compared with the well established simulation, Storedry (Sharp, 1984). But there is no accepted 'gold standard' computer simulation of rapeseed drying with which to compare the output of BulkDryRape, so a set of good quality drying data was needed for validation. A search of available literature did not produce any detailed data suitable for validation and so a deep bed drying experiment on rapeseed was necessary. The best set of data for validation of both the physical and the biological aspects of drying was one in which one treatment was dried in such



a way that there would be evidence of spoilage in the top layers, and the other treatment dried without spoilage. An experiment with this objective was undertaken in the grain store of the Food and Environment Research Agency (Fera, formerly the Central Science Laboratory) in the summer of 2008. Storedry was modified to simulate OSR drying using the same expressions as used in BulkDryRape. Experimental data were compared with output of Storedry, which could be set up to simulate the full complexity of the experiment including intermittent drying. Then comparisons were made between Storedry and BulkDryRape to validate the latter.

## **Methods**

### **First treatment.**

On 7 August, 29.2 t of oilseed rape (OSR), harvested over the previous two days, was split evenly between Bins 5 and 6 in the Fera grain store. The variety was Castille and the average initial moisture contents of 12.9 and 13.3% in bins 5 and 6 respectively.

The bins were square open top bins of 30 t capacity, each fitted with a 5.5 kW fan (type MR280, Air Control Industries Ltd), suitable for ambient air drying. Each fan was connected to two parallel ducts running the length of the bin. Drying of the bins began at 19:00 on 7 August 2006.

The temperature of the OSR was monitored using type T thermocouples at four positions over the surface of each bin, at depths of 0.3, 0.6, 0.9, 1.2 and 1.5 m. Relative humidity of the ambient air near to the fan inlets, of the air at the surface of the OSR and in one of the aeration ducts per bin was measured using Honeywell HIH-3610 series humidity sensors. Temperature was also recorded at these positions using type T thermocouples. Static pressure in the ducts of bins 4 and 6 was measured using a Furness type FCO40 differential pressure transducer. Temperature, pressure and humidity data were logged every hour onto a datalogger, which was downloaded with sufficient regularity to ensure that the logger did not over-write data. Unfortunately data from Bins 5 and 6 was not recorded for the first 5 days because the datalogger was not operating correctly.

Samples were taken regularly from two positions at five depths, down to 2m and the sampled OSR was analysed for moisture content using the International Organisation for Standardisation routine reference method for the determination of moisture

content for oilseeds (ISO 665:2000). The samples were sieved for mites and examined under a microscope for the presence of visible moulds.

Air speed was measured regularly for each bin using a 'Casella' meter at five locations on the grain bed surface.

The final set of samples were taken on 26 August when the moisture content at the surface had fallen, indicating that the drying front had passed through the OSR bed. Ventilation continued for a few days after this to insure that the surface was dried to a safe storage level.

Samples from 7 and 26 August were analysed for fungi. For each mould analysis 20 g of OSR was weighed directly into a stomacher bag, 180 ml of 0.1 % peptone water added and the seeds soaked for 30 minutes. Post soaking, the OSR was stomached for 1 minute and the suspension serially diluted to  $10^{-4}$ . For each dilution three plates of DG18 media were labelled, 0.1 ml of the appropriate suspension was plated onto the agar surface and spread using a sterile hockey stick spreader. DG18 plates were incubated at 25°C for 10 days in the dark, after which colonies were identified and counted (counts were expressed as colony forming units (cfu) per gram grain).

### **Second treatment.**

A further 30.9 t of OSR of the same variety was delivered on 27 and 28 August, which had been harvested 26 and 27 August. This was split evenly between Bins 3 and 4 of the store. The average initial moisture contents were 12.0 and 11.7% in Bins 3 and 4 respectively. In the light of the faster than expected drying measured in Bins 5 and 6 and with no visible mould, the fans for the second pair of replicate bins were run intermittently in order to slow down the drying and allow more time before the tops of the bins dried. Running a fan intermittently is a normal part of many drying strategies so it was considered reasonable to use intermittent ventilation in this experiment.

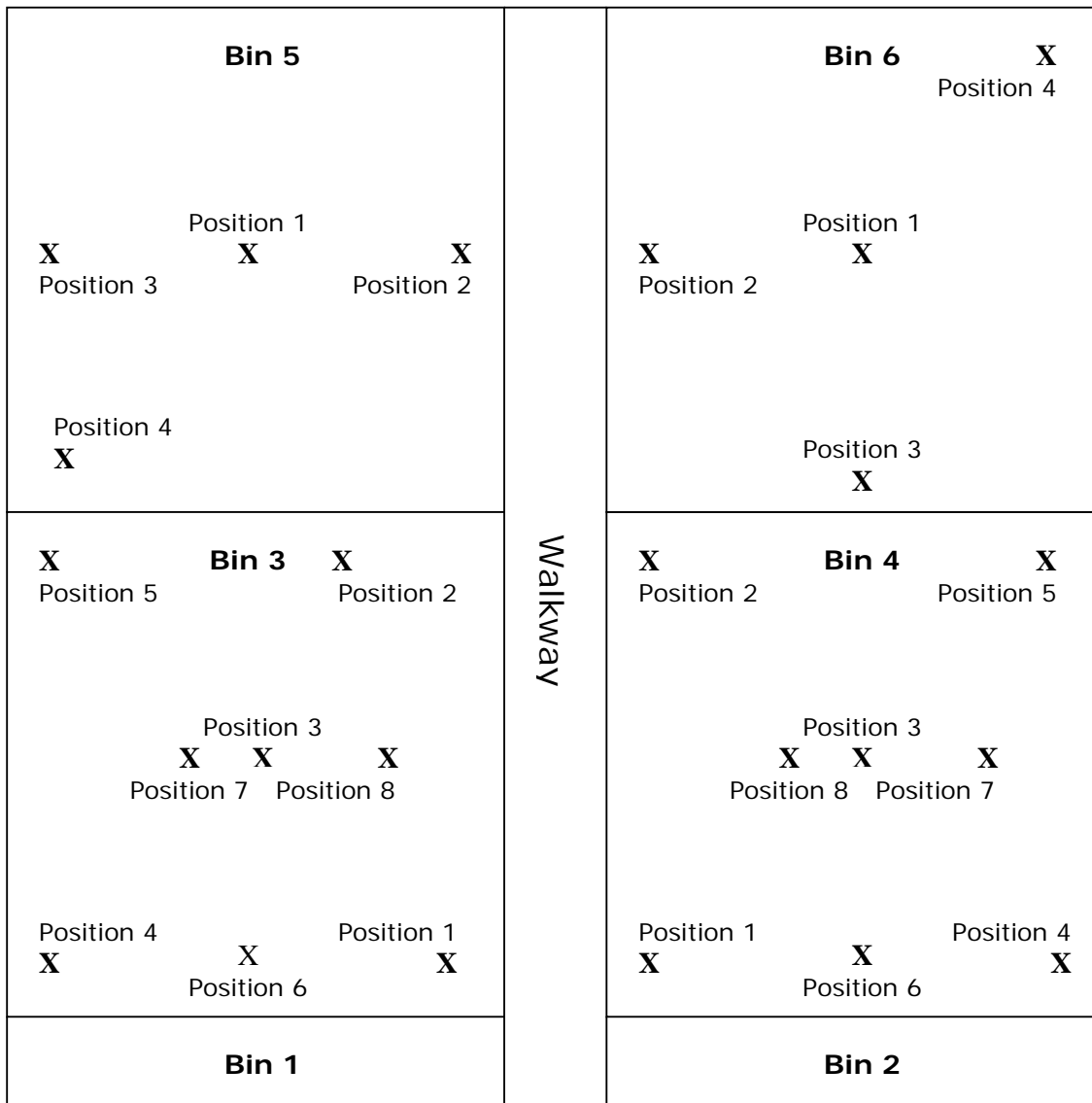
Ventilation began on 29 August and continued intermittently until evidence of spoilage was seen in the samples from the surface and 0.5m, after which continuous ventilation was used.

Temperature and humidity were monitored as before with two extra thermocouple positions at 1.8 and 2.1m at two of the monitoring positions in each bin. Pressure

switches were placed in the ducts to monitor the timing of the fan operation and the static pressure was measured in the duct of Bin 4 as before. The data was recorded using two dataloggers, which logged every half hour.

Samples were taken from various positions in the bulk. Some were analysed for moisture content. Others were sieved for mites and examined under a microscope for the presence of visible moulds as before. Figure 1 shows the sampling and thermocouple positions of the four bins and Table 1 shows which positions were used for thermocouples and which were used for sampling.

