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Improvement of Hardwood Drying Schedules

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Improvement of Hardwood Drying Schedules

Prepared for the

Forest & Wood Products
Research & Development Corporation

by

T. Innes and A. Redman

Summary

Drying of regrowth native hardwoods to satisfactory moisture levels is a significant challenge for the processing industry. Dried quality is becoming increasingly important as sawn hardwood continues to move away from structural markets into appearance applications, but more difficult to achieve as the resource mix being processed becomes younger. An accurate predictive drying model is a powerful tool in schedule development, decreasing the reliance on expensive repetitive drying trials. This project updates the **KilnSched** drying model to allow more accurate modelling of the drying behaviour of regrowth blackbutt, jarrah, messmate, spotted gum and Victorian ash. The effect of high temperature drying and humidity treatments on spotted gum were also investigated, as was the economics of various drying methods on spotted gum and blackbutt.

Contents

1. Introduction

Quality drying of regrowth native hardwoods to satisfactory gross and grade recovery levels is one of the most important challenges associated with processing this material. It has the potential to underpin the continued success of the hardwood sawmilling industry in Australia. Dried quality is becoming increasingly important as sawn hardwood moves away from traditional structural markets into appearance applications. The most important factor determining dried timber quality is the drying process that the timber undergoes.

The objective of this project was to accelerate drying and reduce degrade in Australian hardwoods in an economical and practical manner, specifically:

- To upgrade the **KilnSched** timber drying modelling program to model the predrying behaviour within 20% for the following regrowth species: jarrah (*Eucalyptus marginata*), blackbutt (*E. pilularis*), spotted gum (*Corymbia maculata*), messmate (*E. obliqua*) and Victorian ash (a mixture of mountain ash, *E. regnans* and alpine ash, *E. delegatensis*).
- To investigate the effect of higher temperatures (above 80ºC) and humidity treatments on the dried quality and drying time of regrowth spotted gum.
- To establish the economic viability of the controlled predrying of regrowth spotted gum and regrowth blackbutt.

An accurate predictive computer model of drying is the most powerful tool available to develop schedules that allow drying of timber in the minimum time with minimum degrade. The only real alternative is repeated empirical level drying trials. Of necessity, these are costly and may cause downgrade in a large amount of timber. Empirical trials also add very little to the fundamental understanding of timber drying processes and thus of necessity have to be applied to many species and variations thereof.

Most of the degrade that occurs when drying hardwood takes place during drying from green to fibre-saturation point (predrying). The drying schedule used in controlled-condition predriers is critical in minimising this degrade, particularly for cool climate, collapse prone eucalypts, such as messmate and alpine ash. Schedules can be developed either empirically by conducting many drying trials, or by using a computer simulation program in association with validation drying trials. Such a computer program can also be used to improve air or sheltered drying quality outcomes, and as a training tool.

Over the last decade the **KilnSched** computerised timber-drying model, developed by University of Tasmania researchers, has been successfully used to develop controlled condition predrying schedules for several old-growth eucalypt species throughout Australia. These schedules minimise both degrade and drying time. They have been used extensively in commercial mills. Species specific versions of the program currently in use are: JarrahSched in Western Australia; VicAshSched in Victoria; and TasOakSched in Tasmania. However, several shortcomings became evident with these models, particularly when used for regrowth timbers. The first objective of this project was to identify and address these shortcomings and to undertake the detailed timber testing work necessary to modify, calibrate and verify the model for major regrowth hardwood species. Work addressing the first objective is covered in Chapters 2 to 8 (Innes and Redman) and forms the bulk of the project.

The second objective of this project was to investigate high temperature drying and the effect of humidity treatments on spotted gum. This comprised two separate sub-projects completed by the Queensland Department of Primary Industries and Fisheries (DPI&F) with support from Boral. High temperature drying is covered in Chapter 9 (Redman) and humidity treatments are covered in Chapter 10 (Palmer and Littee).

The third objective of the project, to investigate the economics of different means of drying regrowth spotted gum and blackbutt, was also carried out by DPI&F. The work resulted in a spreadsheet model, which is included as one of the project's outcomes. It is described in Chapter 11 (Davies and Palmer).

This was a joint project of the Timber Research Unit (TRU) of the University of Tasmania and the Queensland DPI&F. It was supported by the Tasmanian Forests and Forest Industry Council (FFIC), and many of Australia's leading hardwood producers including Boral Timber, Gunns, Hyne & Sons, Neville Smith Timber and others.

2. Laboratory scale trials

Initial experimental scale drying trials were carried out to establish the shortcomings of the **KilnSched** model when applied to regrowth timber of the species under study. Trials on Victorian alpine ash, Western Australian jarrah and Tasmanian messmate were carried out by the TRU in a 0.15 m^3 timber capacity tunnel kiln. Trials on Queensland blackbutt, Victorian mountain ash and New South Wales spotted gum were carried out by DPI&F in a 0.25 m^3 experimental kiln. Trials were carried out for a maximum of one month each; the data required did not necessitate drying timber to equilibrium.

2.1. Experimental methodologies

2.1.1. Timber specification and supply

Boards for each trial were specified to be clear of natural feature and as close to purely backsawn or quartersawn as possible (whichever was normal for that species). Each trial closely examined matched pairs of five boards, each cut from a different tree with all logs of typical size and quality for that resource. Boards were docked to the required length, end sealed and wrapped in heavy plastic for shipping. Time between cutting and drying was minimised. All possible steps were taken to minimise drying of boards during transport and handling.

2.1.2. Basic density and initial moisture content

A full board width cross-section sample, cut a minimum of 50 mm from the board end, was used for determination of basic density and initial MC. Volume for basic density was measured by water displacement.

2.1.3. Unconfined shrinkage measurement

A cube of approximately 28 mm side length was cut from the centre of the board width, at least 50 mm clear of the board end. Slices approximately 0.8 mm thick were cut either across the grain or parallel to the grain as shown in Figure 2.1.3. Slices cut across the grain do not generally undergo collapse shrinkage as most fibres are cut and therefore cannot collapse. They are used for measurement of “normal” shrinkage; shrinkage of the fibre wall material due to removal of water. Slices cut parallel to the grain can collapse, so the shrinkage measured on those is “total shrinkage”; normal shrinkage plus collapse shrinkage. For either slicing method, either radial or tangential unconfined shrinkage can be measured, depending on the orientation of marking of the slice. The slicing apparatus is shown in Figure 2.1.1. The slices were restrained from out-of-plane deformation by a wire bridle. Two marks were made on each slice, separated either radially or tangentially as required. The distance between the marks was measured regularly along with the sample weight as the slices dried in the laboratory. The measuring apparatus is shown in Figure 2.1.2. Samples were then oven dried, reweighed and re-measured; bridle masses were also recorded at this point.

For each sample, a shrinkage curve was plotted. From each of the plotted shrinkage curves, three points were chosen by eye: zero shrinkage at the initial MC; shrinkage and MC at fibre saturation point (FSP); and shrinkage and MC at equilibrium. **KilnSched** fits a hyperbola to these three points to calculate unconfined shrinkage from MC.

Figure 2.1.1. Apparatus for slicing timber for shrinkage and moisture content profile measurement.

Figure 2.1.2. Apparatus for monitoring shrinkage of slices.

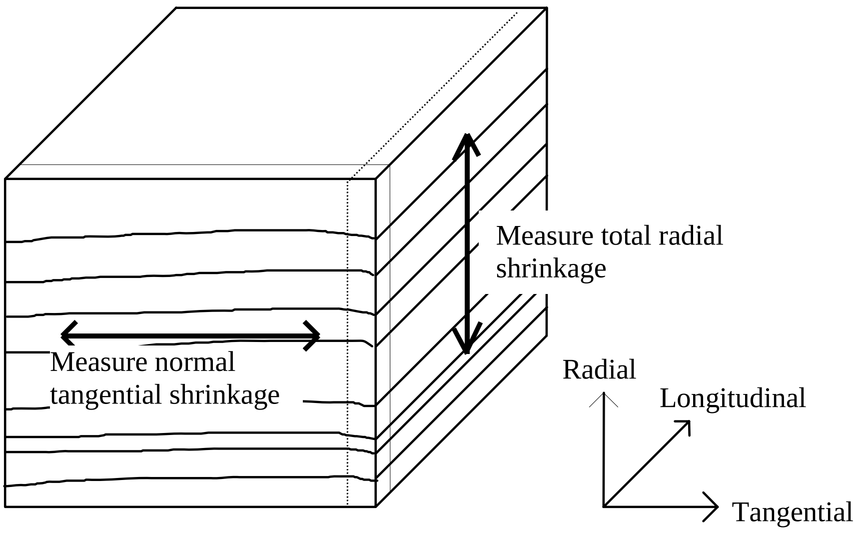

Figure 2.1.3. Orientation for slicing of unconfined shrinkage specimens.

2.1.4. Kiln loading

Rack sticks were all straight and dry (aluminium angle was used in the TRU trials). Five pairs of matched sample boards were used for each trial, half used for monitoring of average MC, the other half for monitoring of MC profile (destructive test). MC profile sample boards had a line marked along their length at mid-width on the top side to preserve their orientation in the stack. Sample boards were racked as shown in Figures 2.1.4. and 2.1.5, with the rest of the rack made up of green dummy boards cut from the same material. Temperature and humidity measurement sensors were located upstream of the stack at a height between the two sets of sample boards. Schedules were made sufficiently harsh to induce surface checking, to test the accuracy of **KilnSched** in stress modelling.

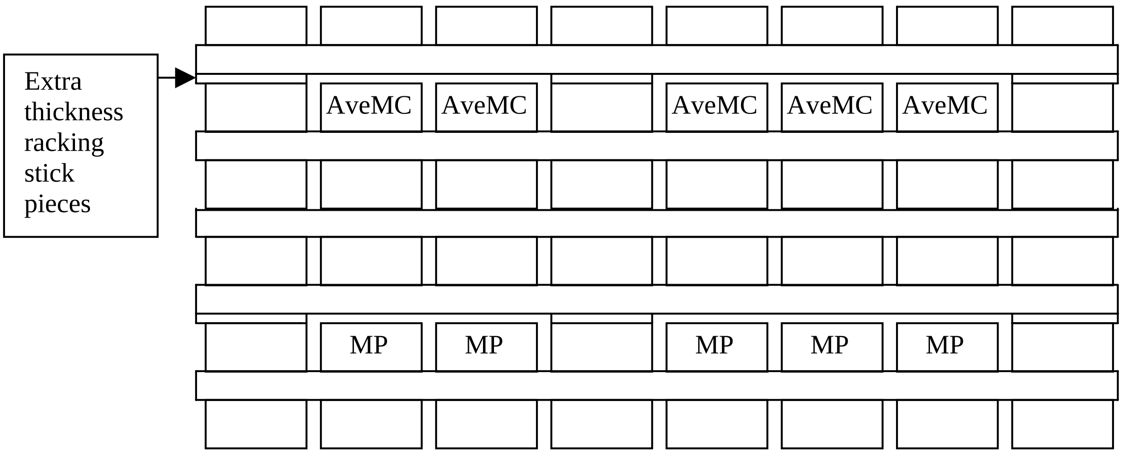

Figure 2.1.4. End view of part of kiln stack. Note extra thickness racking stick pieces to allow Moisture Profile (MP) and Average MC (AveMC) boards to be removed during trial. Note that boards were racked next to each other edge-wise; a gap is shown for clarity only.

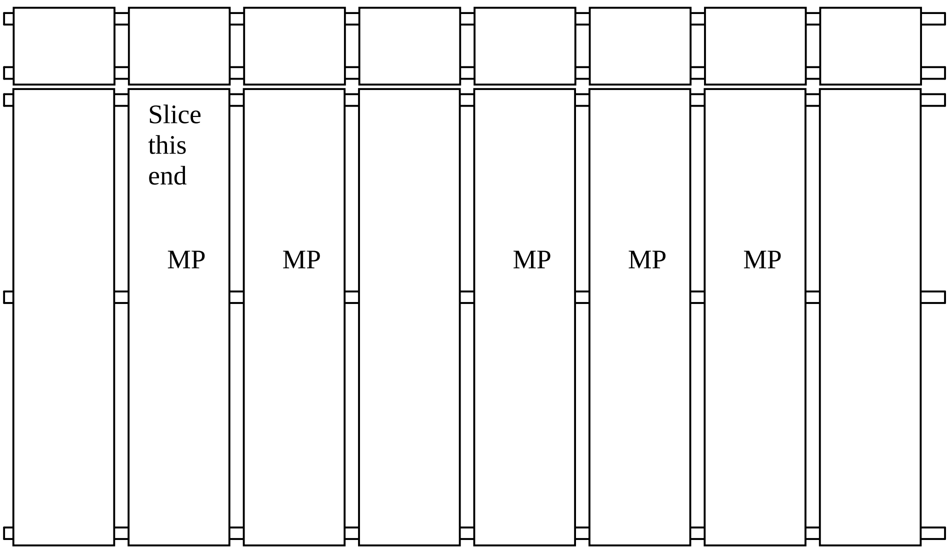

Figure 2.1.5. Top view at MP board level. MP boards were pushed back against short dummy pieces after each slicing to maintain uniform airflow around the end of the MP boards.

2.1.5. Sample board monitoring

Approximate initial moisture content of each average MC sample board was determined by oven dry testing a 50 mm long full board width section cut from adjacent to the sample board.

Average MC of the sample boards was predicted from this measurement by weighing the sample boards periodically throughout the drying trial.

Moisture profile sample boards were removed from the kiln for sampling as required. A cube was cut approximately 30mm clear of the board end, incorporating the line marked on the top surface. The sample board was immediately end-coated with Dussek Campbell Log-Shield and returned to the stack. About eight slices of approximately 0.8 mm thickness were cut from both the top and bottom surfaces of the cube using the apparatus shown in figure 2.1.1. Moisture content of each slice and the central core was determined by oven-drying. The measured moisture contents and slice thicknesses were used to construct moisture content profiles. The algorithm used for this by **KilnSched** extrapolates to the board surface and ensures that the integral of each section of the profile matches the measured value for each slice.

2.1.6. Diffusion coefficient calculation

To calculate diffusion coefficient, a model called **MCProfiles** was utilised. This is a cut down version of **KilnSched**, with the stress and strain calculation parts removed. Calculation of diffusion coefficient was performed by repeatedly modelling the drying trial, adjusting the diffusion coefficient value in **MCProfiles** until predicted and measured MC profiles matched. Predicted and measured average MC were then compared to give a check on the calculated diffusion coefficient.

Note that there is currently no means of directly measuring diffusion coefficient. “Diffusion cell” type measurements, for example Comstock (1963), inevitably measure permeability, that is, movement of water through wood, not diffusion out of fibres and through the wood fibre walls.

2.2. Victorian regrowth alpine ash, **Eucalyptus delegatensis**

Gould’s sawmill at Alexandra, Victoria, supplied five quartersawn boards of 1939 regrowth alpine ash, each sourced from a different log. Log sizes were typical of their supply. Each board was 130 × 28 mm and 2.8 m long, docked into 700 mm lengths for shipping.

2.2.1. Green properties

Unconfined shrinkage was measured on four samples from each of the five boards. For each board, two radial and one tangential normal shrinkage specimens (end-grain slices), and one radial total shrinkage specimen (longitudinal-radial slice) were examined. As the boards were quartersawn, radial shrinkage was required for modelling of stress development. Shrinkage measurement results are shown in Table 2.2.1. Basic density and initial MC were measured on each sample board. Results are shown in Table 2.8.1.

	Radial Shrinkage Fits %				Tangential Shrinkage Fits				Longitudinal-Radial Shrinkage Fits			
	FSP		EMC		FSP		EMC		FSP		EMC	
Board no.	MC	Sr	MC	Sr	MC	St	MC	St	MC	Sr	MC	Sr
1	31	0.5	9.5	3.1	40	0.2	9.6	5	28	1.1	10.1	3.1
	33	0.4	9.1	2.6								
2	31	0.3	7.5	5.1	38	1	9.1	7	24	2	8.1	5.1
	25	0.3	7	4.8								
3	20	0.5	6.8	3.8	32	0.7	5.6	5.4	23	1	9.6	4.1
	35	0.2	5.9	3.9								
4	33	0.4	8	3.7	Collapsed				33	0.7	9.5	3.4
	35	0.3	7.6	4								
5	38	0.3	6.3	4.2	44	0.7	6.6	4.9	32	1.3	8.4	3.9
	39	0.2	6.6	3.8								
Mean	32.1	0.3	7.4	3.9	38.3	0.7	7.7	5.6	28.0	1.2	9.1	3.9

Table 2.2.1. Unconfined shrinkage measurements for alpine ash. All figures in %.

2.2.2. Drying

The ten sample boards were racked at mid-height of the TRU research kiln as shown in Figure 2.1.4. Recorded drying conditions are shown in Appendix A. Unfortunately, ambient temperature exceeded the setpoint during the day (the trial was carried out in January), so dry bulb temperature fluctuated above setpoint. Humidity was controlled relatively well. Average MC sample boards were weighed after 38, 67, 139, 188, 238, 304, 332, 403, 475 and 909 hours drying; results are shown in Figure 2.2.1. MC profile boards were sliced after 67, 139, 188, 306, 475 and 909 hours. Profiles measured on one of the sample boards are shown in Appendix A. They are typical of profiles measured on the sample boards.

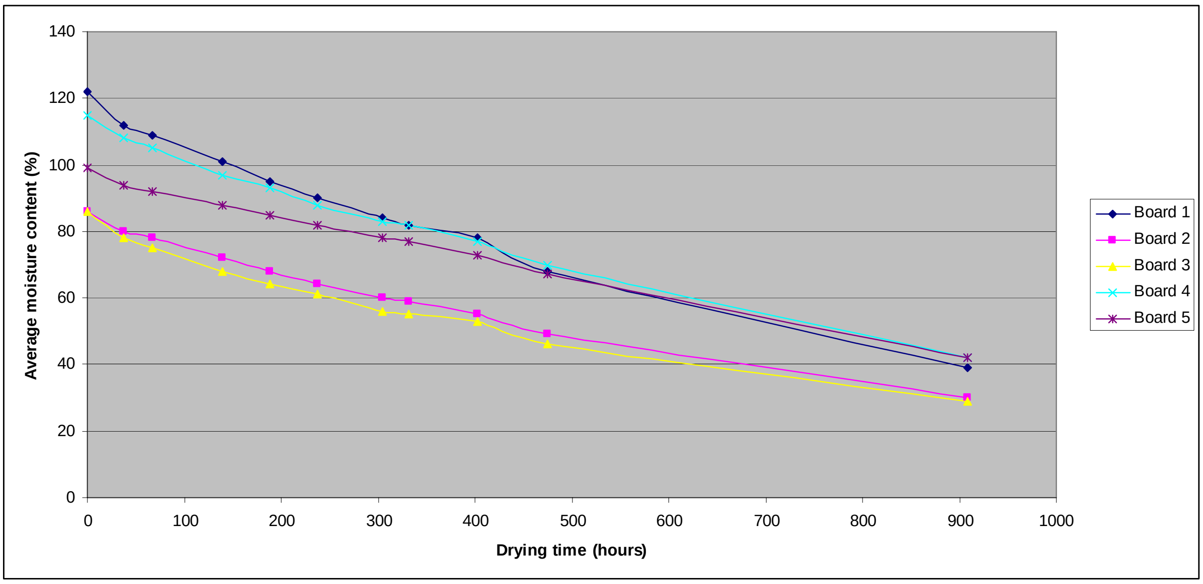

Figure 2.2.1. Average MC of sample boards, alpine ash trial.

Diffusion coefficient was calculated by matching predicted and measured average MC during the trial. Results are shown in Table 2.8.1. Diffusion coefficient is normally calculated by matching measured and predicted moisture content profiles, but in this case the model-predicted profiles did not match the shape of measured profiles.

Unfortunately the elevated temperature resulted in collapse. Where this collapse was close to the surface, the high collapse shrinkage was often seen to result in surface checking, which followed the affected earlywood band along the length of the board. Collapse associated surface checking was observed on sample boards 1, 2, 3 and 4 after 139 hours drying. **KilnSched** did not predict this as it cannot model collapse.

2.3. *Queensland regrowth blackbutt,* Eucalyptus pilularis

The sample timber was obtained from regrowth forest located in State Forest 589 Beerburrum, near the township of Wamuran, between Caboolture and Woodford about 35 km away from the coast. Latitude and longitude are 27°02' S and 152°51' respectively. The selected trees were located on flat country near a creek. According to the ranger responsible for this section of state forest, the chosen trees have an average age of approximately sixty years. Average over-bark diameter at breast height was 43 cm with a standard deviation of 5.4 cm. This forest is representative of most regrowth forests in sub tropical Queensland. It was sawn at the DPI&F sawmill. Sample boards were all nominally 100 × 25 mm (dry dimension), backsawn and initially 1025 mm long.

2.3.1. Green properties

Unconfined shrinkage was measured on one sample for both radial and tangential directions for each of the four samples. Results are shown in Table 2.8.1. Basic density and initial MC are also shown in Table 2.8.1.

2.3.2. Drying

The blackbutt was dried in a 0.25 m^3 research kiln at DPI&F. Four sample boards were used for both MC profile and average MC measurement. Average MC of sample boards during the trial was calculated by integrating the measured MC profiles; results are shown in Figure 2.3.1. Separate average MC boards were not used in this trial, so integration of the MC profiles was the only way of calculating average MC since the MC profile measurement is destructive. Drying conditions for the trial are shown in Appendix A.

The source of the dip in average MC of board 28-j-2 is probably longitudinal variation in MC along the board. As measurement of each MC profile necessitates removal of approximately 40 mm of board length, it is possible for the next profile to be measured from an area of significantly different MC if boards are subject to longitudinal variation.

The diffusion coefficient was calculated by matching predicted and measured MC profiles and average MC during the trial; MC profiles for one board are shown in Appendix A. Unfortunately, surface checking was not recorded during the trial. However, blackbutt is not normally prone to surface checking, so none would be likely from the comparatively mild drying conditions. As a result, no stress modelling was carried out.

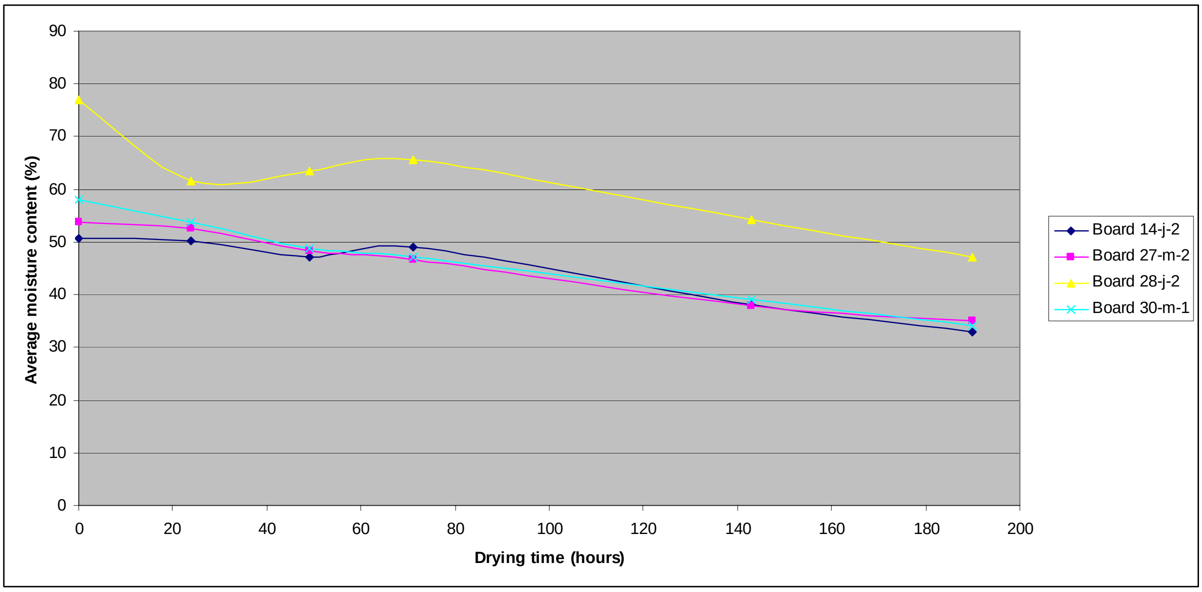

Figure 2.3.1. Average MC of sample boards by integrating measured MC profiles, blackbutt trial.

2.4. *Western Australian regrowth jarrah,* Eucalyptus marginata

Sotico (now Gunns WA) supplied five backsawn boards of regrowth jarrah to the TRU, each sourced from a different log. Log sizes were typical of their supply. Each board was 165 × 28 mm and 2.8 m long, docked to 700 mm lengths for shipping.

2.4.1. Green properties

Unconfined shrinkage was measured on three samples from each of the five boards; one radial and two tangential. Tangential shrinkage results are required for modelling stress development in backsawn boards. Shrinkage measurement results are shown in Table 2.4.1.

	Radial Shrinkage Fits %				Tangential Shrinkage Fits %			
	FSP		EMC		FSP		EMC	
Board no	MC	Sr	MC	Sr	MC	St	MC	St
1	40	0.2	8.6	5.8	39	0.5	9.4	5.88
					30	0.6	9	5.9
2	41	0.6	8.8	5.4	43	0.6	7.1	6.4
					35	0.2	9.4	5.8
3	46	0.3	11.5	4.1	30	0.8	10.8	4.7
					37	0.5	10.3	5.1
4	33.9	1.2	7.5	4.7	32	0.5	7.5	5.8
					32	1	9	6.8
5	46.6	0.3	9.9	4.8	40	0.5	11.2	5.4
					31	0.8	9.3	5.6

Table 2.4.1. Unconfined shrinkage measurements for jarrah. All figures in %.

Basic density and initial MC were measured on each sample board. Results are shown in Table 2.8.1.

2.4.2. Drying

The ten sample boards were racked at mid-height of the TRU research kiln as shown in Figure 2.1.4. Recorded drying conditions are shown in Appendix A. Ambient temperature exceeded the kiln setpoint several times throughout the trial, resulting in temperature exceeding setpoint by up to 2 °C. Relative humidity generally controlled to ± 1 %. Average MC sample boards were weighed after 21, 48, 69, 120, 159, 219, 309, 357, 453, 497, 548, 642, 671, 695, 714, 788 and 814 hours drying; results are shown in Figure 2.4.1. MC profile boards were sliced after 48, 120, 219, 385, and 716 hours. Profiles measured on one of the sample boards are shown in Appendix A. They are typical of profiles measured on the sample boards.

The diffusion coefficient was calculated by matching predicted and measured average MC during the trial. Results are shown in Table 2.8.1. The diffusion coefficient is normally calculated by matching measured and predicted moisture content profiles, but in this case the model-predicted profiles did not match the shape of measured profiles. Surface checking on sample boards was observed at the times shown in Table 2.8.1.

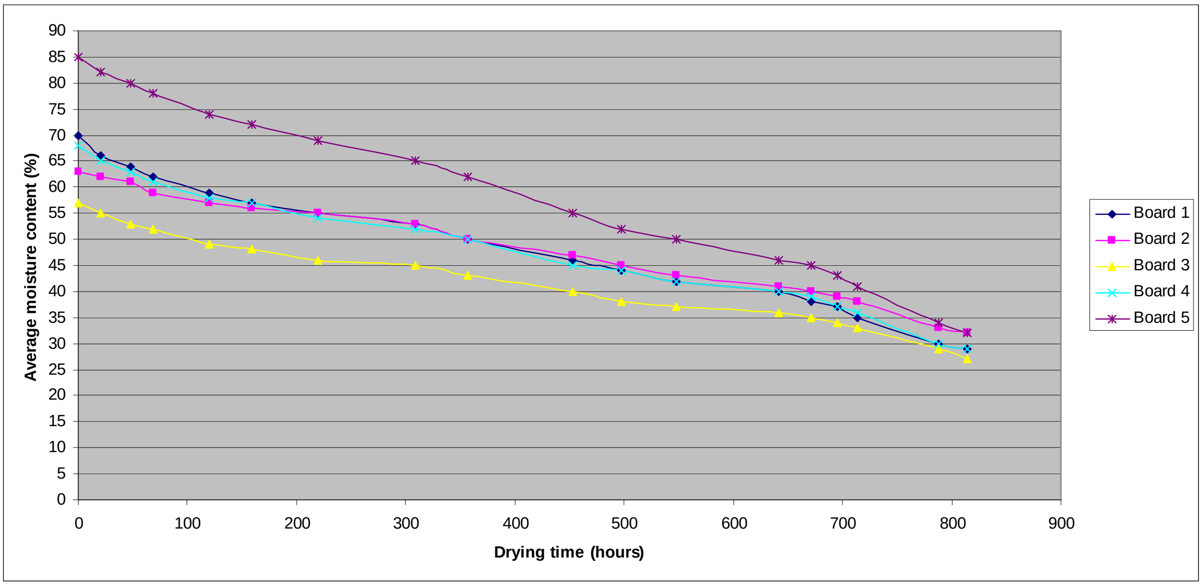

Figure 2.4.1 Average MC of sample boards, jarrah trial

2.5. *Tasmanian regrowth messmate,* Eucalyptus obliqua

Kelly Timbers supplied ten boards of 1939 regrowth messmate from the Tasman Peninsula (coupe Koonya 8B). Boards were backsawn, 130 × 28 mm and 2.8 m long docked to 700 mm lengths for transport. They have been labelled below as boards 1 to 5 and 1a to 5a. Clennett Timber provided a further five boards of the same dimension from their Dover mill. Logs were southern forest regrowth from the Esperance area, coupe EP061E. Trees were regrowth from the fires of 1898 and 1922. These boards were labelled as 1b to 5b.

2.5.1. Green properties

Unconfined shrinkage was measured on five of the Kelly sample boards and five of the Clennett sample boards in radial and tangential directions. Results are shown in Table 2.5.1.

	Radial Shrinkage Fits %				Tangential Shrinkage Fits %			
	FSP		EMC		FSP		EMC	
Board no	MC	Sr	MC	Sr	MC	St	MC	St
1	35	0.3	8	5.2	32.5	0.4	10	5.5
2	24	0.6	7	4.6	23.5	0.3	7.5	4.3
3	30	0.5	8	6.2	28	0.9	7.5	6.5
4	35	0.3	6	5.6	30	0.3	8	10.4
5	35	0.2	7	4.7	29	0.7	7.5	7.7
1a	30	0.5	10	4				
2a	35	0.3	10	4.5				
3a	35	0.5	10	6				
4a	35	0.5	9	6				
5a	35	0.5	12	5.5				
1b	40	0.5	12	6.9	40	0.5	11	6
	40	0.5	10	7				
2b	40	0.5	11	5.5	40	0.5	8	6
	40	0.4	10	6.5				
3b	40	0.5	8	7.6	40	0.5	8	8.5
	40	0.5	10	7.6				
4b	32	0.4	6	5.3	40	0.5	7	6
	35	0.3	7	5.3				
5b	37	0.3	7	6.3	31	0.5	7	6.6
	33	0.5	7	5.5				

Table 2.5.1. Unconfined shrinkage measurements for messmate.

Basic density and initial MC were also measured on all fifteen sample boards. Results are shown in Table 2.5.2.

Board	Basic Density (kg/m^3)	Initial MC (%)
1	586	73
2	541	95
3	569	88
4	600	85
5	630	74
1a	571	100
2a	607	82
3a	591	96
4a	595	92
5a	467	119
1c	535	102
2c	585	92
3c	585	95
4c	548	96
5c	586	78
Mean	573	91

Table 2.5.2. Basic density and initial MC for messmate.

2.5.2. Drying

Three separate drying trials were carried out. The kiln conditions for the first trial were too mild to induce surface checking, so results have been omitted. The third trial was carried out to confirm the results of the second and to provide additional data for modification of **KilnSched**. For each trial the ten sample boards (five matched pairs) were racked at mid-height of the TRU research kiln as shown in Figure 2.1.4.

Drying conditions for the second trial are shown in Appendix A; for the third trial in Figure 2.5.1. Drying progress of the average MC sample boards is shown in Figures 2.5.2 and 2.5.3 respectively. MC profiles measured on one of the sample boards of the second trial are shown in Appendix A. They are typical of the profiles measured.

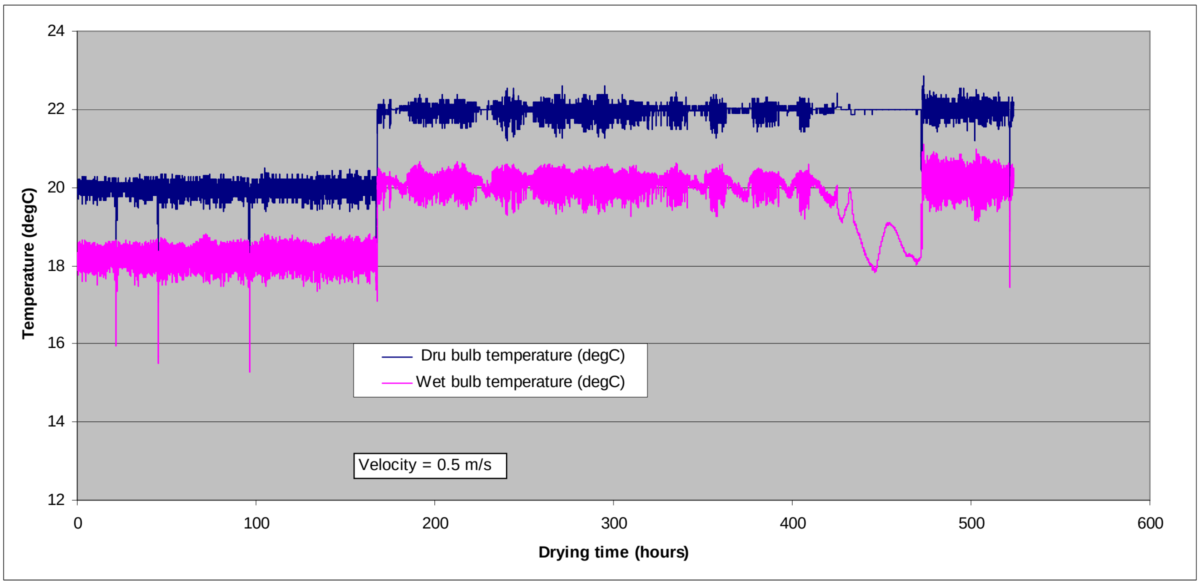

Figure 2.5.1. Recorded kiln conditions for messmate trial 3.

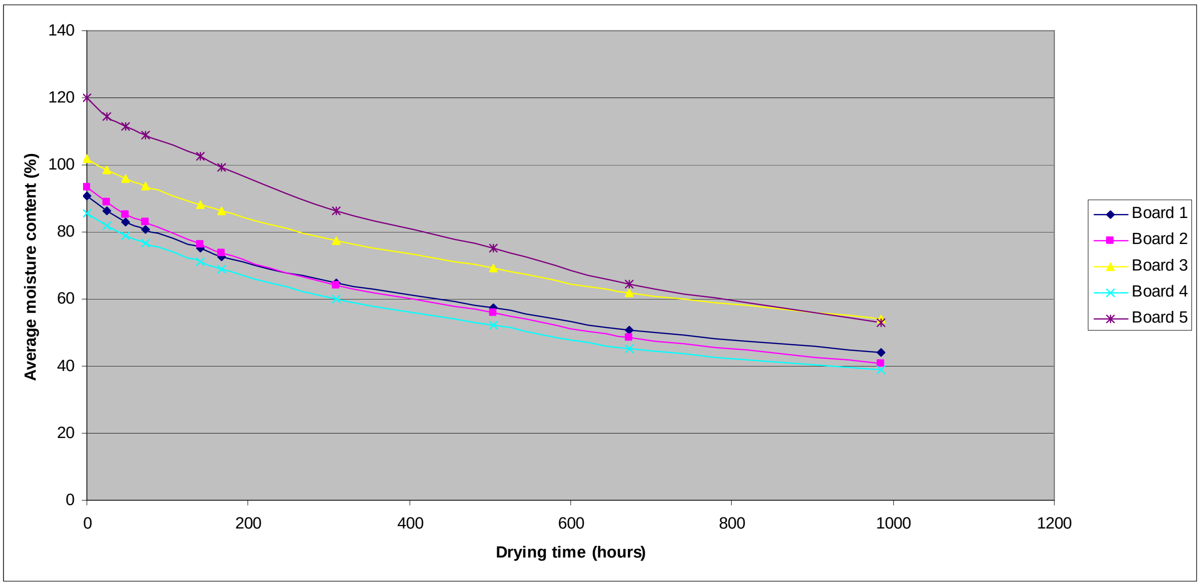

Figure 2.5.2. Average MC of average MC sample boards, messmate trial 2.

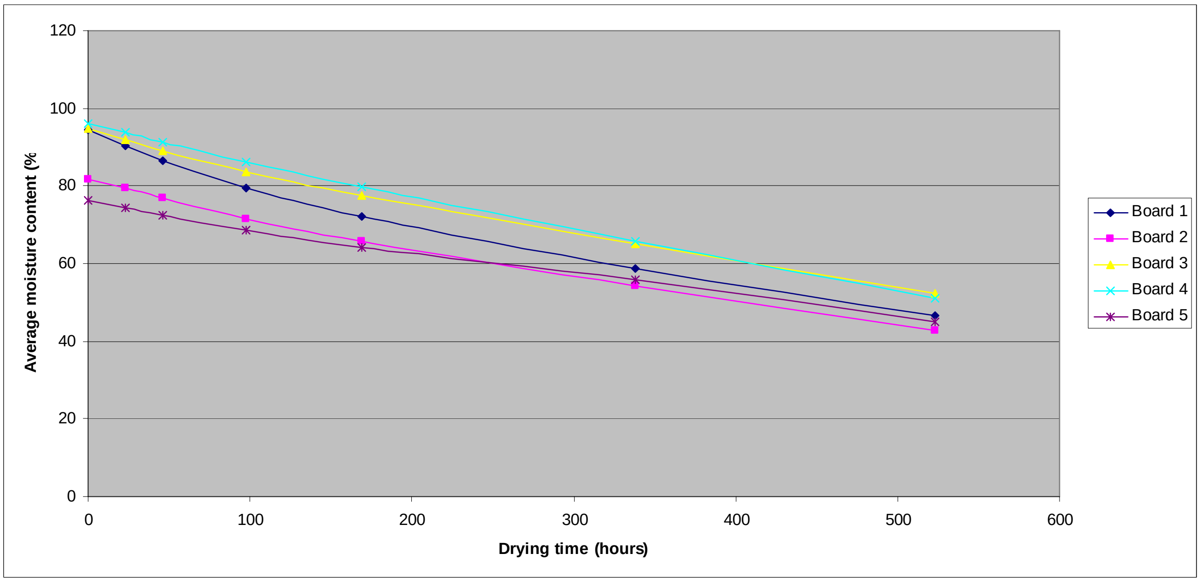

Figure 2.5.3. Average MC of average MC sample boards, messmate trial 3.