**Figure 1. Sampling and thermocouple positions.**



**Table 1. Sampling and thermocouple positions.**

| Bin                    | 3           | 4           | 5       | 6       |
|------------------------|-------------|-------------|---------|---------|
| Thermocouple positions | 2,6,7,8     | 2,6,7,8     | 1,2,3,4 | 1,2,3,4 |
| Sampling positions     | 1,2,3,4,5,6 | 1,2,3,4,5,6 | 1,2,4   | 1,2,4   |

Table 2 shows the timing of the fan operation for Bins 3 and 4 until visible mould had been observed. From 26/09/08 14:15 the fans were run continuously.

**Table 2. Timing of the fan operation for bins 3 and 4.**

| Time the fans were switched on | Drying time (hours) | Total Drying time (hours) |
|--------------------------------|---------------------|---------------------------|
| 29/08/08 15:24                 | 66.3                | 66.3                      |
| 01/09/08 16:07                 | 17.6                | 84.0                      |
| 02/09/08 15:50                 | 17.6                | 101.6                     |
| 03/09/08 15:50                 | 17.1                | 118.7                     |
| 04/09/08 16:12                 | 17.2                | 135.8                     |
| 05/09/08 16:25                 | 64.5                | 200.3                     |
| 09/09/08 16:27                 | 16.8                | 217.0                     |
| 10/09/08 16:03                 | 17.2                | 234.2                     |
| 12/09/08 16:10                 | 0.2                 | 234.4                     |
| 13/09/08 09:45                 | 0.2                 | 234.5                     |
| 15/09/08 12:03                 | 2.8                 | 237.3                     |
| 16/09/08 11:15                 | 3.0                 | 240.3                     |
| 17/09/08 12:30                 | 3.0                 | 243.4                     |
| 18/09/08 10:20                 | 5.7                 | 249.0                     |
| 19/09/08 08:45                 | 6.5                 | 255.6                     |
| 22/09/08 10:09                 | 6.3                 | 261.9                     |
| 23/09/08 09:08                 | 6.9                 | 268.9                     |
| 24/09/08 08:53                 | 3.3                 | 272.2                     |
| 25/09/08 15:11                 | 1.4                 | 273.6                     |
| 26/09/08 08:58                 | 3.2                 | 276.7                     |

The final set of samples were taken on 2 October when the moisture content at the surface had fallen, indicating that the drying front had passed through the OSR. Ventilation was continued for a few days after this to insure that the surface was dried to a safe storage level.

## Results

Visible mould was observed in all samples taken from the surface and at 0.5 m depth in the intermittently ventilated bins, 3 and 4, on 26 September, 31 days after harvest. No mould was observed in the previous sample set taken two days earlier or in any of the samples from Bins 5 and 6, and no mites were observed in any of the samples from any of the bins.

The average static pressures while the fans were operating in the ducts of Bins 4 and 6 were 1860 and 1840 Pa respectively. Table 3 shows the average air flow.

**Table 3. Average flow per ton.**

| Bin | Flow (m <sup>3</sup> /hour/t) |
|-----|-------------------------------|
| 3   | 122                           |
| 4   | 112                           |
| 5   | 109                           |
| 6   | 104                           |

Figures 2 and 3 show the temperature in a central position of Bins 3 and 4 respectively. Each data point is the average of all temperature measurements taken over 24 hours plotted at the mid point time of that 24 hours. This was done to remove the effect of diurnal temperature swings. The average ambient temperature was 14.2 °C.

Figure 2. Temperature at seven depths at Position 7 in Bin 3 against time.

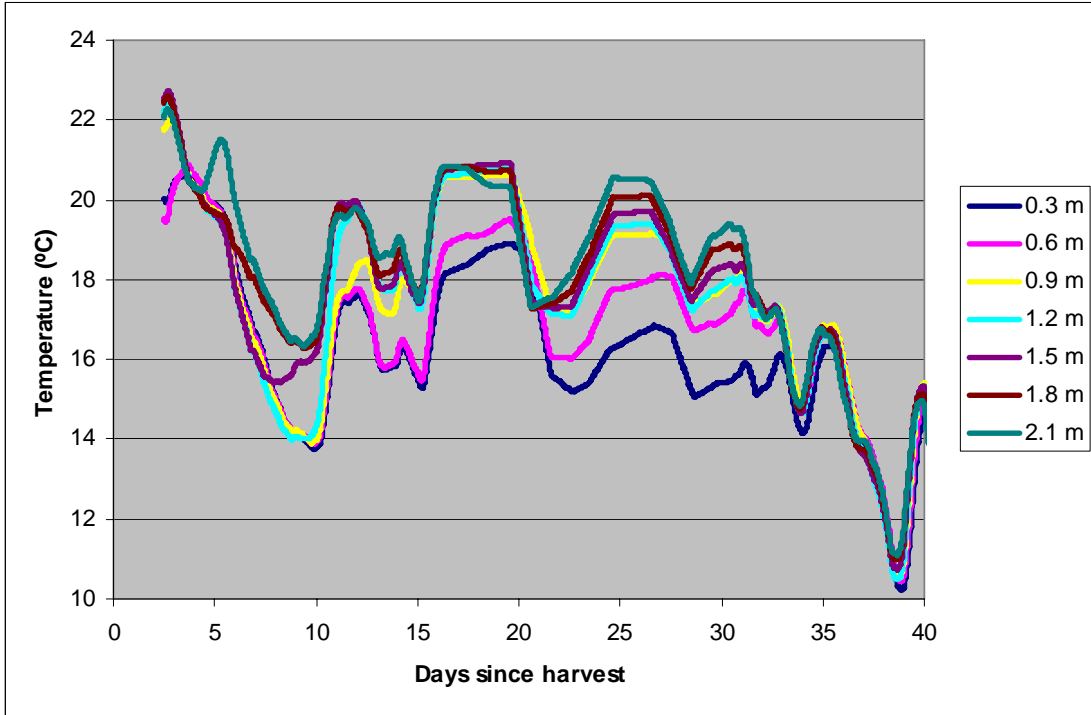
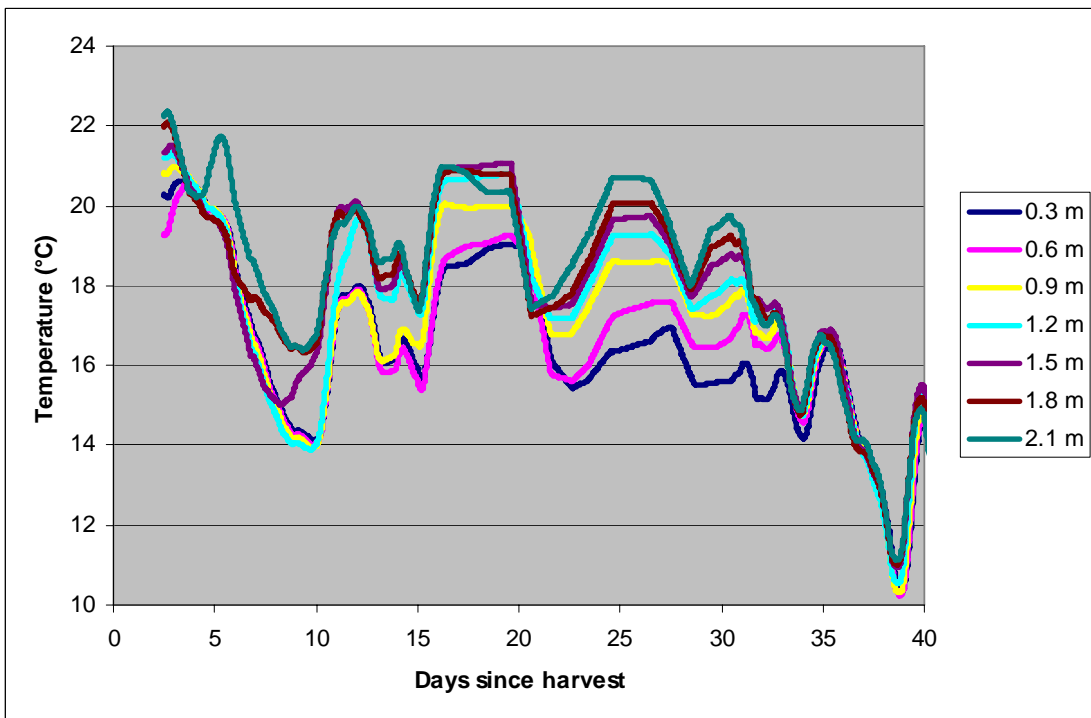