Diffusion coefficient was calculated by matching predicted and measured average MC as predicted profiles did not fit the measurements well. Results are shown in Table 2.8.1. A minor amount of surface checking was observed on all sample boards; this was associated with collapse that occurred despite the low drying temperature.

2.6. *Victorian regrowth mountain ash,* Eucalyptus regnans

Drouin West Timber Sales (DWTS) supplied five quartersawn boards of 1939 regrowth mountain ash, each sourced from a different log. Log sizes were typical of their supply. Each board was 130 × 28 mm and 2.8 m long, docked into 700 mm lengths for shipping.

2.6.1. Green properties

Unconfined normal shrinkage was measured on three cross-grain slices from each board; two radial and one tangential. The two radial measurements from each board were very similar, so separate results have not been presented here. Mean results are shown in Table 2.6.1. Initial MC and basic density were measured on a full cross section of each sample board; results are shown in Table 2.6.2.

	Radial Shrinkage Fits %				Tangential Shrinkage Fits %			
	FSP		EMC		FSP		EMC	
Board	MC	Sr	MC	Sr	MC	St	MC	St
1	26	0.5	9	7	40	0.2	8	8.2
2	25	0.3	7	5	40	0.3	7	6.9
3	35	0.5	8	3.7	30	0.8	8.2	6.6
4	30	0.1	8	4.5	30	0.5	8.6	6.6
5	30	0.1	8	4	30	0.2	8.7	5.3
Mean	29.2	0.3	8	4.84	34	0.4	8.1	6.72

Table 2.6.1. Unconfined shrinkage measurements for mountain ash

Board	Basic density (kg/m^3)	Initial MC (%)
1	593	74
2	454	121
3	473	116
4	570	71
5	485	92
Mean	515	95

Table 2.6.2. Basic density and initial MC for mountain ash

2.6.2. Drying

The ten sample boards (five matched pairs) were racked at mid height of the DPI&F research kiln as shown in Figure 2.1.4. Recorded drying conditions are shown in Appendix A. Average MC sample boards were weighed after 24, 68.5, 120.5, 168.5, 213.5, 309.5, 361, 382, 406, 472 and 502 hours drying; results are shown in Figure 2.6.1. MC profile boards were sliced after 22, 46, 91, 191, 236, 332, 406 and 523 hours. Profiles measured on one of the sample boards are shown in Appendix A. They are typical of profiles measured on the sample boards.

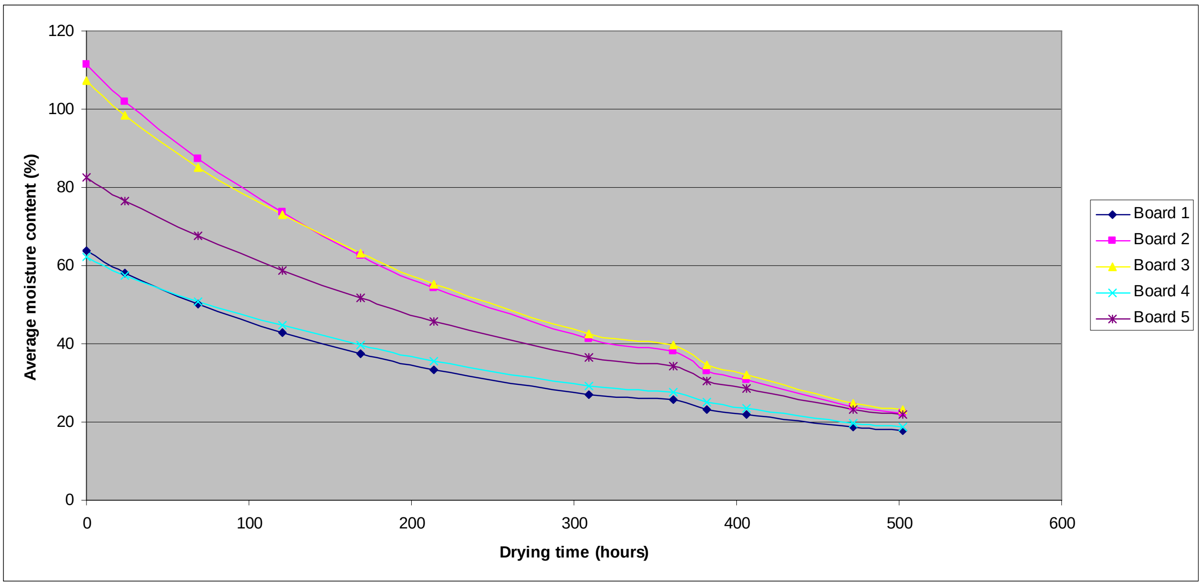

Figure 2.6.1. Average MC of sample boards, mountain ash trial.

Diffusion coefficient was calculated by matching predicted and measured average MC as well as matching predicted and measured MC profiles. Results are shown in Table 2.8.1. A minor amount of collapse-related surface checking was observed on sample boards 1, 4 and 5 after 24 hours drying. Boards 2 and 3 remained clear of surface checking for the duration of the trial but exhibited minor collapse.

2.7. *New South Wales regrowth spotted gum,* Corymbia maculata

Hyne and Sons supplied spotted gum boards from their Maryborough mill. They were typical of the regrowth material processed there. Boards were all nominally 100 × 25 mm (dry dimension), backsawn and initially 1000 mm long.

2.7.1. Green measurements

Unconfined shrinkage was measured on three samples from each of the five MC profile sample boards; two tangential and one radial. Mean results for each board are shown in Table

2.8.1. Basic density and initial MC were measured on each of the ten sample boards. Results are shown in Table 2.7.1.

Board no.	Basic density (kg/m^3)	Initial MC (%)
1	884	34
2	951	34
3	949	28
4	856	40
5	888	33
6	974	34
7	915	30
8	854	36
9	865	45
10	925	37
Mean	906	35

Table 2.7.1. Basic density and initial MC for spotted gum.

2.7.2. Drying

The ten sample boards (five matched pairs) were racked at mid height of the DPI&F research kiln as shown in Figure 2.1.4. Recorded drying conditions are shown in Appendix A. Average MC sample boards were weighed after 27, 48, 77, 98, 143, 187, 211, 239 and 314 hours drying; results are shown in Figure 2.7.1. MC profile boards were sliced after 18, 45, 66, 95, 161, 213, 257 and 330 hours drying. Profiles measured on one of the sample boards are shown in Appendix A. They are typical of profiles measured on the sample boards.

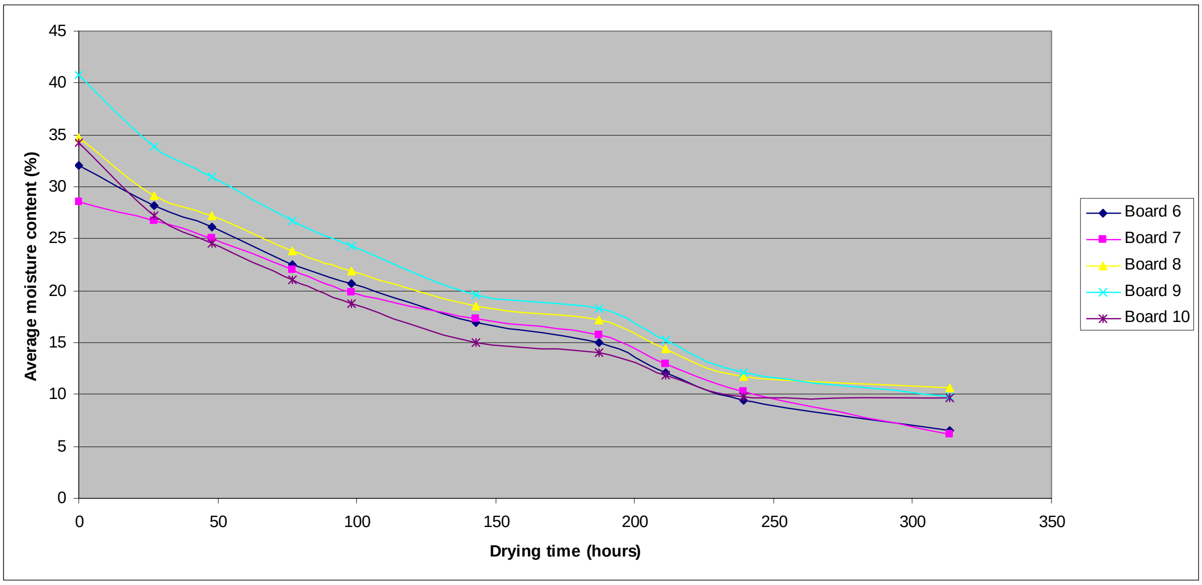

Figure 2.7.1. Average MC of sample boards, spotted gum trial.

Diffusion coefficient was calculated by matching predicted and measured average MC values during the trial. Results are shown in Table 2.8.1. Note that this diffusion coefficient may not be accurate for drying at lower temperatures; the form of the temperature dependence of diffusion coefficient in **KilnSched** is based on data measured at temperatures well below those of the spotted gum trial. No stress modelling was carried out due to the high drying temperature, as well as some drying of sample boards prior to the trial evident from initial MC profile slicing.

2.8. Results from all laboratory scale trials

Summary results from all laboratory scale trials are shown in Table 2.8.1.

Species	Pack	Basic Density kg/m^3	Initial MC %	Thick mm	Diffusion Coefficient m^2/hr	Radial Unconfined Shrinkage Fits %: FSP MC	Radial FSP Shrinkage	Radial EMC MC	Radial EMC Shrinkage	Tangential Unconfined Shrinkage Fits %: FSP MC	Tangential FSP Shrinkage	Tangential EMC MC	Tangential EMC Shrinkage	Time to surface check formation (hours): Observed	Time to surface check formation (hours): Model
alpine ash	1	457	125	27.1	1.00E-07	32	0.5	9.3	2.9	40	0.2	9.6	5.0	67-139*	Clear
Quartersawn	2	564	87	27.4	8.00E-08	28	0.3	7.3	5.0	38	1.0	9.1	7.0	67-139*	Clear
Victoria	3	549	87	25.7	7.00E-08	28	0.4	6.4	3.9	32	0.7	5.6	5.4	67-139*	Clear
TRU	4	497	120	29.5	8.00E-08	34	0.4	7.8	3.9	Collapsed				67-139*	Clear
	5	507	103	27.6	4.00E-08	39	0.3	6.5	4.0	44	0.7	6.6	4.9	Clear	Clear
	Mean	**515**	**104**	**27.5**	**7.40E-08**	**32**	**0.3**	**7.4**	**3.9**	**38**	**0.7**	**7.7**	**5.6**		
blackbutt	14-J-2	558	56	28.0	1.20E-07	26	0.6	12.0	3.4	26	1.0	10.4	5.7	No information	
Backsawn	27-M-2	605	56	27.0	1.20E-07	25	0.5	11.6	3.7	25	0.7	11.2	4.3	No information	
Queensland	28-J-2	596	76	27.0	1.70E-07	26	0.3	11.3	2.0	26	0.5	10.7	4.4	No information	
DPI&F	30-M-1	627	60	26.0	1.20E-07	22	0.4	11.5	3.9	22	0.7	11.1	3.4	No information	
	Mean	**596**	**62**	**27.0**	**1.08E-07**	**25**	**0.5**	**11.6**	**3.3**	**25**	**0.7**	**10.9**	**4.5**		
jarrah	1	632	75	27.4	8.00E-08	40	0.2	8.6	5.8	35	0.6	9.2	5.9		
Backsawn	2	670	65	27.4	7.00E-08	41	0.6	8.8	5.4	39	0.4	8.3	6.1	695-714	723
Western Australia	3	697	65	29.3	1.20E-07	46	0.3	11.5	4.1	33	0.7	10.6	4.9	788-814	>814
TRU	4	638	74	27.4	7.00E-08	34	1.2	7.5	4.7	32	0.8	8.3	6.3	695-714	752
	5	600	83	29.7	1.10E-07	47	0.3	9.9	4.8	36	0.7	10.3	5.5	714-788	720
	Mean	**647**	**72**	**28.2**	**9.00E-08**	**42**	**0.5**	**9.3**	**5.0**	**35**	**0.6**	**9.3**	**5.7**		
messmate	1	571	100	29.1	8.00E-08	30	0.5	10.0	4.0	33	0.4	10.0	5.5	310*	Clear
Quartersawn	2	607	82	28.9	9.00E-08	35	0.3	10.0	4.5	24	0.3	7.5	4.3	310*	Clear
Tasmania	3	591	96	28.5	6.50E-08	35	0.5	10.0	6.0	28	0.9	7.5	6.5	310*	664
TRU	4	595	92	32.9	8.00E-08	35	0.5	9.0	6.0	30	0.3	8.0	10.4	310*	Clear
	5	467	119	29.4	8.00E-08	35	0.5	12.0	5.5	29	0.7	7.5	7.7	310*	478
	Mean	**566**	**98**	**29.7**	**7.90E-08**	**34**	**0.5**	**10.2**	**5.2**	**29**	**0.5**	**8.1**	**6.9**		

Table 2.8.1. Summary results from all laboratory scale trials. Continued below.

Species	Pack	Basic Density kg/m^3	Initial MC %	Thick mm	Diffusion Coefficient m^2/hr	Radial Unconfined Shrinkage Fits % FSP MC	Radial FSP Shrinkage	Radial EMC MC	Radial EMC Shrinkage	Tangential Unconfined Shrinkage Fits % FSP MC	Tangential FSP Shrinkage	Tangential EMC MC	Tangential EMC Shrinkage	Time to surface check formation (hours) Observed	Time to surface check formation (hours) Model
mountain ash	1	593	74	26.9	1.70E-07	26	0.5	9.0	7.0	40	0.2	8.0	8.2	24*	Clear
Quartersawn	2	454	121	30.3	2.10E-07	25	0.3	7.0	5.0	40	0.3	7.0	6.9	Clear	Clear
Victoria	3	473	116	28.7	1.70E-07	35	0.5	8.0	3.7	30	0.8	8.2	6.6	Clear	Clear
DPI&F	4	570	71	27.8	1.70E-07	30	0.1	8.0	4.5	30	0.5	8.6	6.6	24*	Clear
	5	485	92	24.6	1.30E-07	30	0.1	8.0	4.0	30	0.2	8.7	5.3	24*	Clear
	Mean	**515**	**95**	**27.7**	**1.70E-07**	**29**	**0.3**	**8.0**	**4.8**	**34**	**0.4**	**8.1**	**6.7**		
spotted gum	1	884	34	26.4	9.00E-08	30	0.0	6.3	5.0	22	0.0	8.5	6.3	27**	
Backsawn	2	951	34	26.8	6.00E-08	20	0.0	5.0	5.0	26	0.5	7.2	5.2	Clear	
New South Wales	3	949	28	26.1	6.00E-08	22	0.0	7.0	5.0	29	0.0	6.5	4.3	98**	
DPI&F	4	856	40	25.6	1.10E-07	35	0.0	10.0	5.2	27	0.1	10.0	6.1	Clear	
	5	888	33	25.2	1.20E-07	27	0.0	8.0	4.0	25	0.0	8.5	6.5	27**	
	Mean	**906**	**34**	**26.0**	**8.80E-08**	**27**	**0.0**	**7.3**	**4.8**	**26**	**0.1**	**8.1**	**5.7**		

*Surface checking observed on these boards was associated with collapse.

**The initial moisture profiles from these boards suggested that some drying (and hence stress development) had occurred prior to the kiln.

Table 2.8.1. Summary results from all laboratory scale trials. Continued from above.

3. Modifications to KilnSched model

There were two main problems generally found when comparing **KilnSched** predicted moisture content profiles with those measured on regrowth hardwoods in this project. The first was a low modelled MC at the surface (in some cases only below FSP). The second was modelled moisture profiles too "round" in shape; the measured profiles tended to be flatter through centre sections with steeper gradients near the surface. Modelling on a species-by-species basis revealed that two changes to the model resulted in adequate **KilnSched** simulation; changes to the sorption isotherm (this changes predicted surface MC below FSP) and introduction of a correction at the surface (affecting surface MC above FSP, and shape of the modelled profiles).

3.1. Sorption isotherms

A "sorption isotherm" is the relationship between equilibrium moisture content (EMC) in the wood and humidity in the air at a particular temperature. More water can be held by wood following drying than following wetting; that is, the desorption (drying) isotherm is above the adsorption isotherm. The difference is mainly due to bonding between water molecules and cellulose. The difference between desorption and adsorption isotherms is typically a maximum of about 3 % MC. Published charts relating wood EMC to temperature and humidity (of the air) are generally averaged desorption and adsorption isotherms.

The most commonly used EMC chart in Australia is that published by CSIRO. Unfortunately the source(s) for the data behind the chart is not clear, but appears likely to have been unpublished CSIRO work at least 30 years old.

The sorption isotherms used in **KilnSched** are taken from Nelson (1983) based on work by Kelsey (1957) on *Araucaria klinkii*, and are expressed as equation 1:

$$\exp\left[A\left(1-\frac{m}{m_v}\right)\right]=-\frac{RT}{M}\ln\left(\frac{RH}{100}\right) \qquad \text{—1.}$$

Where A = constant

m = moisture content (g/g)

m_v = a measure of fibre saturation point (FSP, g/g)

R = universal gas constant (8.314 kJ/kmol.K or 1.986 kCal/kmol.K)

T = absolute temperature (K)

M = molecular weight of water (18.016 kg/kmol)

RH = relative humidity (%)

Kelsey's results for desorption lead to:

A = 5.116

m_v = 0.328-0.0013T_w, where T_w = temp of air in contact (°C)

These results have proven satisfactory around room temperature for the mature eucalypt timbers on which **KilnSched** has been used in the past. However recent results (Blakemore 2003) have supported observations from experimental kiln trials conducted as part of this project, that desorption isotherms for some of the regrowth species studied were significantly different from those used in **KilnSched**.

The data generated by Blakemore was not intended for the generation of desorption isotherms and is therefore not totally suited for this purpose. Specifically, in his study only a uniform and constant climate was required, and therefore accurate measurements of temperature and humidity surrounding the specimens were not recorded. However, Blakemore's data was the best currently available to the authors and so it has been adapted to this task.

Blakemore's measurements showed that the six regrowth species examined could be separated into two groups, as shown in Figure 3.1.1. The isotherm described above proved satisfactory for four of the six species studied: alpine ash, messmate, mountain ash and spotted gum. However, blackbutt and jarrah proved to be different, but similar to each other. For these two species, the desorption isotherm was modified by using:

$$A = 5.134$$

$$m_v = 0.3592-0.0013T_w$$

Mean measured desorption isotherms for each group are shown along with the model isotherms in Figure 3.1.2. The model isotherms are not especially good fits to the data, but will suffice given the shortcomings of the available data as adapted for this use and the variability inherent in timber. Note that Blakemore's measurements were all performed at 25 °C. The temperature dependence of m_v was thus retained from the original isotherm model.

The adsorption isotherm model was left unmodified as there is no new data available. This was not expected to cause problems as **KilnSched** is not generally used for modelling absorption of water by wood.

Experiments to accurately determine the sorption isotherms for these species are beyond the scope of this project. The extra accuracy afforded by the specific experiments required does not justify the cost at this stage. Similarly, there are other sorption isotherm models than the one used, for example, Hartley (2000), but the accuracy of the data available does not warrant attempts to find a closer model fit.

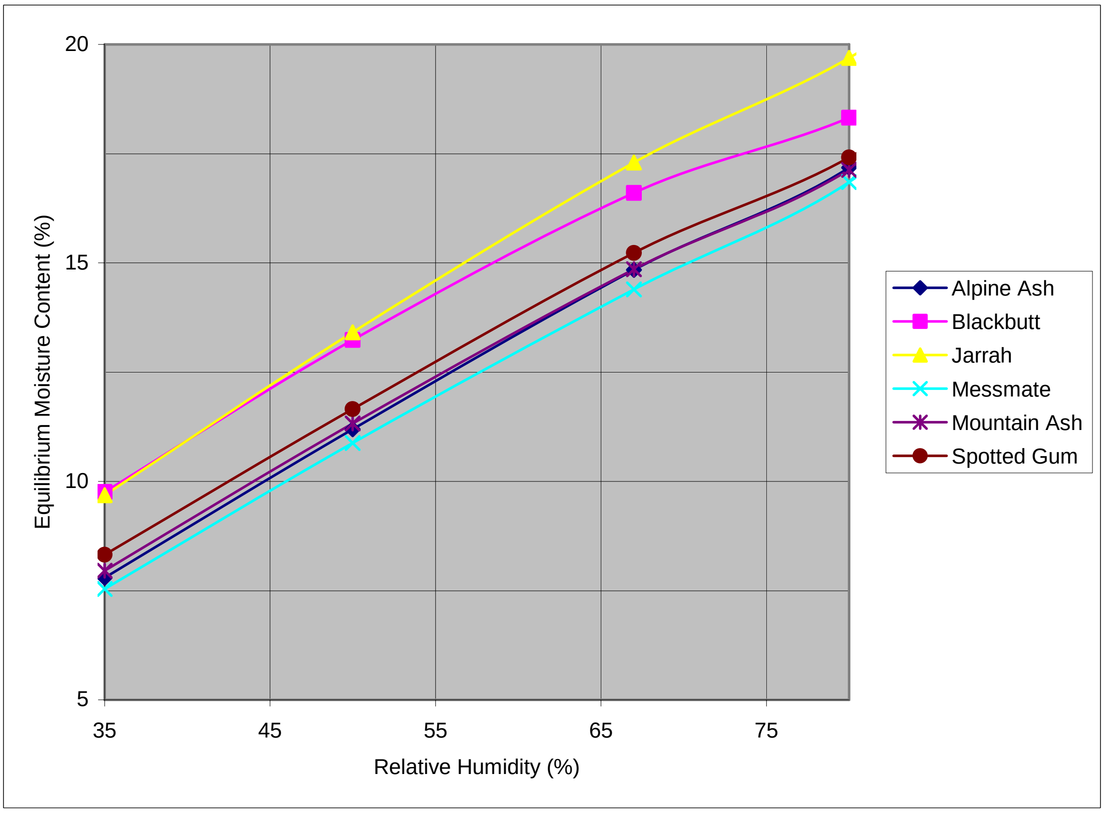

Figure 3.1.1. Desorption isotherms at 25℃ adapted from data of Blakemore 2003.

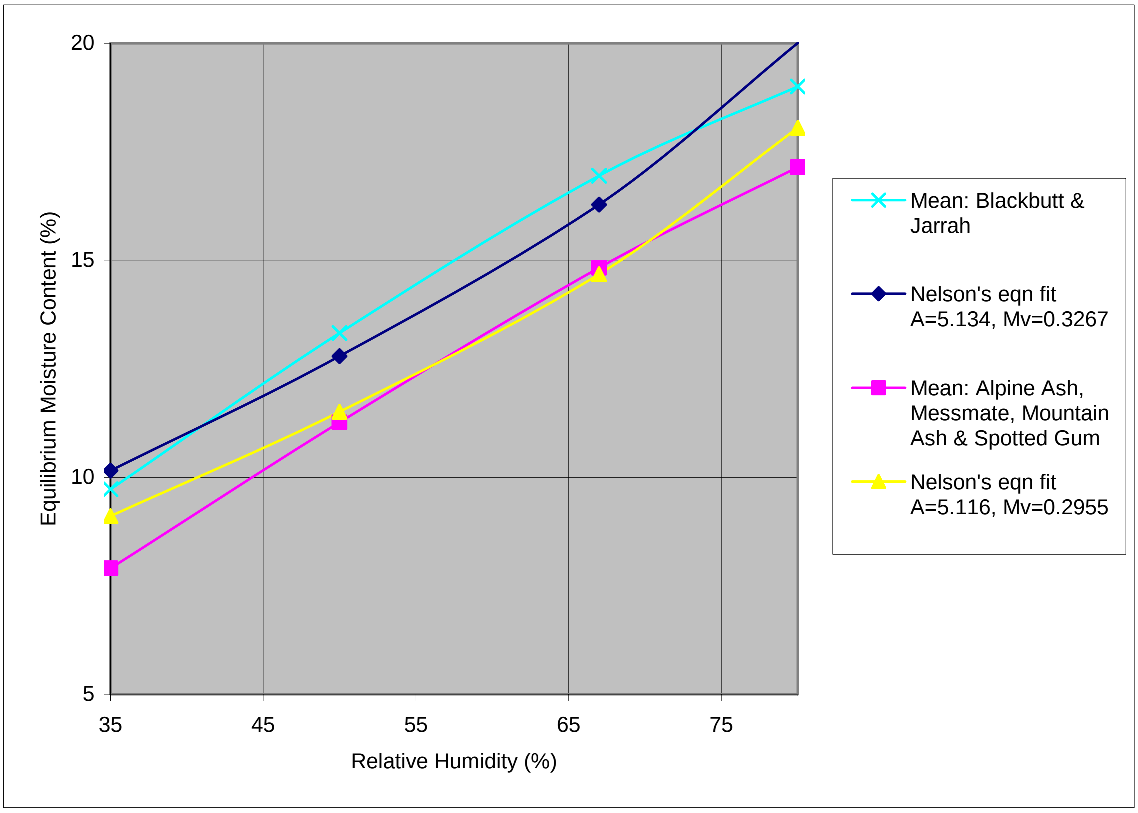

Figure 3.1.2. Model(Nelson's equation 1) and mean measured desorption isotherms for two species groups (adapted from Blakemore 2003).

3.2. Drying behaviour of the wood surface

The experimental drying trials performed in the first part of this project for alpine ash, jarrah and messmate showed different drying behaviour when compared to mature eucalypts and the other species studied. Moisture profiles measured in this trial tended to be fairly flat through the centre parts of boards, with a steep gradient near the surface. An example is shown in Figure 3.2.1.

Many models of drying wood introduce a correction factor (“surface emission coefficient”, “humidity potential coefficient”) to account for the often-observed error found when applying the Reynold’s analogy (similar mechanisms for heat, mass and momentum transfer). To date, the boundary layer theory utilised in **KilnSched** has been satisfactory. However, the observed behaviour in regrowth alpine ash, jarrah and messmate necessitates the introduction of corrections for those species.

Libby and Haygreen (1967) and Simpson (1971) examined the effect of tensile stress on moisture content following the theory of Barkas (1949). The magnitude of the effect measured was a maximum of about 1 % MC at high stress levels and moisture contents.

Dry-shell theory (Salin 2002) provides another possible explanation for surfaces above FSP. He connects this dry-shell with percolation theory (Salin 2003). However, this theory applies to open porous networks, which is applicable for northern European softwoods but not for Australian hardwoods.

Machining of boards prior to drying is reputed to alter the drying characteristics of wood; this appears to be practised in some US sawmills. Presumably surface roughness effects heat and mass transfer through the boundary layer (and laminar sub-layer if it exists, as seems likely in this situation). Thus it seems that surface finish from sawing could effect drying. Alterations to the friction factor in **KilnSched** did not effect modelling results substantially.

It has also been proposed (Oliver 2003 pers comm[1]) that sawing may cause micro-structural damage to the wood surface, which could be expected to effect the surface drying. The magnitude of this effect would vary with the wood’s structural properties.

Determination of exactly what is causing these modelling inaccuracies for each of the three species is beyond the scope of this project. However, the match between measured and modelled results is more important to the use of the model than a deeper understanding of the process involved. In order to get on with implementation of the model, the nature of the change made for the three affected species is the introduction of a surface diffusion coefficient, DCS, which is calculated as a function of the interior diffusion coefficient, DCI. The models for alpine ash and messmate were found to best match the observed drying with DCS = 2 × DCI, while the model for jarrah best matched the measured drying with DCS = 4 × DCI.

[1] AR Oliver, dec, formerly Emeritus Professor in Engineering at the University of Tasmania

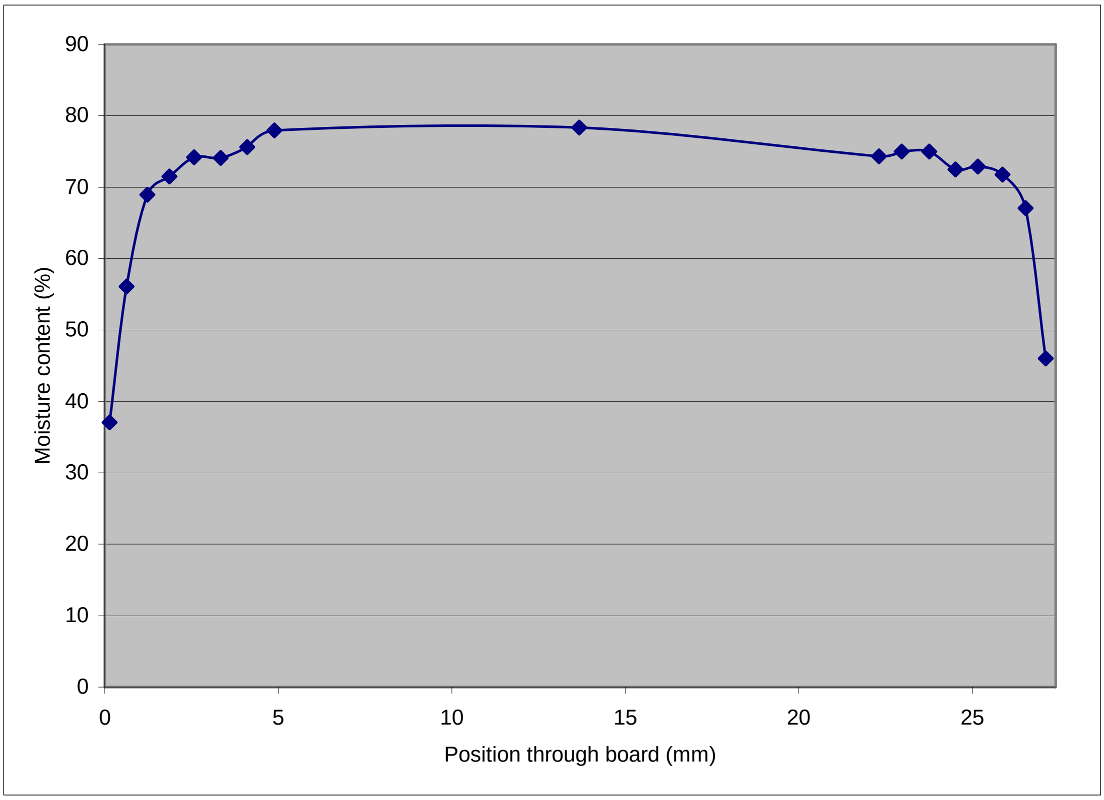

Figure 3.2.1. Moisture content profile after 306 hours drying, alpine ash board 2.

3.3. Models by species.

A summary of the modifications to **KilnSched** to suit each species is shown below. A repeated process of modelling and comparison with measurements determined the nature of the changes required to the model for each species. Appendix A contains examples of modelling results for each species with the new versions of the model.

3.3.1. Alpine ash

The standard sorption isotherm was satisfactory. To satisfactorily predict the surface MC and profile shape, the relationship DCS = 2 × DCI was used.

3.3.2. Blackbutt

The standard model was found to satisfactorily simulate the drying of this species. Note, however, that this drying trial was carried out at 43 °C, so it is likely that changes to the sorption isotherm, as outlined above, may still be necessary at lower temperatures. Unfortunately no degrade data was available, so no comparison was possible for stress modelling. The stress model could not be run anyway without extensive filtering of the kiln record data as the kiln condition data recording suffered from excessive noise. This was remedied before further trials were carried out in the DPI&F kiln.

3.3.3. Jarrah

The new sorption isotherm, as detailed above, was used with:

A = 5.134

$m_v = 0.3592 - 0.0013\ T_w$

The surface diffusion coefficient was increased to 4 × internal diffusion coefficient, i.e.

DCS = 4 × DCI.

3.3.4. Messmate

The standard sorption isotherm proved satisfactory as expected (these trials were carried out at 20 - 22 °C). To satisfactorily predict the profile shape, the relationship DCS = 2 × DCI was used.

3.3.5. Mountain ash

The standard model was found to satisfactorily simulate the drying of this species.

3.3.6. Spotted gum

The drying trials of spotted gum carried out by DPI&F for this project used dry bulb temperatures increasing from 45 °C to 70 °C. Note that the initial MC of this material was very low, around 35 %. It appeared from the initial moisture profiles that some drying of the timber might have occurred prior to delivery to the laboratory. The surface moisture contents predicted by **KilnSched** at the end of drying were consistently significantly higher than the measured values. To account for this, adjustments were made to the sorption isotherm. A fixed value of A = 4.75 was used. This value should probably vary with temperature, but accurate data for this species were not available. The measurement accuracy of slicing for MC profile may have been compromised somewhat by the high drying temperature and consequent rapid MC redistribution.

Unfortunately, it was not possible to perform any stress/strain modelling with this species, for two reasons:

- The drying temperature (up to 70 °C) is much too high for **KilnSched**.
- There had been some drying prior to the boards reaching the kiln so that the surfaces were below FSP. Thus shrinkage and stress development had already occurred, invalidating the assumption of zero stress at the start of modelling.

4. Commercial and near-commercial scale trials

4.1. *Western Australian regrowth jarrah,* Eucalyptus marginata

4.1.1. Materials

Gunns Ltd WA (previously Sotico) supplied 105 green backsawn jarrah boards of 112 × 29 mm × 3.3 m long, making 1.12 m^3. The timber was measured, racked and wrapped in the TRU laboratory in Launceston and then transported to Gunns sawmill at Lindsay St in Launceston for predrying.

Green measurements performed on each board were: length; width; thickness; mass; endsplit numbered end; endsplit other end; surface check top surface; surface check bottom surface; spring >10 mm; bow >25 mm; Twist >10 mm and Director HM200 velocity. No endsplit was found on any boards. Approximately 1.5 m of the total board surface length was affected by surface check as a result of a tear in the plastic wrapping.

Ten boards were sampled for initial moisture content (MC), basic density and unconfined shrinkage (radial and tangential). Shrinkage curves were fitted using three points: zero shrinkage at the initial MC; shrinkage and MC at fibre saturation point (FSP); shrinkage and MC at equilibrium MC (EMC). These results are shown in Appendix B.

4.1.2. Drying

The timber was dried at Gunns Lindsay St, Launceston mill as part of a commercial charge in one of their new 300 m^3 Mahild predriers – see Figure 4.1.1.

Figure 4.1.1. Loading jarrah (top) and messmate (bottom) into Gunns predrier

The schedule used in the predrier was Gunns' standard schedule for the timber making up the charge (38 mm thick Tasmanian Oak). Setting the schedule to a model-generated one optimised for the experimental timber was not feasible.

Temperature and humidity conditions were monitored throughout the trial by means of a Vaisala HMP233 temperature and humidity probe adjacent to the trial timber. This was connected to a HOBO U12-013 data logger, with the unit powered by sealed lead-acid batteries (Figure 4.1.2). The first week of data was unusable due to condensation on the probe; Gunns kiln records were accessed for this period. A further 3 days data was lost due to flat batteries; it was assumed that the conditions of the previous 3 days were repeated. The kiln conditions record is shown in Figure 4.1.3. Regular periodic fluctuations are due to fan reversal. Rises in humidity beginning at approximately 45 and 52 days are due to kiln shutdown associated with steam supply. Gunns have improved kiln control since this trial by altering vent operation.

Air velocity was measured with a vane anemometer at sixteen positions across the rack face. Distribution was uniform within ±20%. Velocity was increased once during the trial from 0.5 m/s to 0.7 m/s. The area above the experimental stacks was baffled, but the end of the stacks was left unbaffled as airflow was sufficiently uniform and drying of the commercial racks in the kiln could not be impeded.

Figure 4.1.2. HOBO datalogger being downloaded

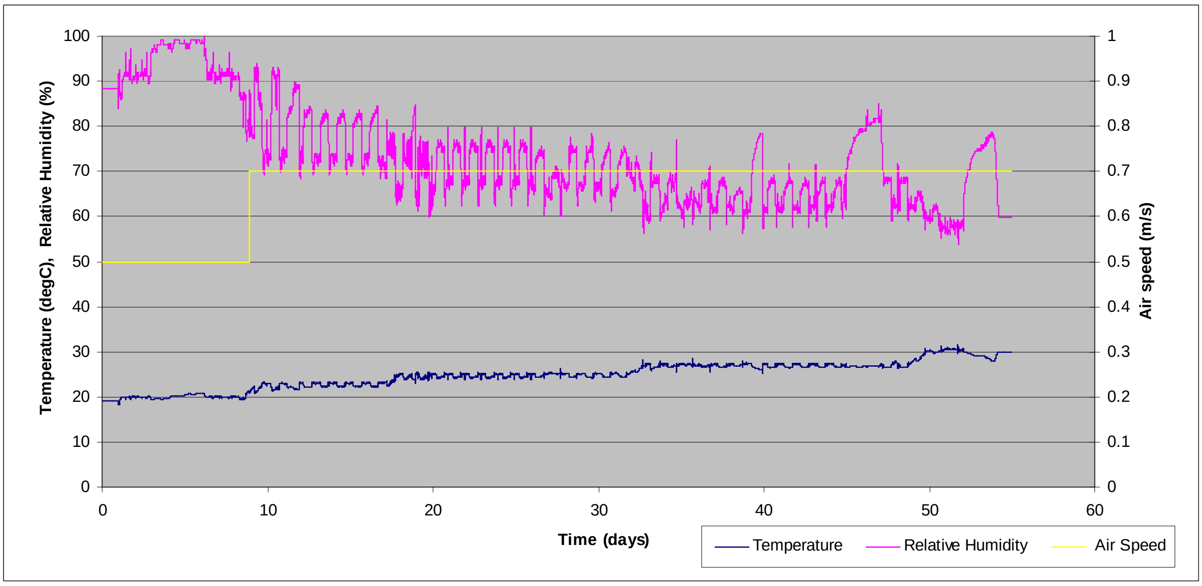

Figure 4.1.3. Kiln conditions record for jarrah and messmate

Five of the ten boards sampled for basic density and initial MC were monitored throughout the trial for weight (to give average MC), width and thickness. The other five were monitored for width, thickness and moisture profile (destructive slicing test). Measurements were carried out after 49 (2), 172 (7), 385 (16), 625 (26) 794 (33), 983 (41), 1152 (48) and 1318 (55 – end of predrying) hours (days) drying. See Figures 4.1.4, 4.1.5 and 4.1.6. Shrinkage in both thickness and width varied widely between boards.