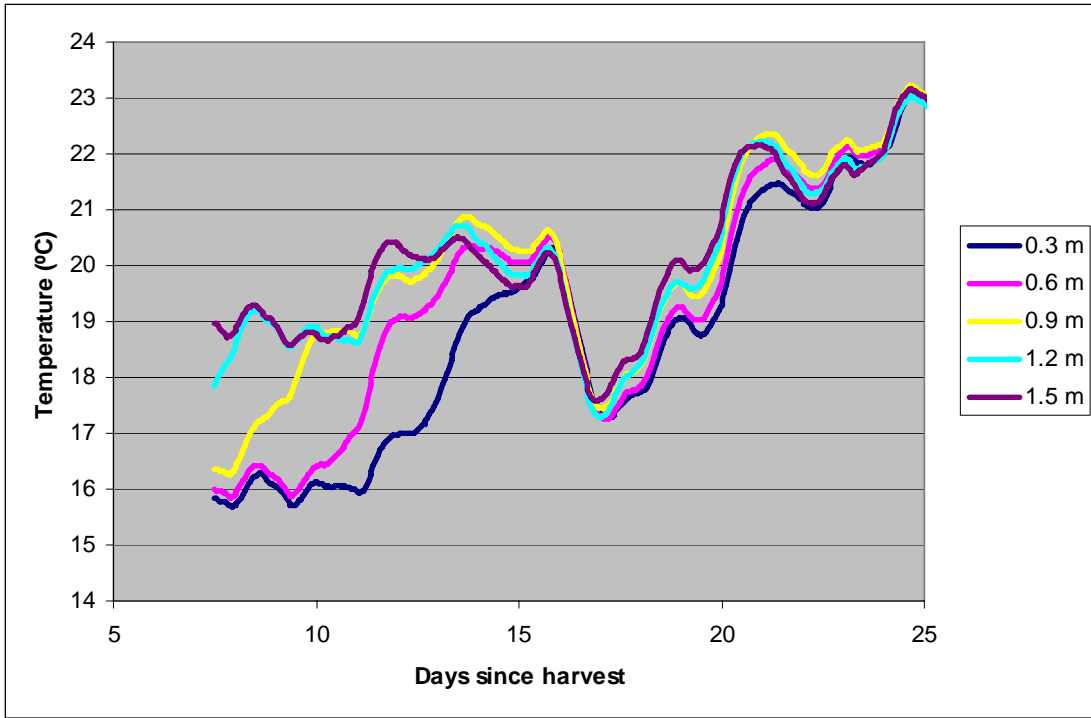
Figure 3. Temperature at seven depths at Position 7 in Bin 4 against time.



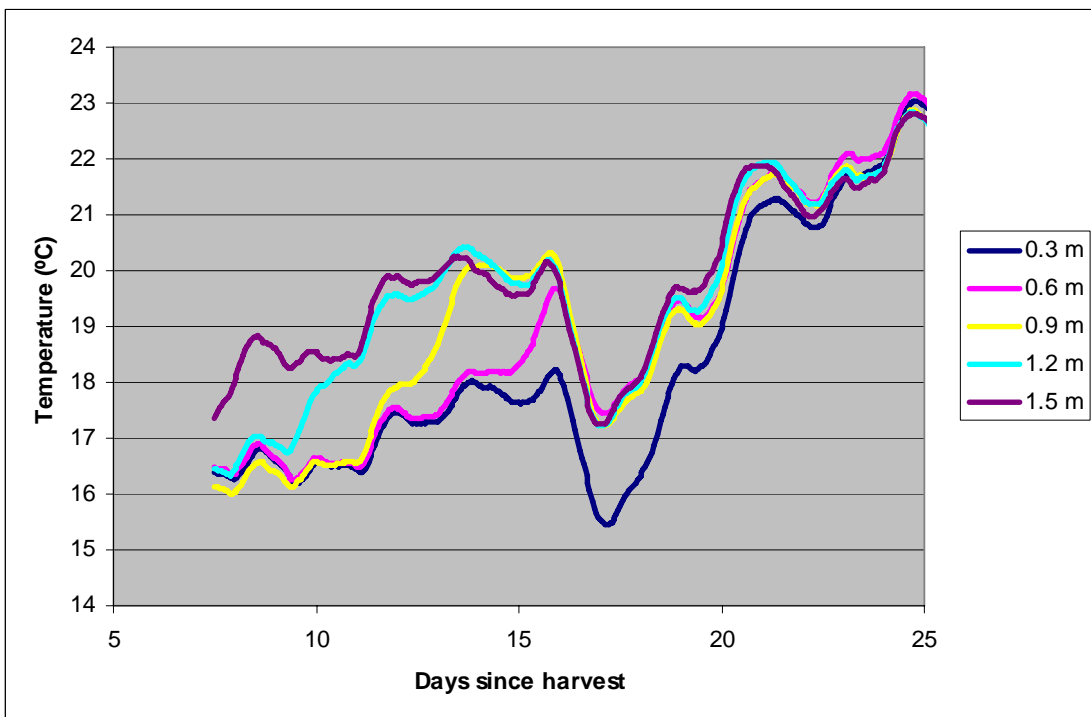
Figures 4 and 5 show the temperature in a central position for Bins 5 and 6 respectively. As before, each data point is the average of all temperature

measurements taken over 24 hours plotted at the mid point time of that 24 hours. The average ambient temperature was 16.6°C.

**Figure 4. Temperature at five depths at Position 1 in Bin 5 against time.**



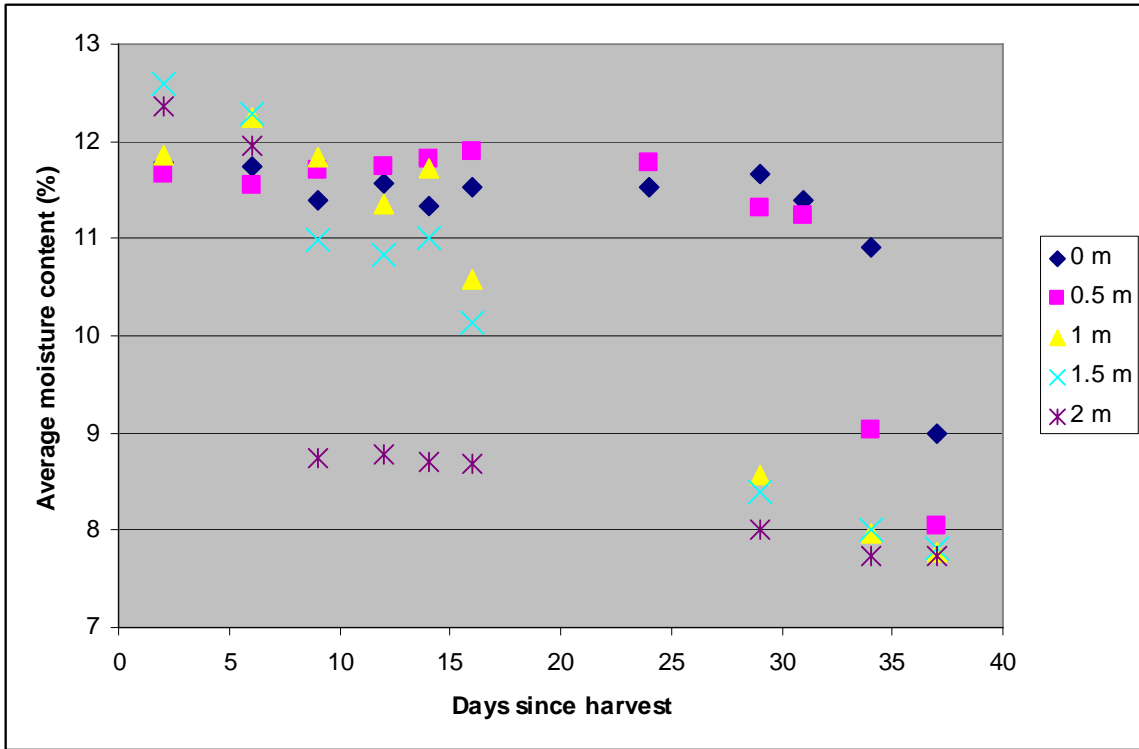
**Figure 5. Temperature at five depths at Position 1 in Bin 6 against time.**





Figures 6 to 9 show the average moisture contents at five depths for the four bins.