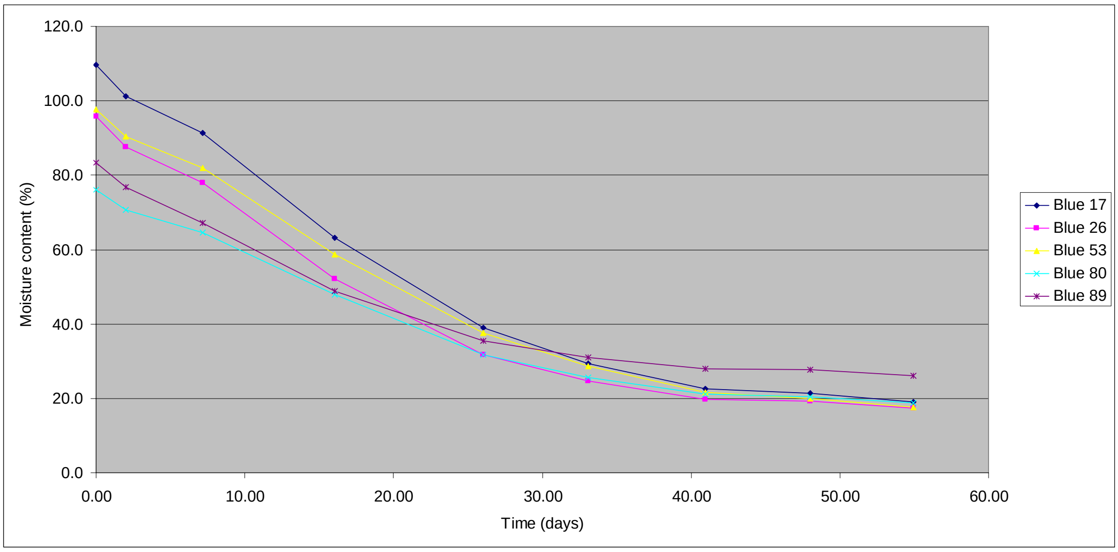

Figure 4.1.4. Moisture content of sample boards during drying

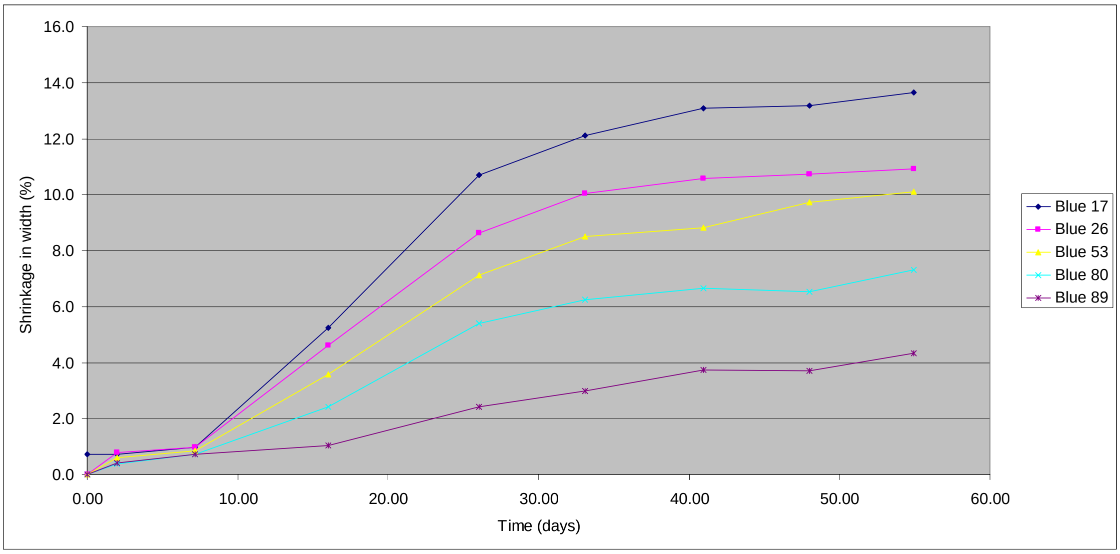

Figure 4.1.5. Shrinkage in width of sample boards during drying

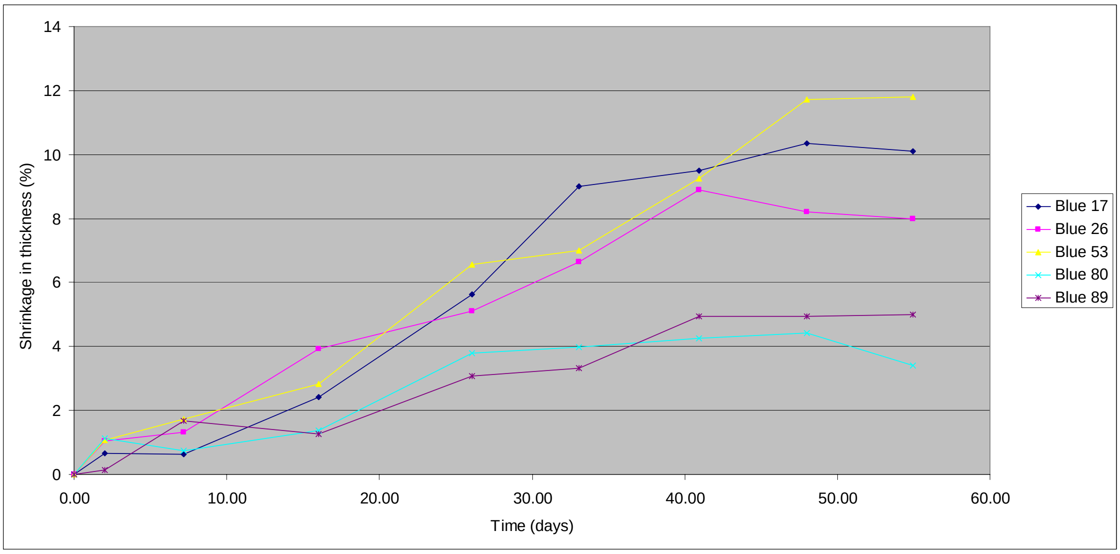

Figure 4.1.6. Shrinkage in thickness of sample boards during drying

The jarrah boards were removed from the Gunns kiln when the messmate was ready for reconditioning on 21/12/2004, as they were to be final dried together. Average MC of the jarrah sample boards at this point was 15.2%. The timber was stored at the TRU laboratory until final drying took place in the FFIC research kiln on the NST Mowbray site in the second week of February. Timber was machined to 19 mm thickness on the 12th of February at NST Mowbray by removing 3 mm from the bottom surface and the rest from the top. Each machined side was graded to AS 2796 by a commercial grader (disregarding distortion). Minimum length for Select grade sections was 900 mm with no length limit on sections downgraded. Each board was then measured for length; width; endsplit numbered end; endsplit other end; length of each face degraded by surface checking; length of each face degraded by machining skip; bow if greater than 19 mm over 2.4 m length; spring if greater than 10 mm over 2.4 m length; twist if greater than 8 mm; cup if greater than 1mm; and average MC and MC gradient to AS4787 (Standards Australia 2001). One end of each board then had 300 mm docked off with the following 20 mm used for oven dry MC measurement. The cut end was assessed for internal checking and board orientation. Following advice from Ian Whiteroad of NST, a note was made of whether internal checking was restricted to sections of the board adjacent to the heart.

4.1.3. Modelling

The new version of **KilnSched** developed for jarrah was used to model the effect of the recorded predrying kiln conditions on each of the five boards monitored for MC profile. The diffusion coefficient was calculated by fitting the measured and modelled moisture profiles in the usual way. An example of measured and modelled moisture profiles during drying is shown in Figure 4.1.7.

A comparison was made of predicted average MC during drying of each MC profile sample board and the average MC calculated from the measured MC profile at each measurement. Results are shown in Figure 4.1.8.

Model predictions of surface check formation (surface instantaneous strain, i.e. greater than 0.02) were compared with observation of sample boards. They were in general agreement; results are in Appendix B. Stress modelling of each board was stopped when surface checking was predicted.

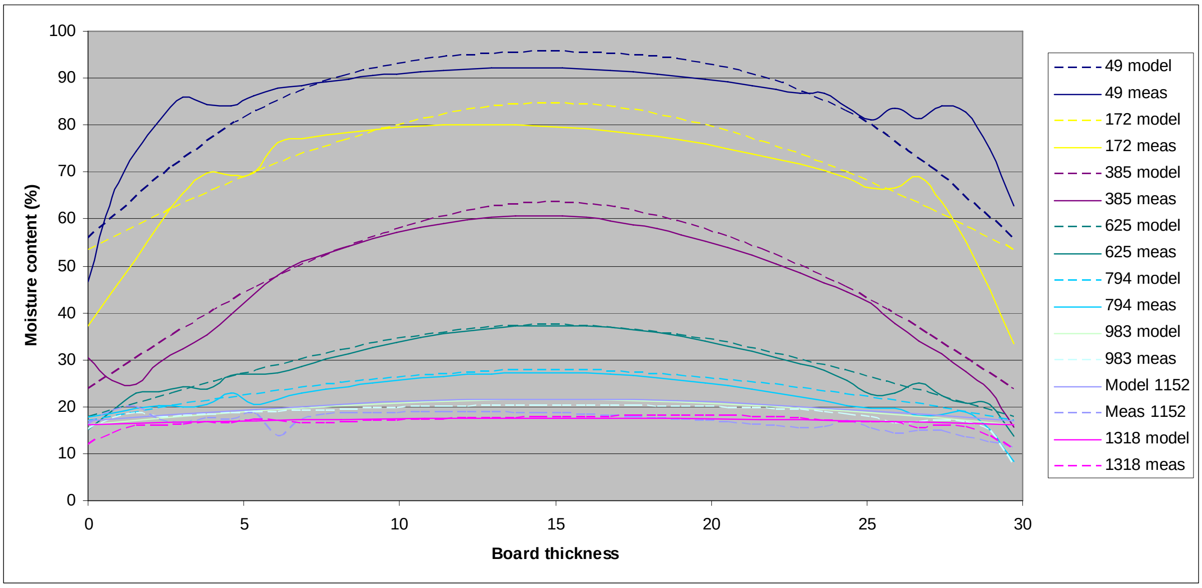

Figure 4.1.7. Moisture content profiles during drying for sample board 18 at various times

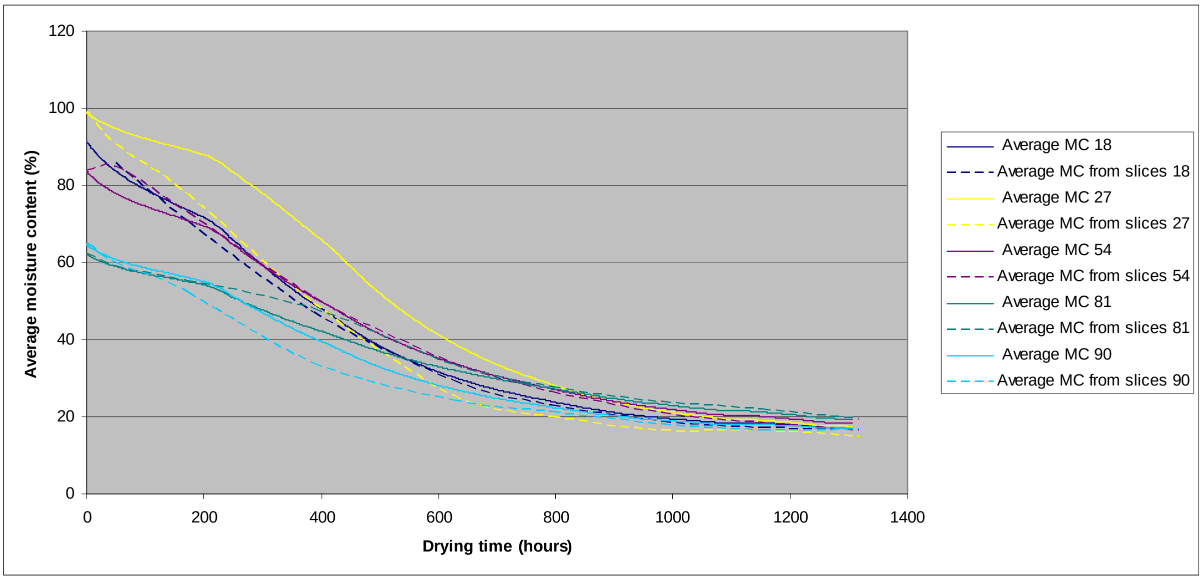

Figure 4.1.8. Average MC measured and predicted by model for sample boards

4.1.4. Dry evaluation

Length of each face of each board was tallied by grade (Figure 4.1.9): results are shown in Table 4.1.1. 57% of boards were graded Select over the whole length of both sides. Downgrading of boards from Select over their whole length was generally due to natural feature. Board faces downgraded over part of their length (approximately 20% of boards) were generally affected by surface checking or skip.

Figure 4.1.9. Evaluation of dried boards in the TRU laboratory

AS2796 grade	Select	Standard	High Feature
% of board length	75.1	7.1	18.0

Table 4.1.1. Percentage of overall board length in each grade (to AS2796)

Length of each board face affected by surface check or machining skip is shown in Table 4.1.2. Short (<30 mm) single surface checks associated with knots were sometimes observed; these were ignored. 7% of boards were affected by internal check; this sometimes extended to the surface and was seen to 'pick up' on machining, so was counted as surface checking.

Top surface		Bottom surface	
Surface check	Skip	Surface check	Skip
6.4	0.5	6.0	3.3

Table 4.1.2. Percentage of overall board length (disregarding endsplit) degraded by surface check or machining skip on both surfaces.

No endsplit was observed on the green boards. Endsplit losses following drying are shown in Table 4.1.3.

	Loss to endsplit	
Total length (m)	Length (m)	% of overall length
343.9	3.2	0.9

Table 4.1.3. Total length of board processed and length lost to endsplit

Percentage of boards meeting each of the first three drying quality classes as specified in AS 4787 (Standards Australia 2001) based on resistance moisture meter and oven dry measurements are shown in Table 4.1.4. Target MC for quality class calculations was 8%. Overall drying quality of a representative sub-sample to AS4787 would be class B.

	Quality class AS4787		
	Target MC	MC gradient	Oven dry MC
A	69.5	69.5	77.1
B	30.5	29.5	15.2
C	0.0	1.0	5.7

Table 4.1.4. Percentage of boards meeting AS4787 drying quality classes for target MC and MC gradient (optional) using meter, and target MC from oven dry

Mean final dried MC assessed by oven drying was 8.3% with a standard deviation of 1.0%. AS4787 uses the resistance meter reading with pins at 1/3 of the timber thickness (MC1/3) as an approximation of the average MC; the mean MC1/3 was 7.6%. This is in agreement with recent meter corrections in the range of measurement of zero (Blakemore 2003).

Figure 4.1.10. Deltron DCR22 resistance moisture meter connected to voltmeter & computer.

Mean shrinkage in width was 10.6% with a standard deviation of 2.5%. No board had distortion exceeding the limits for flooring of AS2796.

4.1.5. Discussion

The schedule used for this trial was not optimised for the timber as it was not feasible to change the schedule for a 300 m^3 timber load in the Gunns predrier. However, the early part of the drying schedule was useful in providing conditions sufficiently harsh to cause surface checking in some boards but not in others. This was a valuable test of the modified **KilnSched's** ability to predict surface checking, which it did satisfactorily.

Model-predicted MC profiles matched those measured satisfactorily. Predicted average MC during the drying trial generally matched measurements satisfactorily. Some discrepancies between measured and predicted MC occurred early in drying, probably due to the temperature and humidity data logged by Gunns being less accurate for the experimental stack than the experimental monitoring equipment used for the rest of the trial. The monitoring equipment in use for control consisted of wet and dry bulb RTD pairs located approximately half way along the length of the kiln, several metres from the experimental stacks.

Both MC profile and average MC predicted by **KilnSched** became less accurate at lower MC for two reasons: measurements on slices are less accurate as weight change is smaller, inducing measurement errors and errors extrapolating between measurement points for the slices and interpolating to the board surfaces; and drying conditions were not as harsh as ideal, so that fluctuations in kiln conditions could cause moisture re-absorption, which **KilnSched** is not designed to model.

One of the jarrah sample boards exhibited substantial collapse and an internal check, both in one growth ring. On evaluation following drying, 7% of boards were found to have at least one internal check. Experience with other eucalypt species (for example Innes 2005) suggests that it is likely that this problem will become more prevalent as younger regrowth jarrah is cut. Incidence of internal check is expected to reduce with lower drying temperature, although temperature during this trial was already low.

Incidence of drying induced surface checking was low with approximately 6% of total board length being affected. Modelling predicted surface checking in three of the five sample boards, but predicted peak surface instantaneous strain was only slightly above the value generally indicative of surface check formation (2%). Thus surface checking was seen in only a small number of boards. Drying conditions for this trial were harsher than ideal, particularly early in the trial during periods when the jarrah was on the air entry face of the stack. The fluctuation in relative humidity due to fan reversal was high at over 10%. Slight amelioration of the drying conditions could be expected to virtually eliminate surface checking.

Dried quality was high with an overall dried quality class of B according to the rules of AS4787 (Standards Australia 2001) for both average MC and MC gradient. Mean final MC from oven-dry testing was 8.3% with a standard deviation of 1.0%.

These measurements indicate that the modifications made to the **KilnSched** model to suit regrowth jarrah have been successful; the model can now be confidently used in predrying schedule development.

4.1.6. Conclusions

The modified version of the **KilnSched** model proved sufficiently accurate to confidently use it for modelling of the drying of regrowth jarrah. Predictions of surface checking, moisture content profile and average moisture content were all satisfactory. However, caution needs to be exercised in its use as the model depends on a large number of both directly measured and assumed parameters, and the small sample used may not be representative of all the resource.

4.2. Tasmanian regrowth messmate, **Eucalyptus obliqua**

4.2.1. Materials

Logs of naturally regenerated messmate resulting from fires in 1934 were supplied from Warra 14b coupe in the south of Tasmania to Neville Smith Pty Ltd's Huon Wood Centre sawmill as specially marked commercial log loads by Forestry Tasmania. One hundred and three boards were selected, from 80 to 160 mm wide, 28 mm thick and between 3 and 4 m long giving a total volume of 1.18 m^3; see Figure 4.2.1. The timber was wrapped for transport to the TRU laboratory in Launceston where it was measured and racked (Figure 4.2.2). It was then rewrapped and transported to Gunns sawmill at Lindsay St in Launceston. It was dried there as part of a commercial charge in one of their new 300 m^3 Mahild predriers along with the jarrah of section 4.1 – see Figure 4.1.1.

Figure 4.2.1. Board selection at Neville Smith Pty Ltd's Huon Wood Centre sawmill

Figure 4.2.2. Measuring and racking

Green measurements performed on each board were: length; width; thickness; mass; endsplit numbered end; endsplit other end; surface check top surface; surface check bottom surface; spring >10 mm; bow >25 mm; twist >10 mm and Director HM200 velocity.

Ten boards were sampled for initial moisture content (MC), basic density and unconfined shrinkage (radial and tangential). Shrinkage curves were fitted using three points: zero shrinkage at the initial MC; shrinkage and MC at fibre saturation point (FSP); shrinkage and MC at equilibrium MC (EMC). These results are shown in Appendix B.

4.2.2. Drying

The schedule used in the predrier was Gunns' standard schedule for the timber making up the charge (38 mm thick Tasmanian Oak). Setting the schedule to a model-generated one optimised for the experimental timber was not feasible.

Temperature, humidity and air velocity measurement is described in section 4.1.2. Recorded conditions are shown in Figure 4.1.3. Five of the ten boards sampled for basic density and initial MC were monitored throughout the trial for weight (to give average MC), width and thickness. The other five were monitored for width, thickness and moisture profile (destructive slicing test). Measurements were carried out after 49 (2), 172 (7), 385 (16), 625 (26) 794 (33), 983 (41), 1152 (48) and 1318 (55 – end of predrying) hours (days) drying. See Figures 4.2.3, 4.2.4 and 4.2.5. Boards 11 and 42 both suffered collapse between 16 and 26 days drying (Figure 4.2.5).

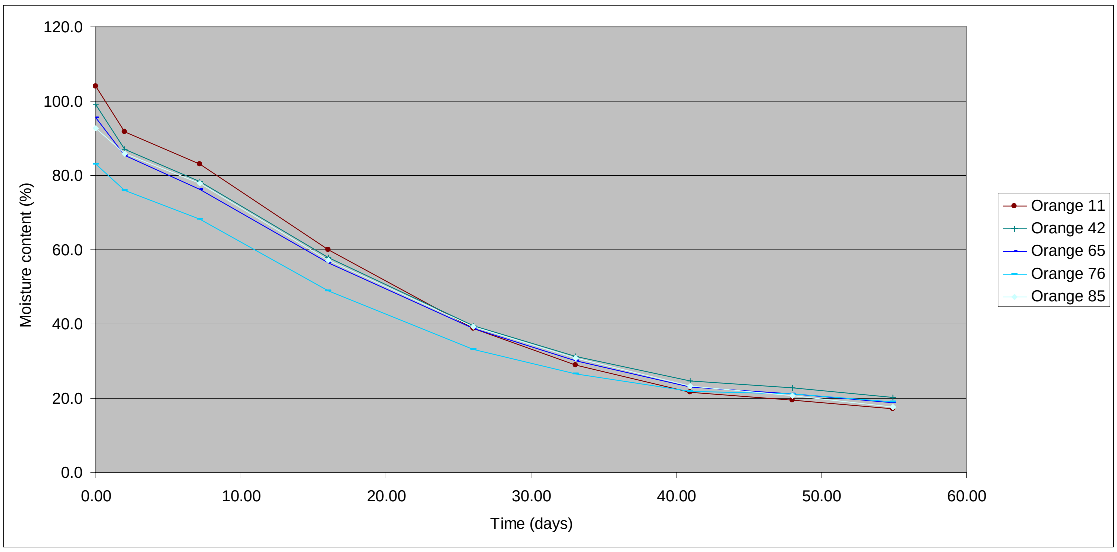

Figure 4.2.3. Moisture content of sample boards during drying

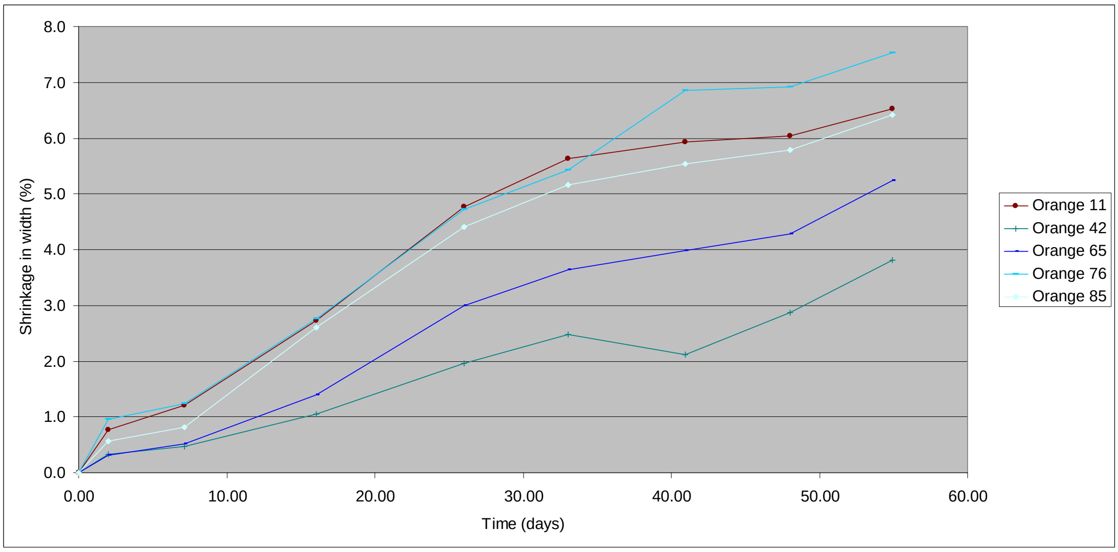

Figure 4.2.4. Shrinkage in width of sample boards during drying

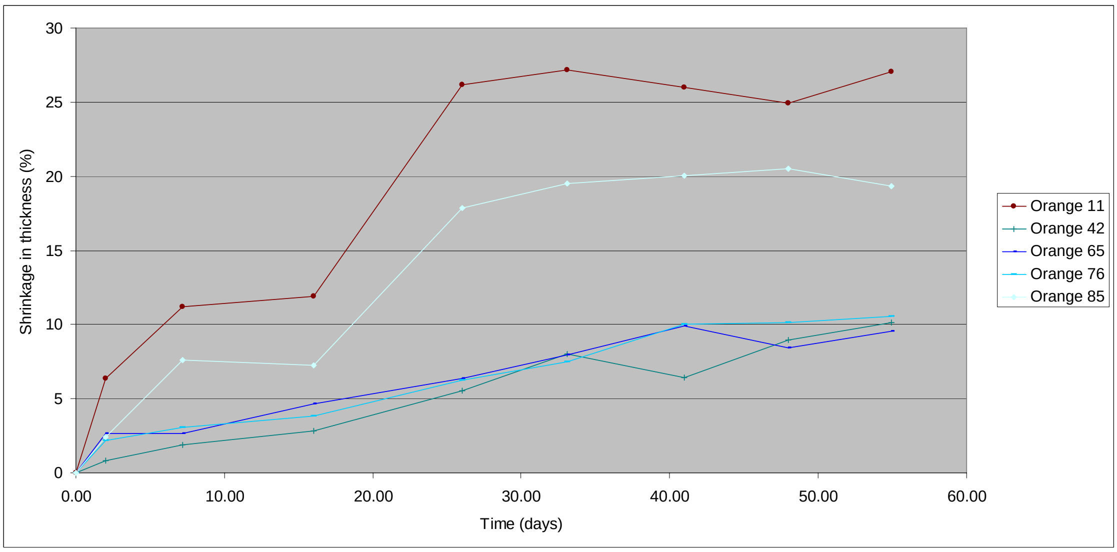

Figure 4.2.5. Shrinkage in thickness of sample boards during drying

The timber was removed from Gunns' predrier on 21/12/2004 after reaching target MC for reconditioning. Predicted mean of the average MC from sample boards was 15.7% at this time (lower than ideal as sample boards were only monitored weekly) Timber was immediately transported to NST's Mowbray mill for reconditioning the following day then returned to the TRU laboratory for storage over the Christmas mill shutdown. Final drying took place in the FFIC research kiln on the NST site in the second week of February, following which timber was returned to the TRU laboratory for evaluation. Timber was machined to 19 mm thickness on the 12th of February at NST Mowbray by removing 3 mm from the bottom surface and the rest from the top. Each machined side was graded to AS 2796 by a commercial grader (disregarding distortion). Minimum length for Select grade sections was 900 mm with no length limit on sections downgraded. Each board was then measured for: length; width; endsplit numbered end; endsplit other end; length of each face degraded by surface checking; length of each face degraded by machining skip; bow if greater than 19 mm over 2.4 m length; spring if greater than 10 mm over 2.4 m length; twist if greater than 8 mm; cup if greater than 1mm; and average MC and MC gradient to AS4787 (Standards Australia 2001). One end of each board then had 300 mm docked off with the following 20 mm used for oven dry MC measurement. The cut end was assessed for internal checking and board orientation. Following advice from Ian Whiteroad of NST, a note was made of whether internal checking was restricted to sections of the board adjacent to the heart.

4.2.3. Modelling

The new version of **KilnSched** developed for messmate was used to model the effect of the recorded kiln conditions during predrying on each of the five boards monitored for MC profile. The diffusion coefficient was calculated by fitting the measured and modelled moisture profiles in the usual way. An example of measured and modelled moisture profiles during drying is shown in Figure 4.2.6.

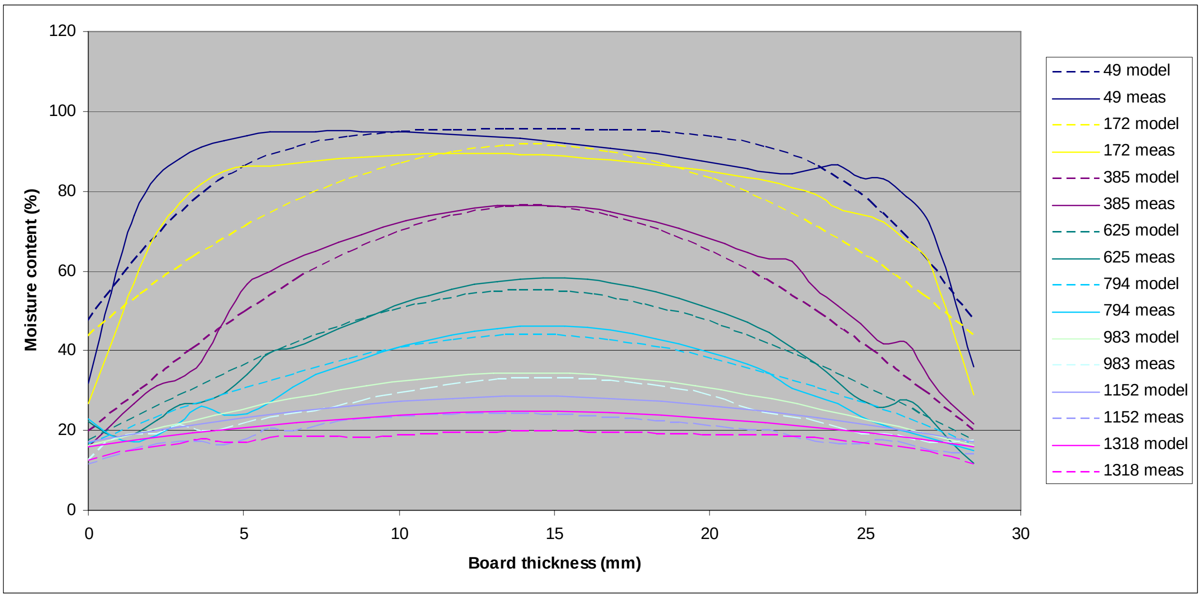

Figure 4.2.6. Moisture content profiles during drying for sample board 33 at various times

A comparison was made of predicted average MC during drying of each MC profile sample board and the average MC calculated from the measured MC profile at each measurement. Results are shown in Figure 4.2.7.

Model predictions of surface check formation (surface instantaneous strain greater than 0.02) were compared with observation of sample boards. They were in general agreement; results are in Appendix B.

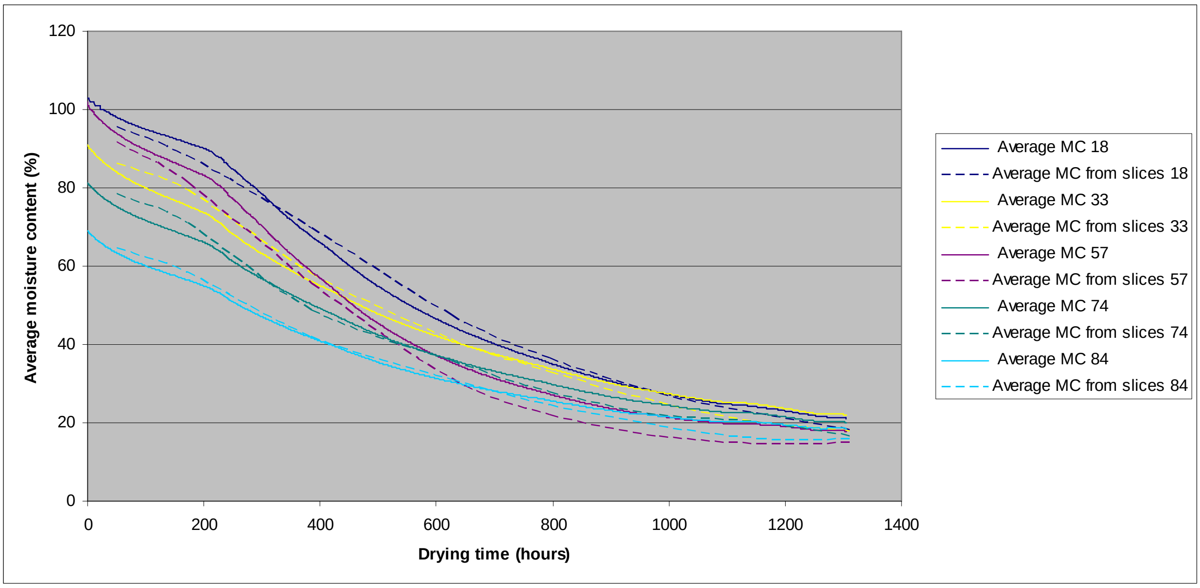

Figure 4.2.7. Average MC measured and predicted by model for sample boards

4.2.4. Dry evaluation

Overall board face length (both faces) was tallied by grade; results are shown in Table 4.2.1. 41% of boards were graded Select over their whole length on both sides. Most downgrade was due to knots and gum vein. Some "shake" was also observed (extensive radial splitting extending the length of boards). This is likely to be a felling or resource issue.

AS2796 grade	Select	Standard	High Feature
% of board length	55.7	32.4	13.6

Table 4.2.1. Percentage of overall board length in each grade (to AS2796)

Length of each board face affected by surface check or machining skip is shown in Table 4.2.2. 3% of boards were affected by internal checking.

Top surface		Bottom surface	
Surface check	Skip	Surface check	Skip
1.5	2.5	1.5	2.2

Table 4.2.2. Percentage of overall board length (disregarding endsplit) degraded by surface check or machining skip on each face.

Length of board lost to endsplit green and dry is shown in Table 4.2.3.

Green			Dry		
	Loss to endsplit			Loss to endsplit	
Total length (m)	Length (m)	% of length	Total length (m)	Length (m)	% of length
336.2	5.3	1.6	335.5	14.5	4.3

Table 4.2.3. Total length of board processed and length lost to endsplit green and dry.

No boards displayed distortion outside the allowances for flooring of AS2796 (Standards Australia 1999). Only three boards suffered internal checking.

Percentage of boards meeting each of the first three drying quality classes as specified in AS 4787 (Standards Australia 2001) based on resistance moisture meter and oven dry measurements are shown in Table 4.2.4. Target MC for quality class calculations was 8% for meter measurements and oven dry measurements. Overall drying quality class to AS4787 was A, or B if MC gradient was included, assuming that a representative sub-sample was chosen.

	Quality class AS4787		
	Target MC	MC gradient	Oven dry MC
A	89.3	66.0	79.6
B	10.7	33.0	16.5
C	0.0	1.0	2.9

Table 4.2.4. Percentage of boards meeting AS4787 drying quality classes for target MC and MC gradient (optional) using meter, and target MC from oven dry

Mean final dried MC assessed by oven drying was 7.7% with a standard deviation of 1.0%. Mean MC1/3 from resistance meter readings (AS4787) was 8.2%. This supports Blakemore's (2003) meter corrections for messmate over this range of 0%.

4.2.5. Discussion

The schedule used for this trial was not optimised for the timber as it was not feasible to change the schedule for a 300 m^3 timber load in the Gunns predrier. However, the early part of the drying schedule was useful in providing conditions sufficiently harsh to cause surface checking in some boards but not in others. This was a valuable test of the modified **KilnSched's** ability to predict surface checking, which it did satisfactorily. Prediction of surface checking was complicated by the formation of collapse. Several of the sample boards displayed collapse with associated surface checking. **KilnSched** cannot model collapse, so will not predict formation of associated surface checking.

Model-predicted MC profiles matched those measured satisfactorily. Predicted average MC during the drying trial also matched measurements satisfactorily. Both became less accurate at lower MC for two reasons: measurements on slices are less accurate as weight change is smaller, inducing measurement errors; and errors extrapolating between measurement points for the slices and interpolating to the board surfaces; and drying conditions were not as harsh as ideal, so that fluctuations in kiln conditions could cause moisture re-absorption, which **KilnSched** is not designed to model.

There was very little surface checking (1.5% of board length affected) or machining skip (2.5% of board length affected) in experimental boards. Surface checking was concentrated in a small number of boards, reflecting the variability of shrinkage shown in Appendix B. Amelioration of drying conditions would probably not improve grade recovery significantly. There was very little internal checking; half that found in jarrah in fact.

Most board downgrade was due to natural feature, principally knots and gum vein. Losses of board length to endsplit were significant at 1.6% green and 4.3% dry. Drying quality was high with boards easily meeting drying quality class B under AS4787 (Standards Australia 2001) and final dried MC of 7.7% with a standard deviation of 1% from oven dry tests.

4.2.6. Conclusions

The modified **KilnSched** model can now confidently be used in schedule development for predrying of regrowth messmate. Lack of a model for collapse continues to be a limitation in its use; temperature during predrying needs to be restricted to minimise formation of collapse and associated defect. Caution needs to be exercised in use of the model as it depends on a large number of both directly measured and assumed parameters, and the small sample used may not be representative of all the resource.

4.3. Victorian regrowth mountain ash and alpine ash, **Eucalyptus regnans** *and* **E. delegatensis**

4.3.1. Materials

It was hoped to have separate trial batches of mountain ash and alpine ash, however the two are usually mixed together in commercial operations. This was the case for the two Victorian sawmillers providing timber for this project; Drouin West Timber Sales Pty Ltd (DWTS) and JL Gould Sawmills Pty Ltd. The differences found between mountain ash and alpine ash in the laboratory scale trials may have been a result of the small samples used being unrepresentative. To be of industrial use, a single model had to adequately model both species together. As a result, two batches of "Victorian ash" were collected: 55 slabs 31 mm thick, varying from 106 to 298 mm in width and approximately 3 m long from Gould's mill at Alexandra (Figure 4.3.1); and 105 boards 32 mm thick varying from 104 to 140 mm in width and approximately 5 m long from DWTS at Morwell (Figure 4.3.2).

Figure 4.3.1. Board selection at JL Gould's sawmill, Alexandra

Figure 4.3.2. Board selection at Drouin West Timber Sales, Morwell

Green measurements performed on each board were: length; width; thickness; mass; endsplit numbered end; endsplit other end; surface check top surface; surface check bottom surface; spring >10 mm; bow >25 mm; Twist >10 mm and Director HM200 velocity.

Ten boards of the DWTS batch and eight from Gould's were sampled for: initial moisture content (MC), basic density and unconfined shrinkage (radial and tangential). Shrinkage curves were fitted using three points: zero shrinkage at the initial MC; shrinkage and MC at fibre saturation point (FSP); shrinkage and MC at equilibrium MC (EMC). These results are shown in Appendix B.