**Figure 6. Average moisture content at five depths in Bin 3.**



**Figure 7. Average moisture content at five depths in Bin 4.**

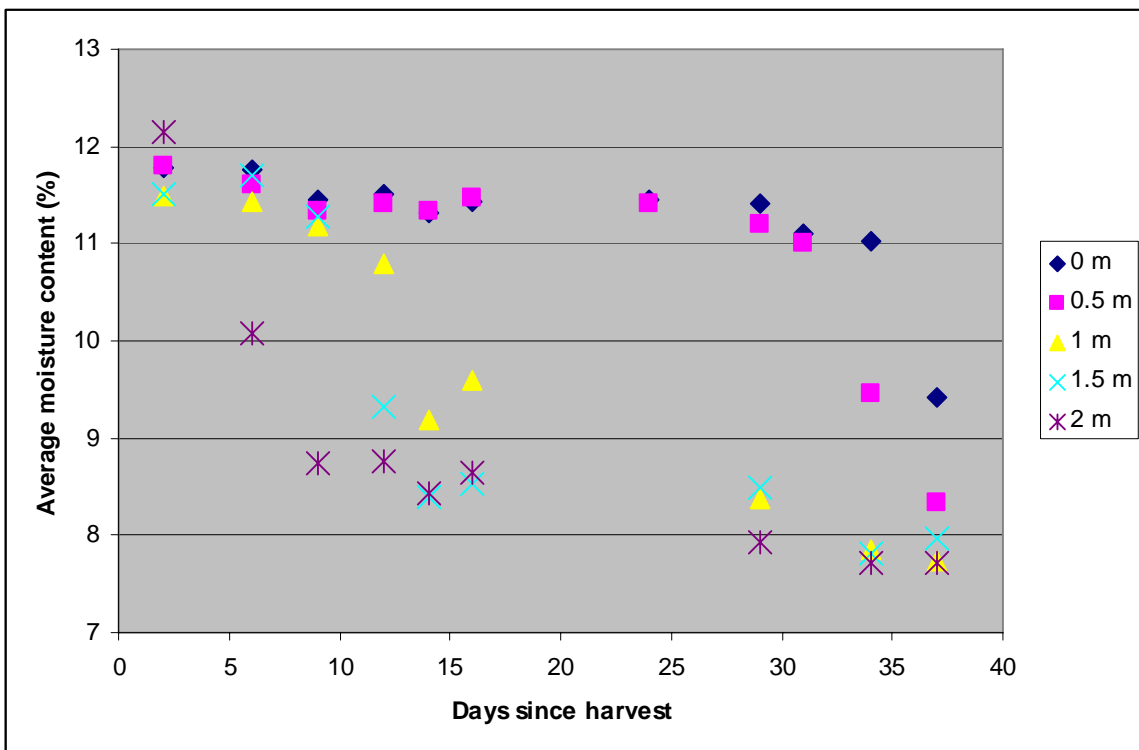


Figure 8. Average moisture content at five depths in Bin 5.

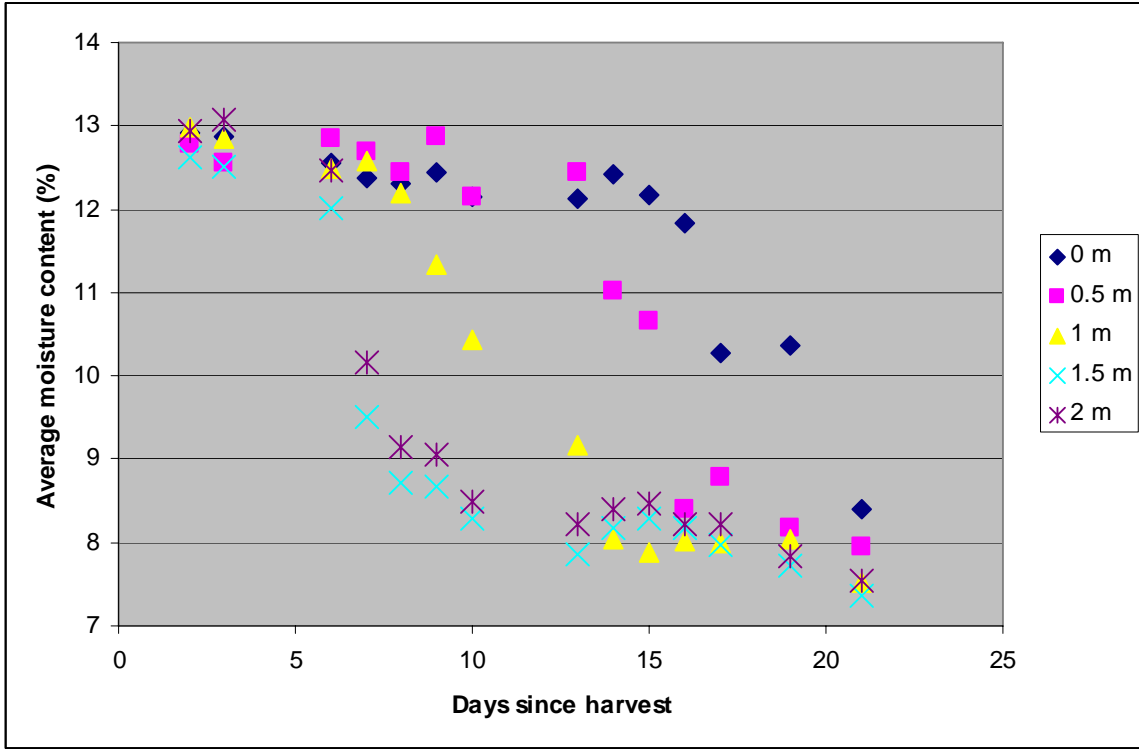
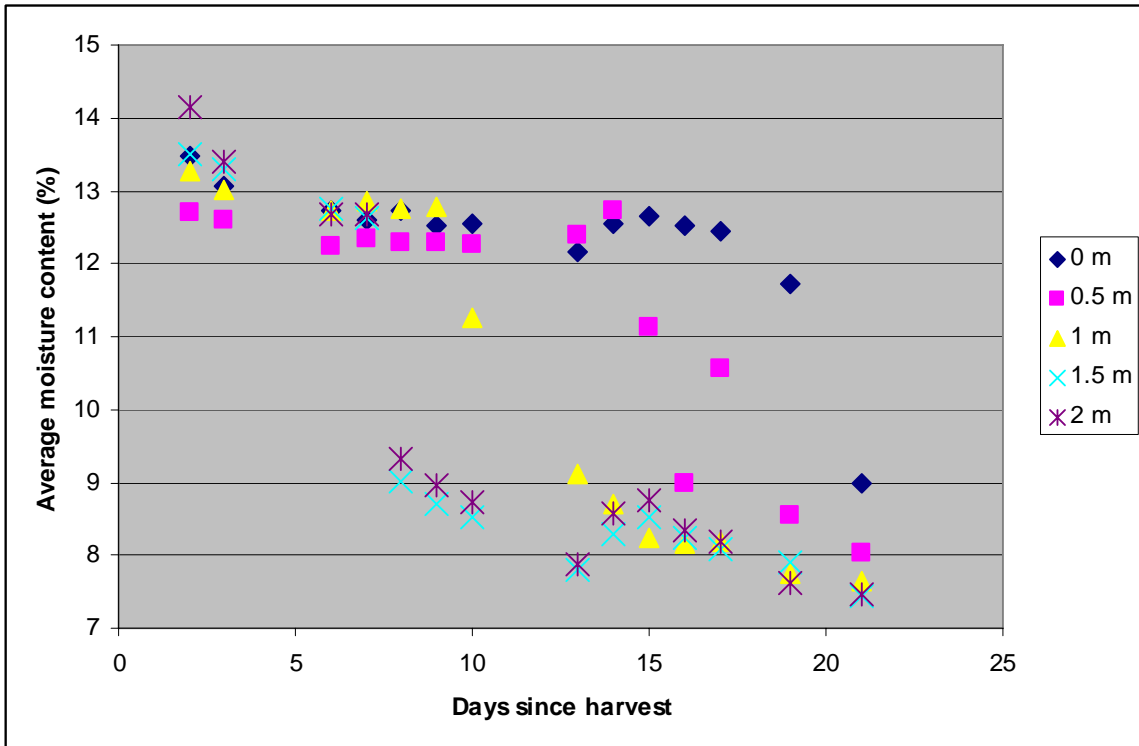


Figure 9. Average moisture content at five depths in Bin 6.



**Table 4. Storage and field moulds present at the start and end of drying**

| Bin | Time taken for drying front to reach the surface (days) | Field moulds and yeasts present at the start (log <sub>10</sub> cfu/g) | Field moulds and yeasts present at the end (log <sub>10</sub> cfu/g) | Storage moulds present at the start (log <sub>10</sub> cfu/g) | Storage moulds present at the end (log <sub>10</sub> cfu/g) |
|-----|---|--|--|---|---|
| 3   | 37  | 5.10   | 5.10   | 1.52  | 5.59  |
| 4   | 37  | 4.97   | 4.68   | 2.00  | 5.09  |
| 5   | 21  | 5.51   | 4.89   | 2.85  | 4.66  |
| 6   | 21  | 5.21   | 5.01   | 2.73  | 4.63  |

Table 4 shows the storage and field moulds present at the start and end of drying. Counts of field fungi, mainly yeasts, *Cladosporium* and *Altenaria* spp, were of the order of 10<sup>5</sup> cfu/g at the start of the test and changed little.

Counts of storage fungi varied between 10<sup>1</sup> and 10<sup>3</sup> cfu/g at the start and consisted of *Penicillium* and *Eurotium* spp. By the end of drying, counts of storage fungi had increased to 10<sup>4</sup> cfu/g in bins 5 and 6 and 10<sup>5</sup> cfu/g in Bins 3 and 4, which had been dried more slowly. These counts were mainly *Wallemia* and *Penicillium* but also included *Eurotium* and *Asperguillus* spp.