4.3.2. Drying

The two batches of Victorian ash were dried together in the FFIC 10 m^3 research kiln located on NST's Mowbray site, with the remainder of the kiln baffled off. A datalogging system similar to that described in 4.1.3 was used to monitor kiln conditions, but was not available until the trial had been underway for two weeks. Conditions prior to that have been modelled as the kiln setpoints. The NST site housing the kiln only operates a boiler for five days per week. Sections of the kiln record from weekends and other periods when steam was unavailable have been deleted as only limited drying could occur in the still-air, high humidity environment of the kiln when it was switched off. Modelling of any drying with the kiln switched off was not possible as air velocity was zero. The kiln was also shut down for the Christmas break with the timber left sitting in the kiln until the plant restarted. The mean of predicted average MC from the sample boards at this point was 32%. Kiln conditions were not monitored for modelling purposes after the shutdown as the predrying process was sufficiently advanced that formation of surface checking was unlikely and the drying and moisture redistribution the timber underwent (in still air) would have interfered with the modelling process.

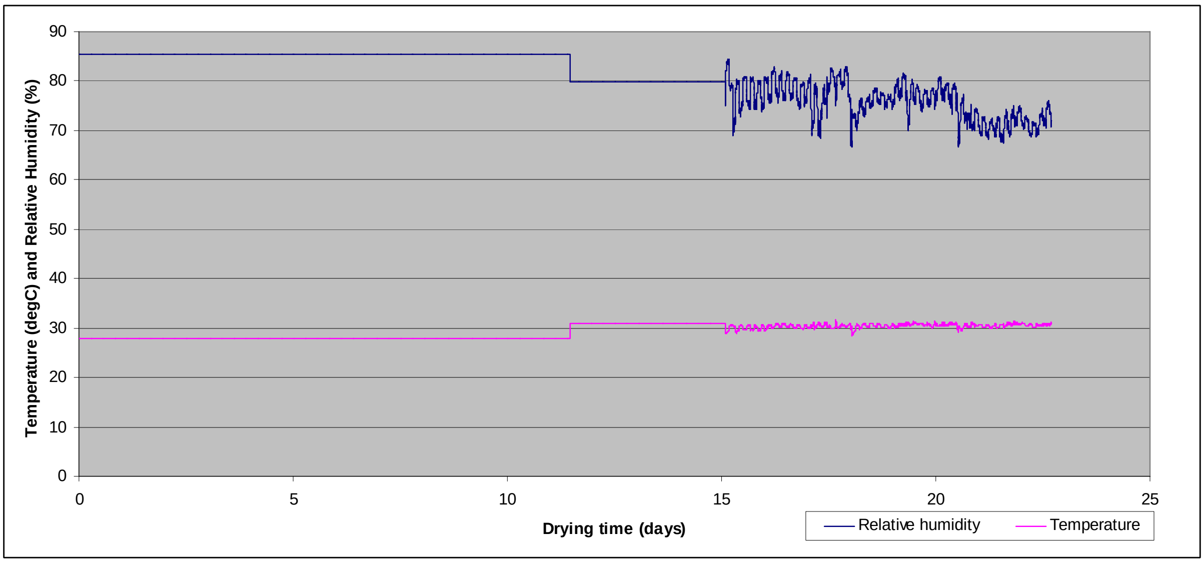

Figure 4.3.3. Drying conditions for Victorian Ash, velocity 0.5 m/s

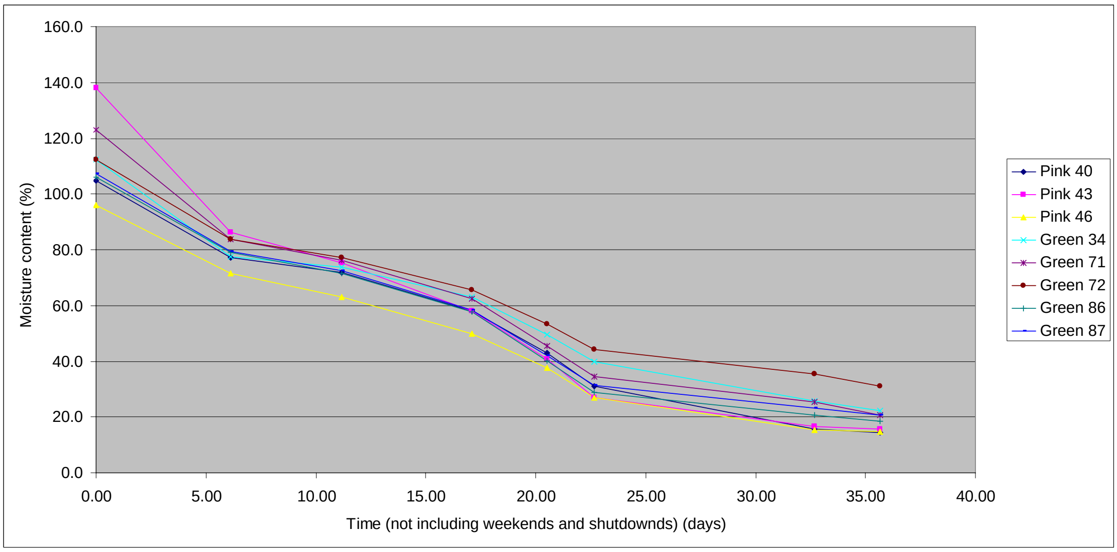

Figure 4.3.4. Moisture content of sample boards during drying; pink-Gould, green-DWTS

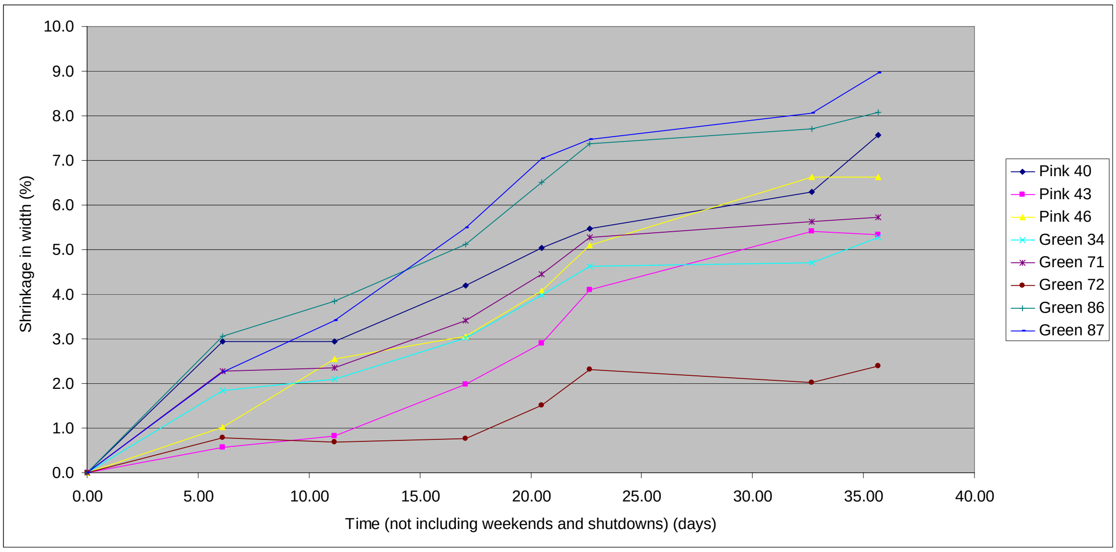

Figure 4.3.5. Shrinkage in width of sample boards during drying; pink-Gould, green-DWTS

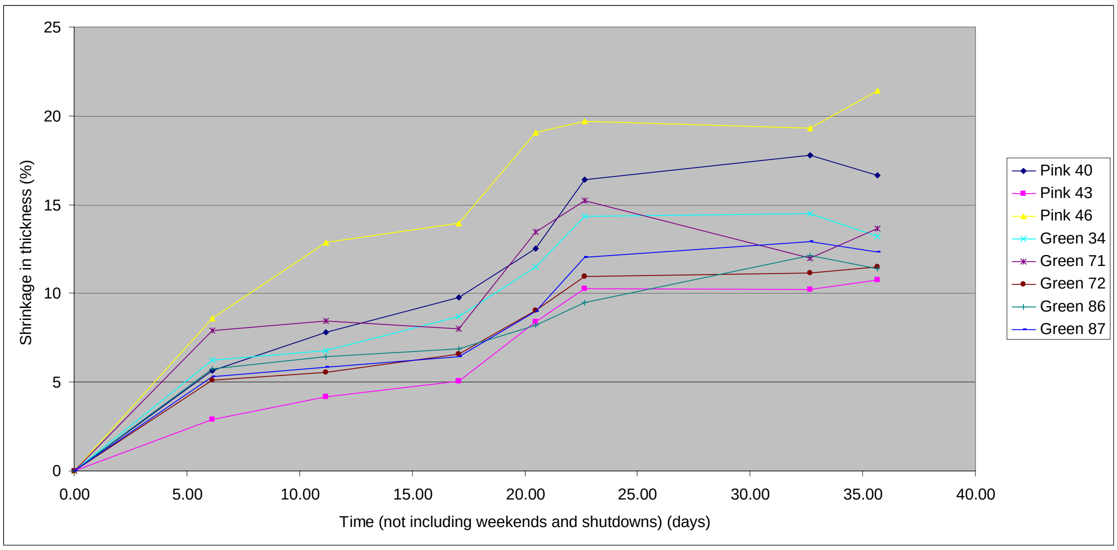

Figure 4.3.6. Shrinkage in thickness of samples during drying; pink-Gould, green-DWTS

Five of the DWTS boards and three of the Gould boards sampled for basic density and initial MC from each batch were monitored throughout the trial for weight (to give average MC), width and thickness; see Figures 4.3.4, 4.3.5 and 4.3.6. The other five of each were monitored for width, thickness and moisture profile (destructive slicing test). Measurements were carried out after 147 (6), 268 (11), 387 (16) and 506 (21) (hours (days) drying, following the Christmas break, and before reconditioning. Reconditioning took place in a commercial chamber at NST in the first week of February. Final drying took place in the FFIC research kiln on the NST site in the second week of February.

Timber was machined to 19 mm thickness on the 12th of February at NST Mowbray by removing 3 mm from the bottom surface and the rest from the top. Each machined side was graded to AS 2796 by a commercial grader (disregarding distortion). Minimum length for Select grade sections was 900 mm with no length limit on sections downgraded. Each board was then measured for: length; width; endsplit numbered end; endsplit other end; length of each face degraded by surface checking; length of each face degraded by machining skip; bow if greater than 19 mm over 2.4 m length; spring if greater than 10 mm over 2.4 m length; twist if greater than 8 mm; cup if greater than 1mm; and average MC and MC gradient to AS4787 (Standards Australia 2001). One end of each board then had 300 mm docked off with the following 20 mm used for oven dry MC measurement. The cut end was assessed for internal checking and board orientation. Following advice from Ian Whiteroad of NST, a note was made of whether internal checking was restricted to sections of the board adjacent to the heart.

4.3.3. Modelling

The new version of **KilnSched** developed for alpine ash was used to model the recorded kiln conditions for each of the five boards monitored for MC profile for each of the two batches of timber. The diffusion coefficient was calculated by fitting the measured and modelled moisture profiles in the usual way. Examples of measured and modelled moisture profiles during drying from each of the two batches are shown in Figures 4.3.7 and 4.3.8.

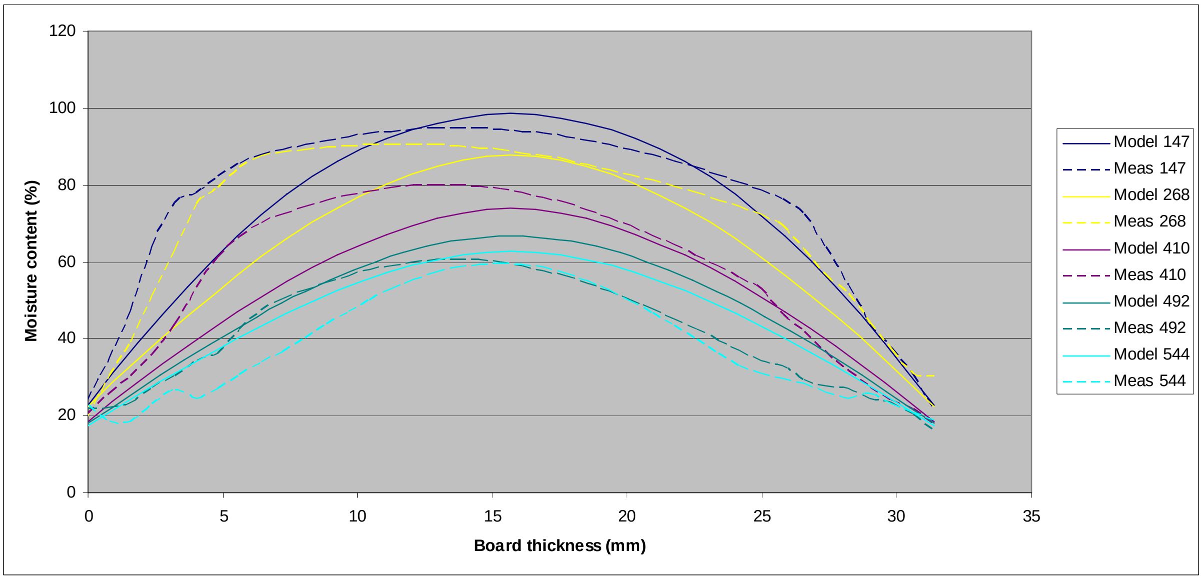

Figure 4.3.7. Moisture content profiles during drying for sample board Gould 10

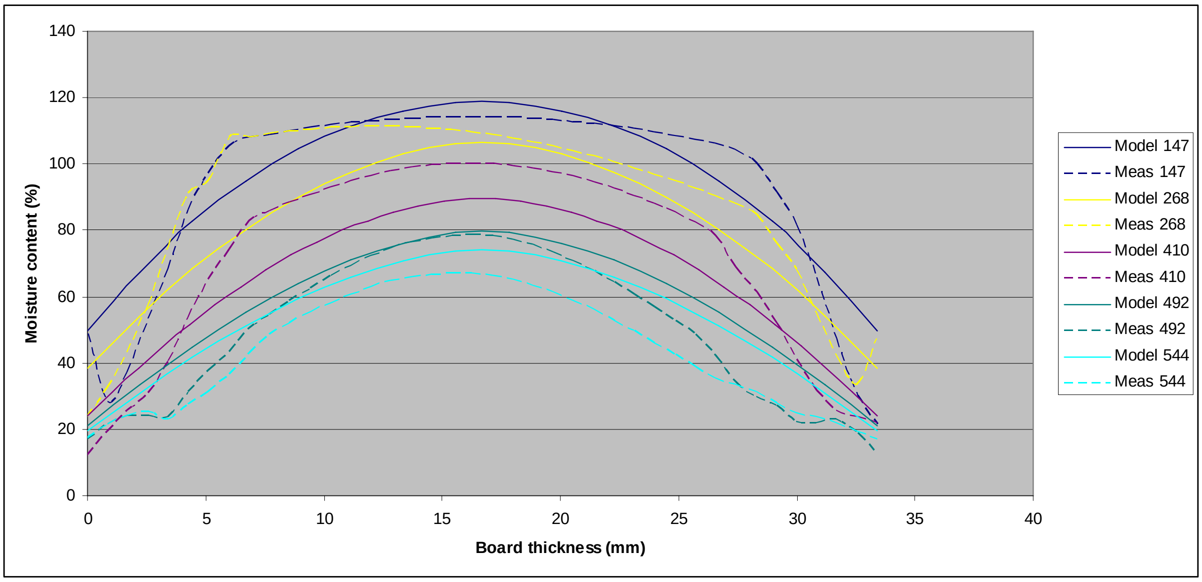

Figure 4.3.8. Moisture content profiles during drying for sample board DWTS 33

A comparison was made of predicted average MC during drying of each MC profile sample board and the average MC calculated from the measured MC profile at each measurement. Results are shown in Figures 4.3.9 and 4.3.10 for the two batches.

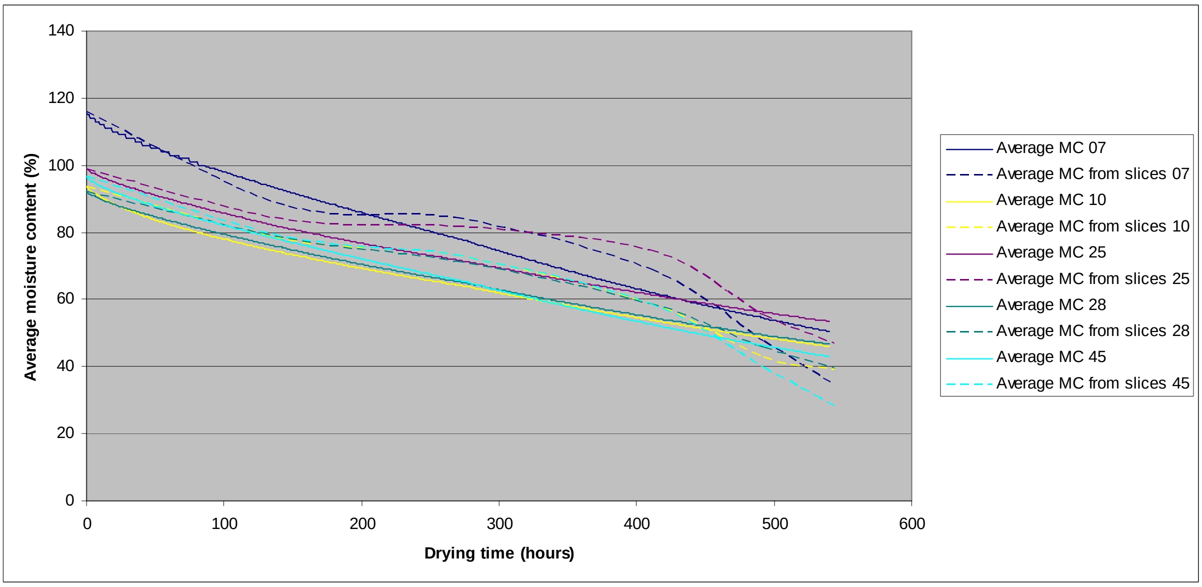

Figure 4.3.9. Average MC measured and predicted by model for Gould sample boards

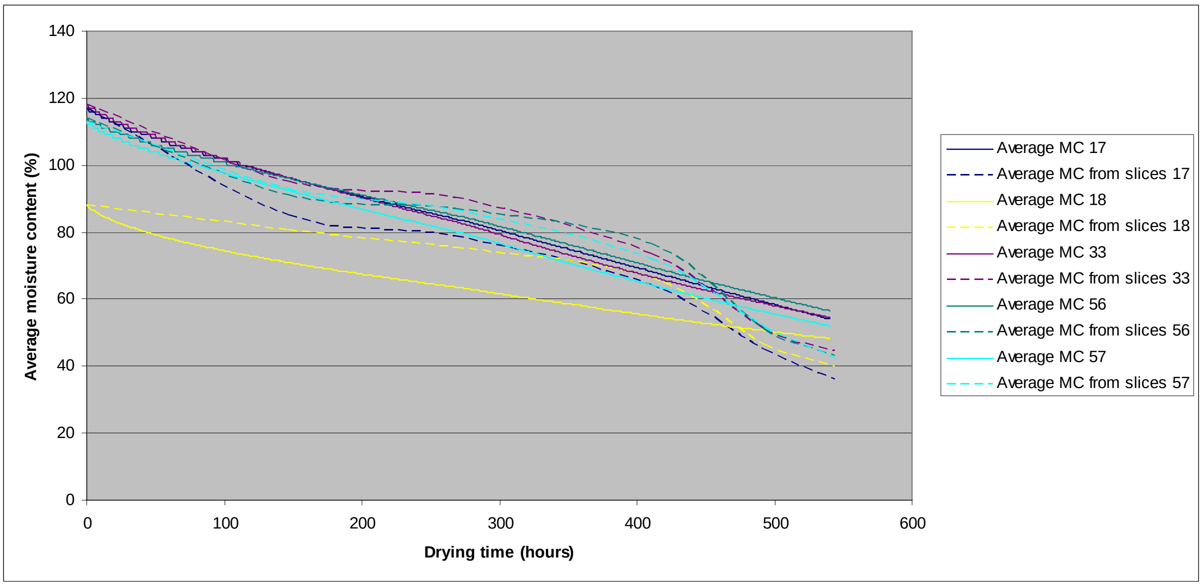

Figure 4.3.10. Average MC measured and predicted by model for DWTS sample boards

Eleven of the eighteen sample boards exhibited surface checking, generally after less than two weeks drying. This surface checking was all associated with collapse, being seen to coincide with (or be adjacent to) collapsing growth bands.