Table 5 shows the average count of storage moulds at the end of drying for the four bins at the 5 depths sampled. Counts at 2m where the OSR was dried first were of the order of 10<sup>3</sup> cfu/g rising to 10<sup>5</sup> cfu/g at 0.5m and at the surface where the OSR was dried last.

**Table 5. Average storage moulds at 5 depths in the four bins at the end of drying**

| Depth (m) | Average storage moulds present at the end (log <sub>10</sub> cfu/g) |
|-----------|---|
| 0         | 5.48  |
| 0.5       | 5.39  |
| 1         | 4.35  |
| 1.5       | 4.05  |
| 2         | 3.45  |

The average count of storage moulds in the top 0.5m in bins 3 and 4, where visible mould was observed, was  $5.7 \log_{10}$  cfu/g. In bins 5 and 6, where visible mould was not observed, the average count was  $4.9 \log_{10}$  cfu/g.

## Discussion of Experiment

The moisture content sampling allowed the time course of moisture to be followed for the upper 2m of the beds of OSR. Figures 6 to 9 show, as would be expected, development of a drying front that then moves up through the bed. The moisture content at 2m depth first falls to an equilibrium, followed by that at 1.5m, and so on up through the bed. Finally the drying front emerges from the surface and the surface moisture content falls rapidly. As the inlet air was at a sufficiently low relative humidity (r.h.), the moisture content reached, in equilibrium with this r.h., was safe for long term storage. Until the surface moisture content has fallen close to that equilibrium, conditions in the OSR at the surface are favourable to fungi. Average counts of storage moulds present at the end of the trial were greater at the surface than those at a depth of 2m by a factor of 100.

Temperatures in the bed (Figures 2 to 5), measured down to 2.1m depth, show a cooling front which accompanies the progress of the drying front up through the bed. Below this cooling front, the temperature of the OSR follows that of the incoming air, whereas in the vicinity of the front, where drying is in progress, the seed is cooled due to evaporation of moisture. The incoming air was some 3 to 4°C above ambient because of heating by the fan, which is a much greater temperature rise than in a typical farm system and is due to an obstructed air path leading to turbulence and pressure loss. The situation is equivalent to having a small heater in the duct.

In Bins 3 and 4, the fans were run intermittently so the temperature graphs show periods of little change when fans were off, followed by quite rapid change when the fans were started up after a break. However, records of temperature from all four bins show the convergence of temperatures once the cooling front had passed through the bed. Breaks in ventilation also show up clearly in the moisture content data and their cumulative effect towards the end of drying is evident in the increased time between the fall in moisture content at each sampling depth, especially between 1.0m and 0.5m.

Burrell et al. (1980), in a study based on small scale tests, observed visible mould after 26 days in samples with a moisture content of 12.3% at 15°C. The absence of visible mould in bins 5 and 6 and the timing of the appearance of visible mould, 31 days after harvest, in bins 3 and 4 is in line with these results.

In the present study, visible mould appeared when the mould count was of the order of  $10^5$  cfu/g.

## **Validation**

The mathematical model being validated, due to Morey et al. (1979), is an equilibrium type of model in which certain assumptions are made to simplify the calculations. These assumptions were as valid for OSR as they are for cereal grains, so the model seemed appropriate. The version of the Morey model being evaluated here was implemented in the FORTRAN language in a simulation program Storedry. In BulkDryRape, the same Morey model was implemented in a different language by Cranfield University but the same expressions and constants to enable the models to simulate oilseed rape were adopted in both implementations.

The approach to validation was based on the simulation program Storedry. Using the recorded data and calculated values, an input file was prepared to enable Storedry to simulate drying in Bin 5 using the Morey model. Data for Bins 5 and 6 were sufficiently similar that simulating the two runs separately was not considered necessary, and similarly for Bins 3 and 4. One of the outputs of the simulation is the spoilage index at each depth and time. The spoilage calculation for OSR was based on an empirical equation with three constants, fitted to data of Burrell et al. (1980) on the time before appearance of visible mould. The equation used only the OSR m.c. and temperature, so if these are available from the simulation or measurements, the spoilage index can then be calculated. When this index exceeds 1, the safe life has expired and hence visible mould would be expected on the OSR. For Bin 5, moisture and temperature values were available for all positions and times from the simulation and for certain positions and times from the measurements.

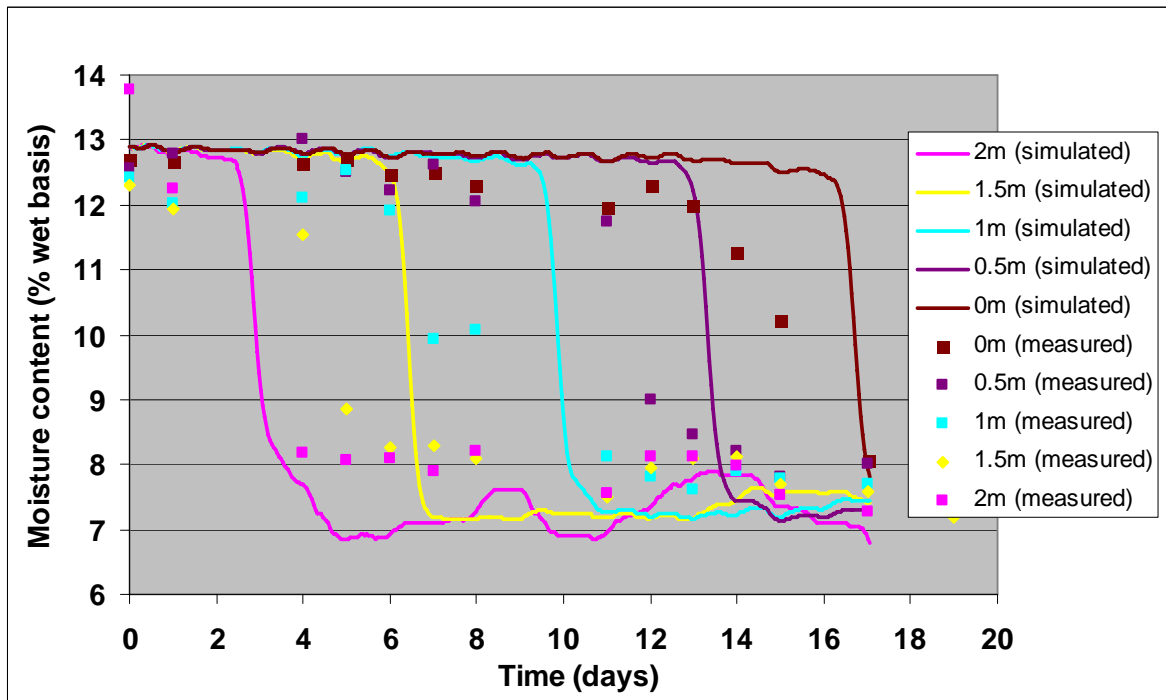
Input values to the simulation:- The temperature and r.h. of air in the plenum ducts were converted into a form suitable for the simulation program Storedry to read. Values of the following were calculated; effective bed depth of a bed with a flat

bottomed, as opposed to a tapering, bin, average initial, average final and final surface OSR moisture content (m.c.), mass of ventilated OSR in the bin, average initial OSR temperature and airflow per unit mass dry matter.

Output values: - at each depth in the bed, temperature and m.c. of OSR, temperature and r.h. of air and value of spoilage index, air temperature rise owing to fan, and r.h. of air exhausted from bed.

Moisture content from experiment for Bin 5 and from simulation versus time are compared in Figure 10. Simulated m.c. showed a similar pattern to that measured, m.c. The value reached by the model was similar to that measured, but the rate of fall from initial to equilibrium m.c. was faster in the simulation.

**Figure10. Simulated vs measured moisture content at five depths in Bin 5.**



Comparison of the drying time had two aspects; the time to reach the equilibrium m.c., and time for which the wettest seed, in the uppermost layers of the bed, remained in the range of m.c. at which fungi grow. The time for the major part of the bed to reach equilibrium was well predicted at 15 days but the predicted time for which the uppermost part of the bed remained at initial m.c. was too long by about 4 days. The difference meant that the spoilage calculated in the model would be a little

more advanced than measured. Though this was not ideal, it was an acceptable direction for such an error because strategies for drying selected using the model would be conservative.

Figure 11 shows 24h averaged temperatures, simulated at depths of 1.2m and 0.6m and measured at the centre of the bin. Temperatures before and after the passage of the drying zone were in good agreement but the rise in measured temperatures behind the drying zone occurred some 2.5 days sooner than simulated. Figure 12 shows the same comparison at the side of the bin where there was good agreement in that the time difference was no longer present. This suggests that the airflow up through the bed was less at the edge than in the centre where drying was consequently faster.

**Figure 11. Simulated vs measured temperatures at centre of bin 5.**

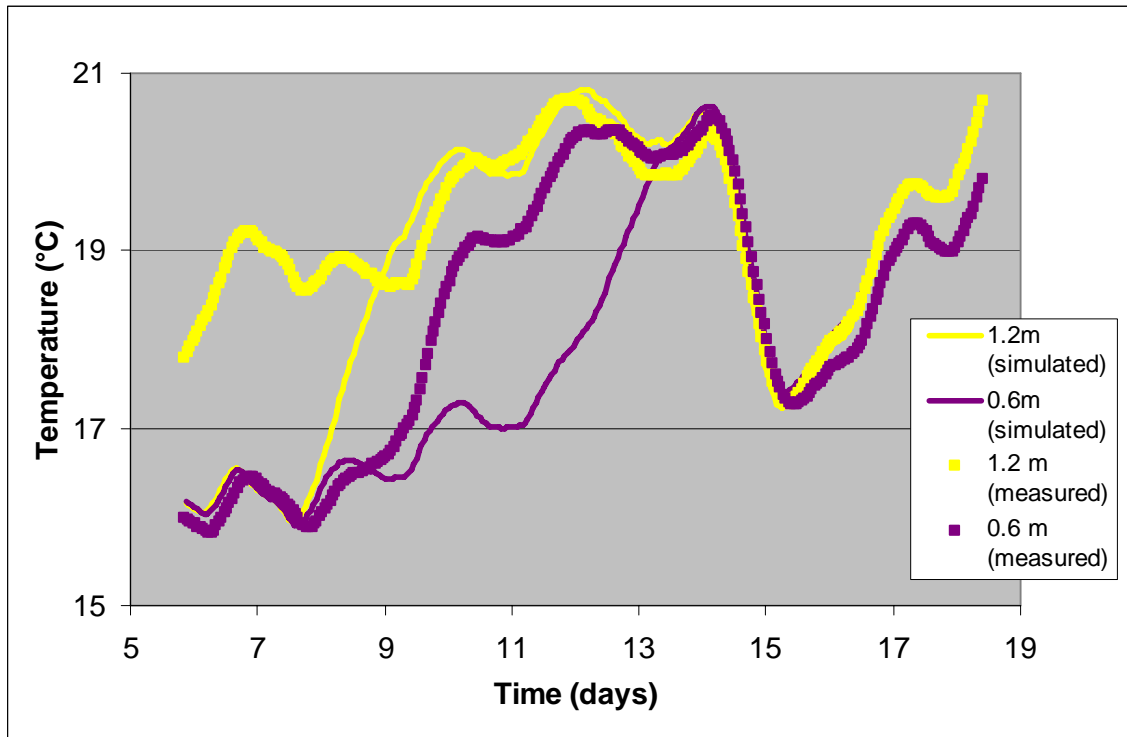


Figure 12. Simulated vs measured temperatures at side of bin 5.

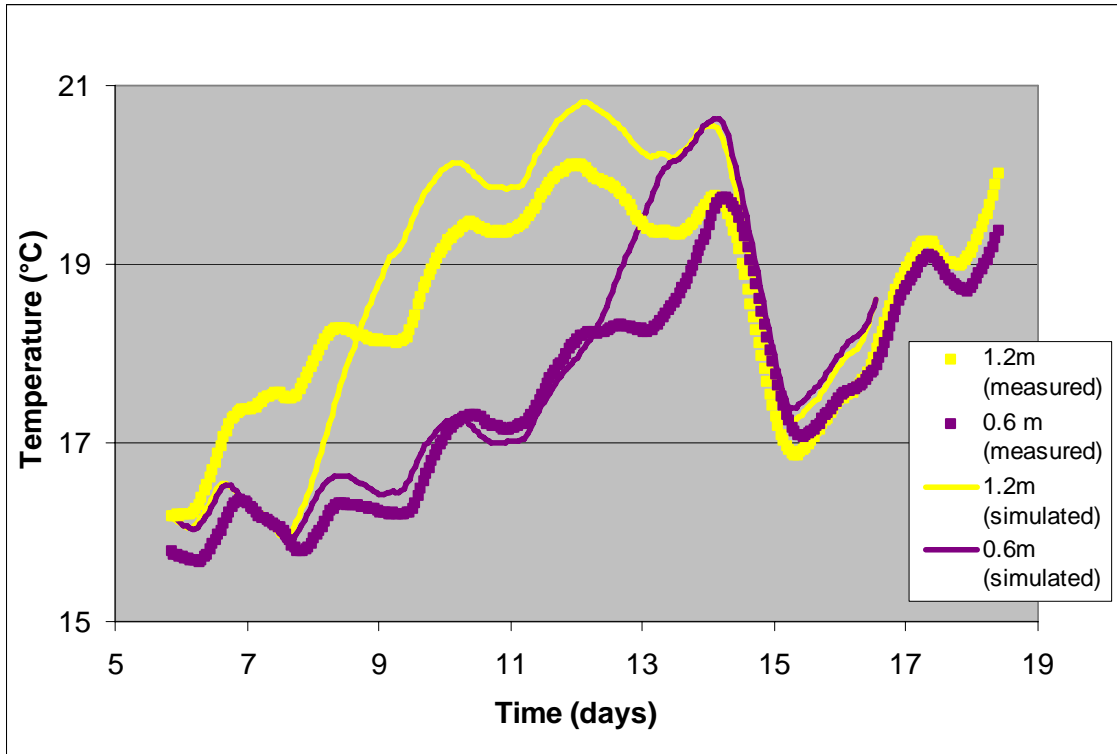
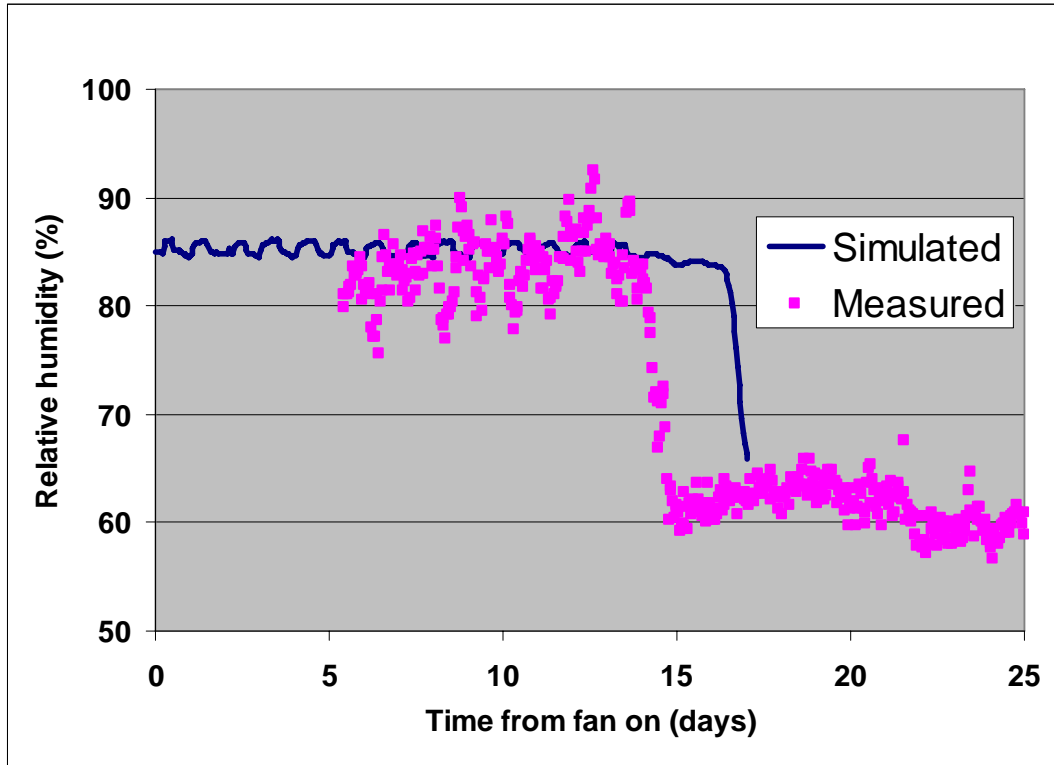


Figure 13 shows measured and simulated r.h. of the exhaust air from Bin 5. The air exhausting from the bed remained at high humidity while the drying zone had not reached the surface but then fell, reflecting the drying of the uppermost layers. Agreement was good for levels of r.h. before and after the fall and in the steep slope of the fall itself. The time difference, of about 3 days, reflects the fact that the drying zone reached the surface faster in the centre of the bin where the r.h. sensor was located.



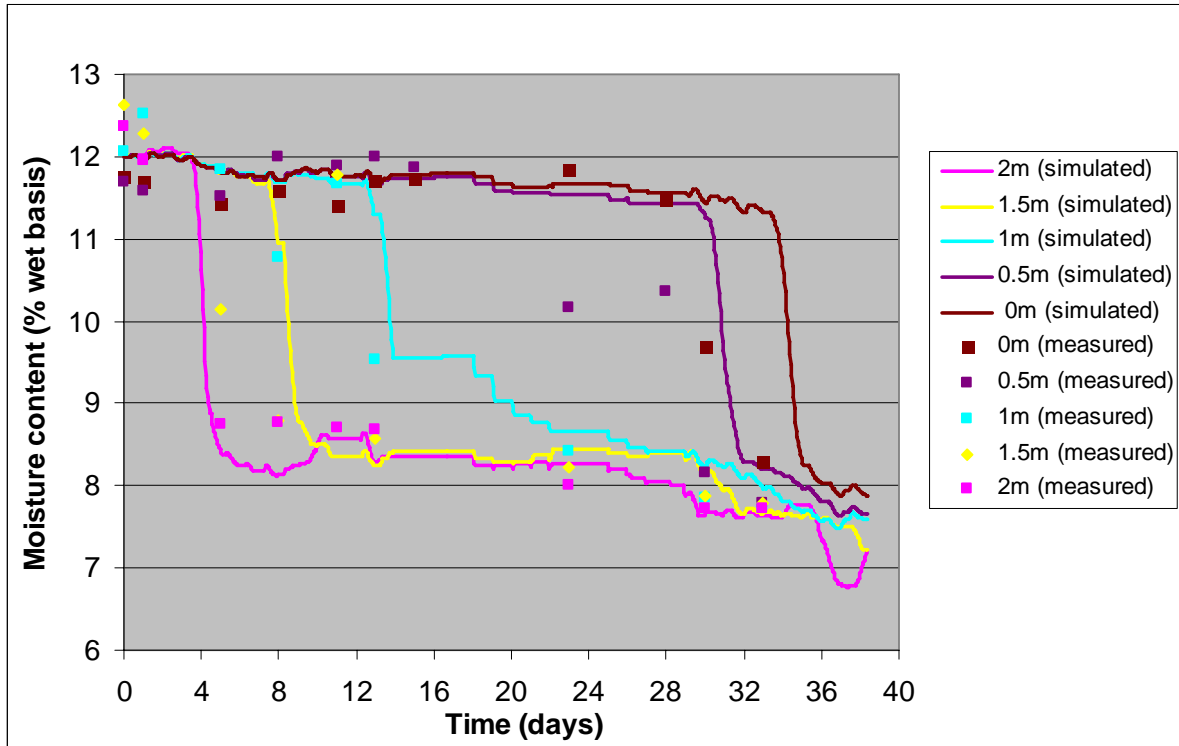
Figure 13. Relative humidity of exhaust air from Bin 5.



Storedry calculated the spoilage index in each layer of the bed throughout the drying. At the end of drying the value of the index was highest, as would be expected, in the uppermost layer because it was wettest for longest. For Bin 5 this was 0.68. Because it was less than 1, the model indicated no risk of visible mould. In the experiment no mould was observed, and so the simulation and experiment were in agreement.

For validation of drying Bin 3, Storedry was adapted to use the experimental ventilation times. Figure 14 shows simulated versus experimental m.c. values for Bin 3. There was no change in m.c. during periods when the fan was off so these show up as horizontal lines. Time to reach the same average m.c. as the experiment was 34.5 days, in good agreement with experiment, while the time for the wettest layer to reach agreement with the data was 38.6 days, also close to that observed. As before, the rate of fall of m.c. was higher in simulation than in experiment.

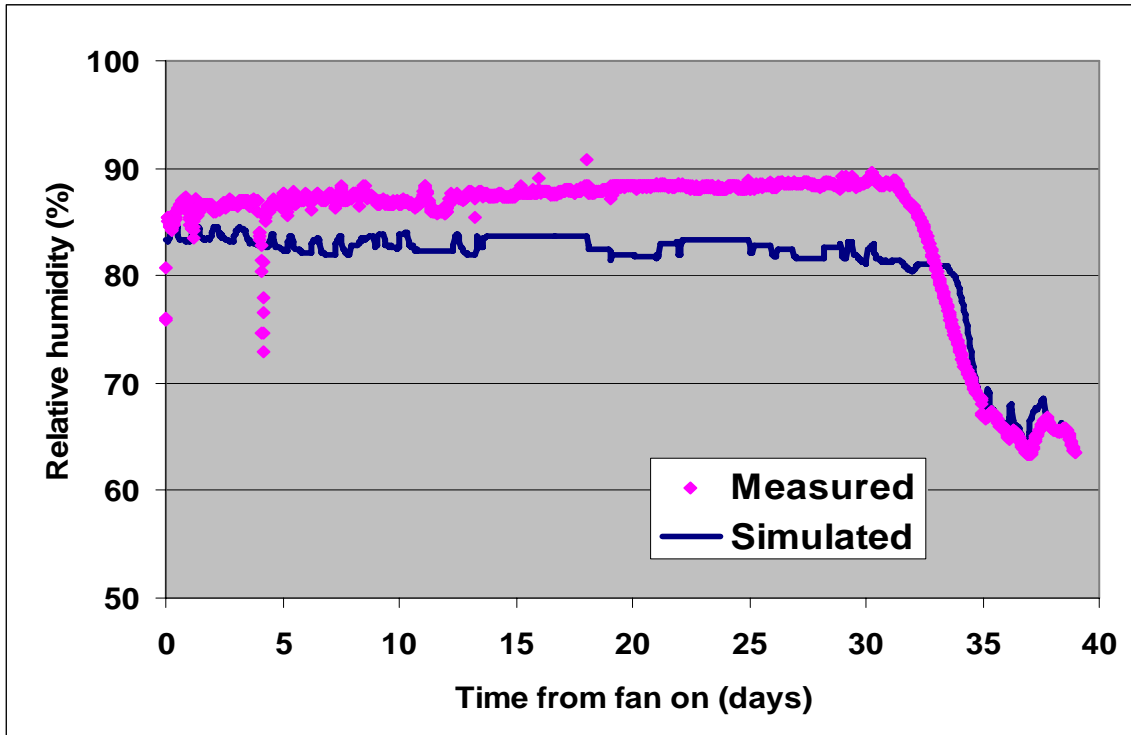
Figure14. Simulated vs measured moisture content at five depths in Bin 3.



Temperatures in Bin 3 at 0.6m and 1.2m depth for the centre of the bin and for the side were compared with those from the simulation. At the centre of the bin there was good agreement of measured and simulated values throughout the run whereas at the side of the bin the simulated values were higher than the measured ones but the differences were not large.

Measured relative humidity was less variable for Bin 3 than for Bin 5, which may indicate the sensor for Bin 5 had been on, rather than just below, the surface. The r.h. predicted was lower than measured but the time, steepness and final value of the drop once the drying zone had emerged were well modelled, shown in Figure 15.

Figure 15. Relative humidity of exhaust air from Bin 3.



From the simulation of drying Bin 3, the spoilage index at day 31 for the uppermost layer was 0.95, whereas when the simulated run finished at 38.6 days, the spoilage index had risen to 1.06. It is clear that the spoilage index calculation was effective at predicting the likelihood of visible mould.

The pressure generated in the simulation as a result of the specified airflow and bed characteristics for Bin 3 was 1900 Pa whereas the measured average pressure was 189 mm water gauge or 1890 Pa, in good agreement. No information for other flows or pressures was available for this bin from the experiment.

## Conclusions

This study produced a comprehensive data set from drying of OSR in bins using ambient air from two levels of moisture content appropriate to UK conditions.

These were used to validate predictions by the Morey model, which is at the core of BulkDryRape. Comparisons gave confidence that the model predicted well the measured drying behaviour and safe life before occurrence of visible mould using strategies of continuous and of intermittent ventilation.

Overall, the simulation predicted well the measured drying behaviour in both continuous and intermittent drying, and so it can be confidently used as the basis of the BulkDryRape software.

BulkDryRape will allow the user to simulate near ambient drying of OSR, simply and quickly, and to understand how the progress of drying is influenced by bed depth, equipment, control actions and weather and the limitations imposed by fungal action..

## References

Air Control Industries (2006). Centrifugal fans MR280.

[http://www.aircontrolindustries.com/pdf%20june%2007/Centrifugal%20Fans\(pdfs\)/MR280.pdf](http://www.aircontrolindustries.com/pdf%20june%2007/Centrifugal%20Fans(pdfs)/MR280.pdf)

Bruce D.M., Jonsson N. and Armitage D.M. 2006. Practical strategies for minimising the production of Ochratoxin A in damp cereals. Project Report No. 399, HGCA, London.

Burrell, N.J., Knight, P., Armitage, D.M. and Hill S.T. (1980), Determination of the time available for drying rapeseed before the appearance of surface moulds. J. Stored Prod. Res. Vol. 16 pp 115-118

INTERNATIONAL ORGANISATION FOR STANDARDISATION (2000), Oil seeds - Determination of moisture and volatile matter content. ISO 665:2000.

Morey, R.V.; Cloud, H.A., Gustafson, R.J.; Petersen, D.W. (1979) Evaluation of the feasibility of solar energy grain drying. Transactions of the American Society of Agricultural Engineers, 22 (2) 409-417

Sharp, J.R. (1984). The design and management of low temperature grain driers in England – A simulation study. J Agric Eng Res 29 123-131

## Appendix

The following expressions were selected for use in 'BulkDryRape'. As far as could be determined they were the most appropriate available in the literature, in that the data and theory are of high quality, and the range of applicability is appropriate for use in simulation of near-ambient drying of oilseed rape.

### Air-seed equilibrium equation

Of the generally used equations, the modified Halsey equation is considered the best for rapeseed by Yang & Cenkowski, 1995, Sun & Byrne 1998 and Nellist *et al.* 1992.

The equation, which can be inverted if required, is

$$\Phi = \exp(-\exp(C_1 + C_2 T) M^{-C_3})$$

Inverted, the expression becomes

$$M = (-\ln \Phi / \exp(C_1 - C_2 T))^{-1/C_3}$$

where

$\Phi$  = equilibrium relative humidity, decimal fraction

T = temperature, °C

M = equilibrium moisture content, % dry basis

Nellist *et al.* (1992) fitted this equation to 5 high quality data sets (Pixton & Warburton, 1977, Pixton & Henderson, 1981, Henderson & Wilkin, 1985). The range of temperature and equilibrium relative humidity covered by the data is approximately 5-35 °C and 20-90% respectively. The fitting process was restricted to force the effect of hysteresis on to only one of the three coefficients,  $C_1$ . Despite this restriction, which simplifies the equations for use in simulation, the fit of the equation to the data was very good, accounting for more than 99.5% of the variance. The fitted coefficients were:-

$$C_1 \text{ desorption} = 2.910$$

$$C_1 \text{ absorption} = 2.833 \text{ (Desorption coefficient was not used directly in Storedry)}$$

$$C_2 = -0.00652$$

$$C_3 = 1.713$$

### **Bulk density**

The value of 0.690 tonne/m<sup>3</sup> is given on p52 of Nellist (1998) for seed at safe storage moisture content. BulkDryRape does not require a dependency of bulk density on moisture content.

### **Resistance to airflow of the bed of seed**

This is expressed by the equation

$$P = a v^n D$$

where

$P$  = pressure drop, Pa, across bed of depth  $D$ , m

$v$  = superficial air velocity into the bed, ms<sup>-1</sup>

$a$  = experimentally determined coefficient, Pa s <sup>$n$</sup>  m<sup>-( $n+1$ )</sup>

$n$  = experimentally determined exponent of  $v$

For oilseed rape, coefficients from p46 of Nellist (1998) are

$$a = 22700$$

$$n = 1.19$$

The range of moisture for which the expression is valid is not given but as it comes from 6 sources, it is likely to be satisfactory. Nellist (1998) presents a table over the range of airflow of 0.005 to 0.2 ms<sup>-1</sup> so it is likely that the equation would be appropriate for near ambient drying of rapeseed. The values predicted by this equation agree well with the graph on P11 of the HGCA Grain Storage Guide, Armitage & Wildey (2003).

### **Safe storage time**

The prediction of spoilage risk by the program is based on the concept of safe storage time ( $t_s$ ). For seed kept at a given temperature ( $T$ ) and moisture content ( $M$ ), the safe storage time is the time until a defined mycological risk becomes significant. In BulkDryRape, this is based on observations of visible mould growth by Burrell *et al.* (1980), reproduced in Table 1.

**Table 1. Maximum mould-free period (days) without visible colonies**

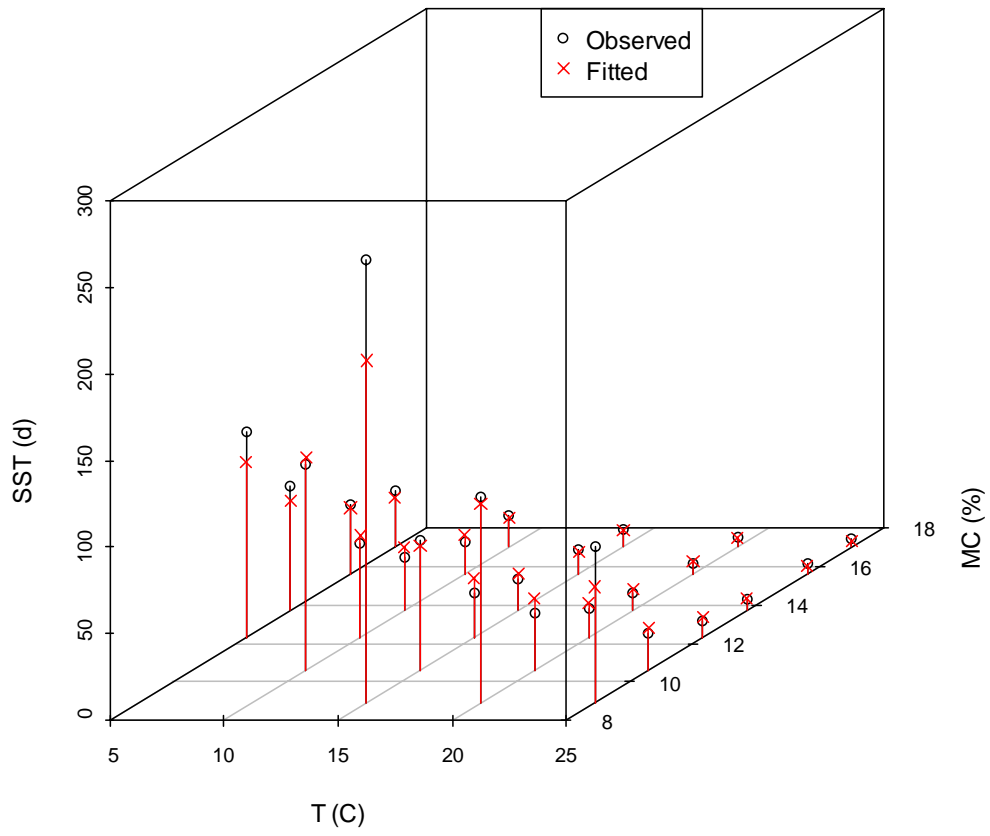
| Initial<br>Moisture<br>(% wb) | Temperature (°C) |      |      |      |      |
|-------------------------------|------------------|------|------|------|------|
|                               | 25               | 20   | 15   | 10   | 5    |
| 17                            | 5                | 6    | 10   | 18   | 33   |
| 15.6                          | 6                | 6    | 14   | 19   | 40   |
| 13.7                          | 7                | 10   | 18   | 31   | 72   |
| 12.3                          | 10               | 17   | 26   | 54   | 119  |
| 10.6                          | 21               | 33   | 75   | 119  | >300 |
| 8.9                           | 90               | 119  | 256  | >300 | >300 |
| 6.7                           | >300             | >300 | >300 | >300 | >300 |

These data were explored by plotting  $\log_e(t_s)$  against various transformations of T and M, it was determined that the most appropriate form of model was

$$t_s = \exp(a - bT + c/M)$$

This model was fitted by multiple linear regression, giving  $a=0.57$ ,  $b=0.108$  and  $c=56.39$ . The resulting model gave a good fit; the largest errors, which occur in conditions giving long safe storage times are underestimates, so the model is conservative (Figure 1).





**Figure 1. Comparison of the fitted model and safe storage time data**

## References (Appendix)

Armitage, D.M. and Wildey, K.N. (2003). The Grain Storage Guide. 36pp HGCA, London.

Burrell, N.J., Knight, G.P., Armitage, D.M., Hill, S.T. (1980) Determination of the time available for drying rapeseed before the appearance of surface moulds. *J. Stored Products Research*, 16, 115-118

Henderson, S., Wilkin, R. (1985) Relationship between water content and equilibrium relative humidity for 3 oilseed rape cultivars. *Informations-technique, -CETIOM*. No 93, 17-20

Nellist, M.E. (1998) Bulk storage drying of grain and oilseeds. *Research Review No. 38, HGCA, London.*

Nellist, M. E., Bruce, D. M., Wilkin, D. R., Cox, P. D. (1992) Drying and storage of oilseed rape in the UK. *Oilseeds Research Review (OS6), HGCA, London.*

Pixton, S.W., Warburton, S. (1977) The moisture content/equilibrium relative humidity relationship and oil composition of rapeseed. *Journal of Stored Products Research* 13; 77-81

Pixton, S.W., Henderson, S. (1981) The moisture content/ equilibrium relative humidity relationship of five varieties of Canadian wheat and of candle rapeseed at different temperatures. *J. Stored Prod Res.* Vol 17(4), 187-190

Sun, D.W.; Byrne, C. (1998) Selection of EMC/ERH isotherm equations for rapeseed. *Journal of Agricultural Engineering Research* 69 307-315

Yang, W. H.; Cenkowski, S. (1995) Enhancement of the Halsey equation for canola isotherms. *Canadian Agricultural Engineering* vol. 37 ( 3 ): p.169-182