4.3.4. Dry evaluation

Length of each face of each board was tallied by grade; results are in Table 4.3.1. 35% of Gould boards and 59% of DWTS boards were graded Select over the whole length of both sides. Most degrade was from gum vein and knots.

AS2796 grade	Select	Standard	High Feature
Gould	44.2	28.3	27.8
DWTS	64.0	28.3	7.9

Table 4.3.1. Percentage of overall board length in each grade (to AS2796)

Percentage of overall length of boards affected by surface checking or skip is shown in Table 4.3.2. Most surface checking was associated with internal checking. 70% of the Gould boards affected by internal check were affected only in areas adjacent to the heart (Figure 4.3.11); 45% of those from DWTS. The higher amount of internal check in the Gould timber was largely due to it being cut as slab; resawing to board would eliminate a significant proportion of the internal check as material adjacent to the heart would be eliminated.

	Top surface		Bottom surface		
	Surface check	Skip	Surface check	Skip	Internal check
Gould	4.3	4.0	6.6	2.1	49.1
DWTS	9.1	0.1	4.7	0.4	29.5

Table 4.3.2. Percentage of overall board length (disregarding endsplit) degraded by surface check or machining skip on both surfaces

Figure 4.3.11. Victorian Ash board showing internal checking near heart only.

Length of board affected by endsplit green and dry is shown in Table 4.3.3.

	Green			Dry		
		Loss to endsplit			Loss to endsplit	
	Total length (m)	Length (m)	% of length	Total length (m)	Length (m)	% of length
Gould	174.4	3.7	2.1	173.9	10.2	5.9
DWTS	544.6	20.8	3.8	538.1	33.5	6.2

Table 4.3.3. Total length of board processed and length lost to endsplit

Percentage of boards meeting each of the first three drying quality classes as specified in AS4787 (Standards Australia 2001) based on resistance meter and oven dry measurements are shown in Table 4.3.4. Mean MC1/3 was 8.4%, mean oven dry MC was 8.5% with a standard deviation of 1.1%. Overall drying quality class was B.

		Quality class AS4787		
		Target MC	MC gradient	Oven dry MC
Gould	A	81.8	32.7	89.1
	B	14.5	58.2	9.1
	C	3.6	9.1	1.8
DWTS	A	74.3	52.4	75.2
	B	21.0	42.9	11.4
	C	1.9	1.9	8.6

Table 4.3.4. Percentage of boards meeting AS4787 drying quality classes for target MC and MC gradient (optional) using resistance meter, and target MC from oven dry.

Less than 2% of boards from either batch had distortion outside the limits of AS2796 (Standards Australia 1999) for flooring.

The Director HM200 acoustic velocity tool was used on each board before drying. It was hoped that it may prove to be a predictor of material prone to internal check. Summary results are shown in Table 4.3.5.

	Checked - mean	Unchecked - mean	Standard deviation - all
Gould	3.84	3.97	0.60
DWTS	3.67	3.82	0.27

Table 4.3.5. Director HM200 acoustic velocity readings on green boards, divided into internally checked and unchecked boards following drying.

The Gould data failed a normality test, so a Mann-Whitney rank sum test was performed to compare HM200 readings from checked and unchecked boards. This showed a difference, but only at the 8% level. A t-test on DWTS data showed no significant difference between HM200 readings from checked and non-checked material.

4.3.5. Discussion

The two groups of timber had significantly different basic density (Mann-Whitney rank sum test) and radial shrinkage (t-test) at the 5% level, though differences in initial MC (t-test) and diffusion coefficient (Mann-Whitney rank sum test) were not statistically significant. It is possible that the mix of the two species (*E. delegatensis* and *E. regnans*) was different from the two sites. The new version of **KilnSched** for alpine ash was used as it better fitted the measured MC profiles. This version would be best for generic Victorian ash modelling.

Drying modelling was generally satisfactory. Profile fits and average MC fits (derived from the profile modelling) were compromised somewhat by the non-continuous kiln drying. **KilnSched** cannot model the periods of sitting in still air when the kiln was off, including cooling down. Not much drying could be expected to take place during these times, but there was undoubtedly redistribution of moisture and drying stresses. The drying between measurements at 410 and 544 hours (days) was unexpectedly high; this discrepancy was probably a result of the kiln being off for several days during this period.

Most surface checking observed was associated with collapse; surface checks were observed to correspond to a collapsed growth ring running along the surface of the board. The drying temperature selected was too high for this material, resulting in a large amount of collapse (Innes 1995). The temperature was based on a combination of industry advice (normal practice) and on summer climate conditions to provide an indication of expected air drying quality. **KilnSched** cannot simulate the effect of collapse or predict its occurrence, so modelling of strain development within the sample boards while collapse was occurring was generally not useful. Some success has been found previously with a version of **KilnSched** modelling wood as a heterogeneous material (Innes 1996), but until occurrence of collapse can be predicted, this approach to minimising collapse-related degrade will not be practicable. Alexandra averages 41 days per year with a maximum temperature over 30°C; Morwell 25 days (Bureau of Meteorology 2005). Air drying at these or similar sites in summer could be expected to induce levels of internal checking similar to those observed here.

Overall endsplit losses were similar for timber slab cut (Gould) and that cut into board (DWTS). A larger study would be needed to verify this, however it appears that there was no benefit in reduced losses to endsplit or spring from drying slab rather than cutting boards green.

The Director HM200 acoustic velocity tool was not a useful predictor of material prone to form internal check on drying.

4.3.6. Conclusions

Application of the new version of **KilnSched** for Alpine Ash to the drying of Victorian ash (mixed *E. delegatensis* and *E. regnans*) was partially successful. Drying was modelled with reasonable accuracy given practical constraints, but the timber suffered extensive collapse and related degrade due to drying at too high a temperature. Collapse cannot currently be modelled, so schedules developed using **KilnSched** must use conditions mild enough to avoid collapse. Caution needs to be exercised in use of the model as it depends on a large number of both directly measured and assumed parameters, and the small sample used may not be representative of all the resource.

4.4. New South Wales regrowth spotted gum, Corymbia maculata

4.4.1. Materials

One hundred and five boards of backsawn regrowth spotted gum nominal 100 × 25 mm 1.6 to 2.7 m long were sent from J Notaras & Sons Pty Ltd to Brisbane for treatment to prevent insect attack. They were then sent to the DPI&F laboratories (Queensland) for drying to a schedule provided by the TRU.

Green measurements performed on each board were: length; width; thickness; endsplit numbered end; endsplit other end; surface check top surface; surface check bottom surface; spring > 10 mm; bow > 25 mm; and twist >10 mm. Seven boards had minor surface checking prior to entering the kiln due to breakdown of the pack wrapping during transport.

Ten boards were sampled for: initial moisture content (MC), basic density and unconfined shrinkage (radial and tangential). Shrinkage curves were fitted using three points: zero shrinkage at the initial MC; shrinkage and MC at fibre saturation point (FSP); shrinkage and MC at equilibrium MC (EMC). These results are shown in Appendix B.

4.4.2. Drying

Unfortunately, due to a misunderstanding the kiln conditions were not reset from the initial conditions for 24 days (rather than the 4 days specified in the schedule). Recorded kiln conditions used for modelling are shown in Figure 4.4.1; velocity was constant at 1.0 m/s. The first 19 days have been discarded as very little drying happened in this time and the very high humidity conditions caused problems in modelling.

Five of the boards sampled for basic density and initial MC from each batch were monitored throughout the trial for weight to give average MC as shown in Figure 4.4.2. The other five were monitored for width, thickness and moisture profile (destructive slicing test). Measurements were carried out after 170 (7), 336 (14), 500 (21), 664 (28) and 713 (30) hours (days) drying.

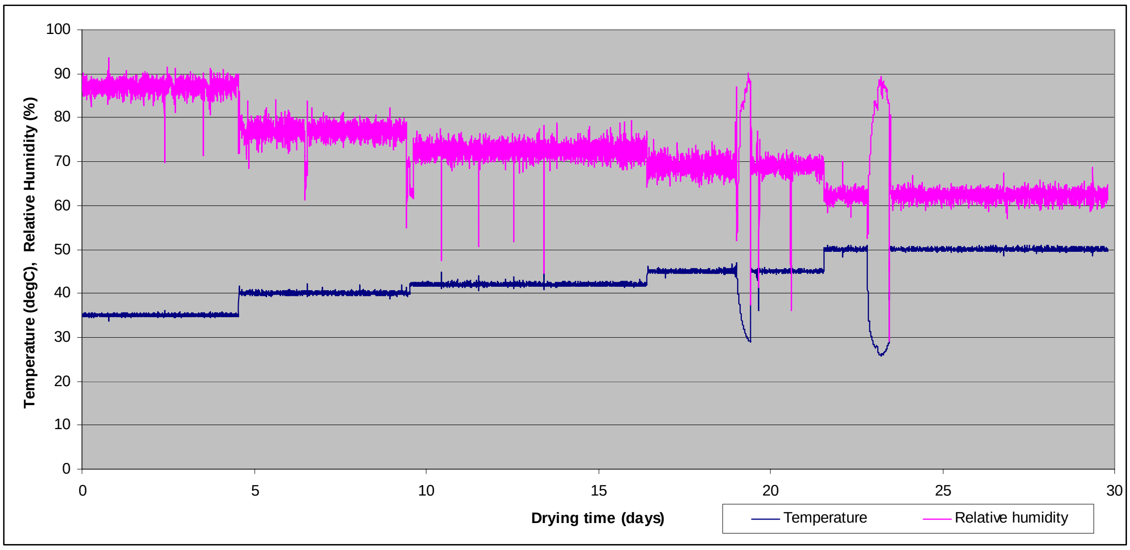

Figure 4.4.1. Recorded kiln conditions for spotted gum

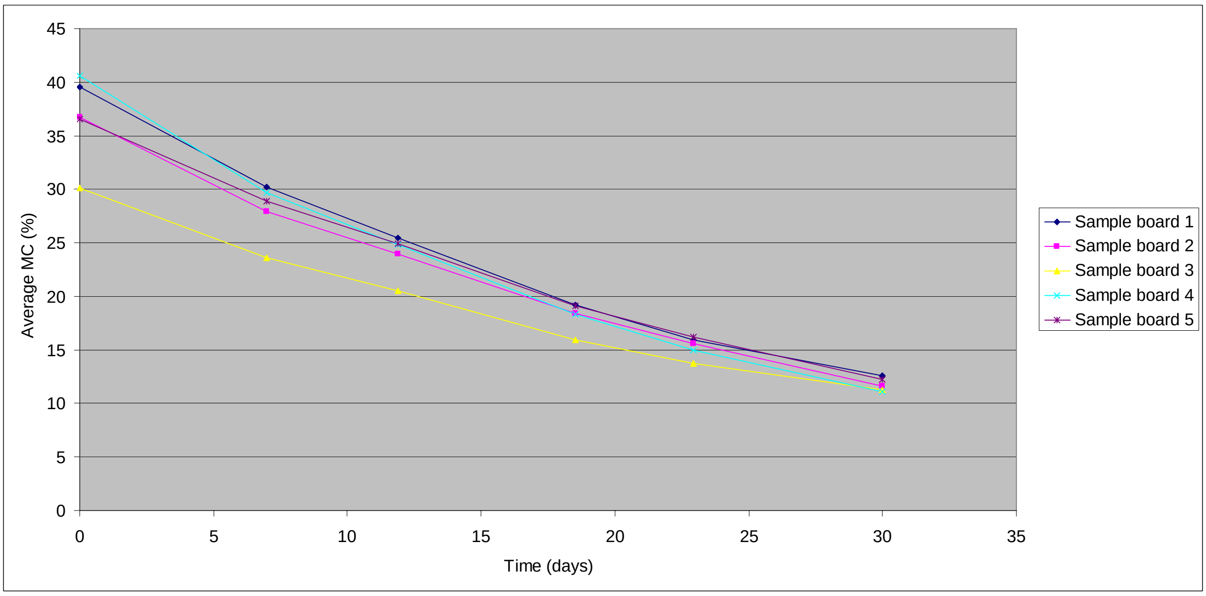

Figure 4.4.2. Moisture content of sample boards during drying

4.4.3. Modelling

The very high humidity for the first 21 days meant that small kiln condition fluctuations caused re-absorption of moisture at the surface, a condition **KilnSched** is not designed to accurately model. The rest of the time-based schedule was followed from 571 hours (24 days - chosen as a moisture profile measurement was made at that time). Little drying and stress development occurred up to that point, so modelling disregarded that time.

The new version of **KilnSched** developed for spotted gum was used to model the effect of recorded kiln conditions on each of the five boards monitored for moisture content profile. An example of measured and modelled moisture profiles is shown in Figure 4.4.3. A comparison of modelled average MC during drying and average MC calculated from measured MC profiles in shown in Figure 4.4.4. The model predicted no formation of surface checking for any of the sample boards; none was observed during drying.

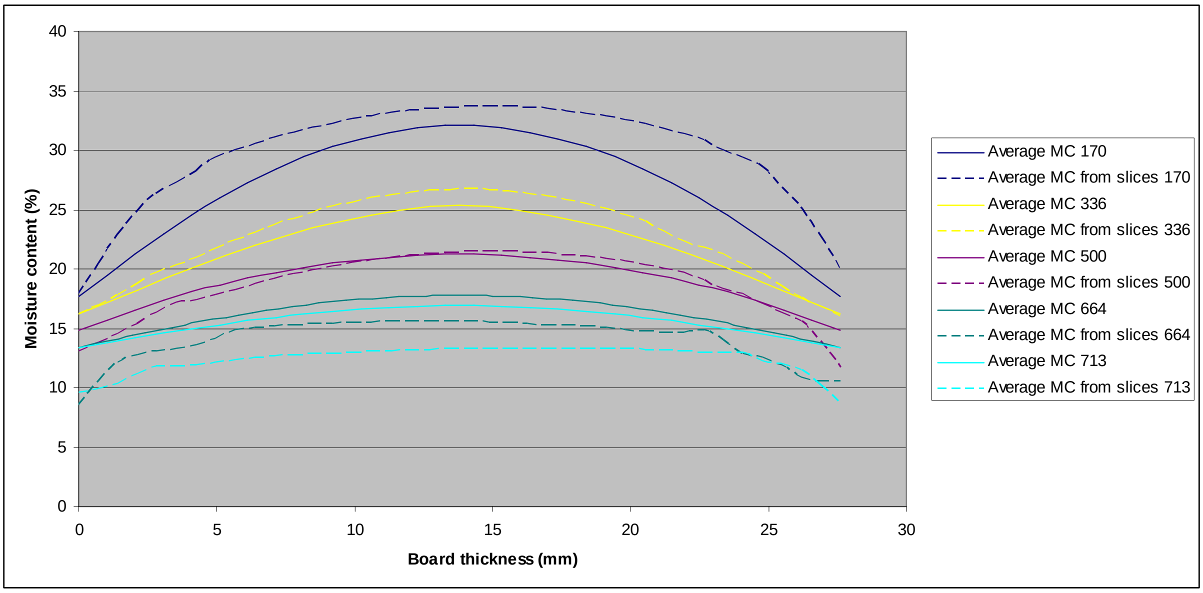

Figure 4.4.3. Moisture content profiles during drying for spotted gum sample board 2.

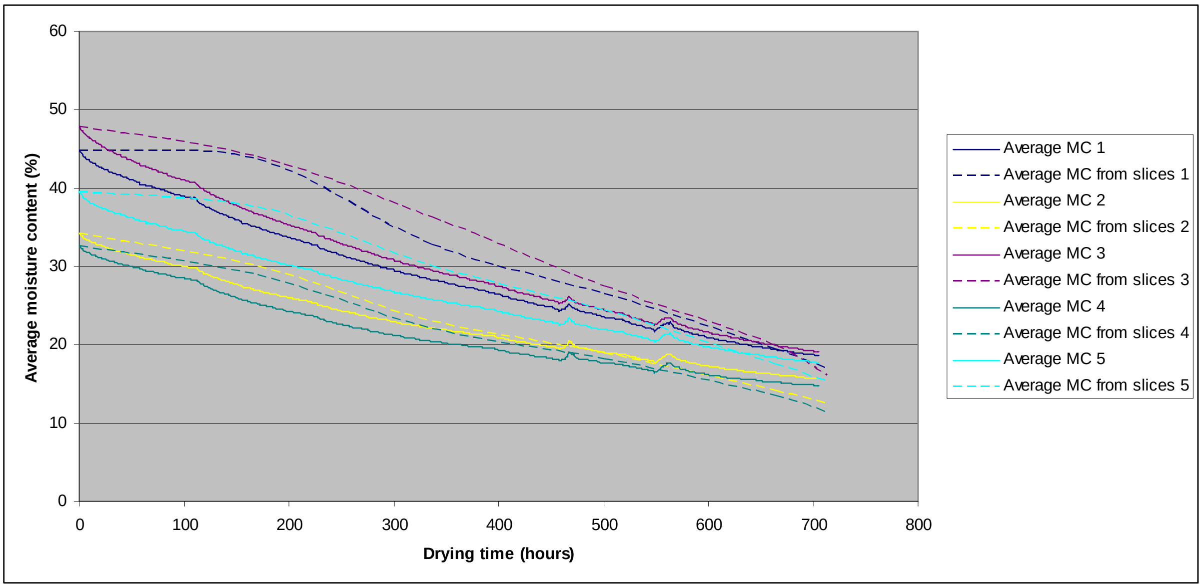

Figure 4.4.4. Average MC measured and predicted by model for spotted gum

4.4.4. Dry evaluation

Following drying, 95 boards (105 less the 10 sample boards) were machined to 19 mm thickness and evaluated. Grading was carried out to AS2796 (Australian Standards 1999) on the best side only, disregarding distortion; Table 4.4.1. Minimum grade length was 1200 mm with increments of 100 mm above that. Nearly all downgrade was due to natural feature, mainly tight gum vein.

AS2796 grade	Select	Standard	High Feature
% of board length	75.2	16.9	7.9

Table 4.4.1. Percentage of overall board length in each grade (to AS2796)

Total board length lost to endsplit was 440mm, 0.2% of total length. Only two boards were downgraded due to surface check: 400 mm of one board and 40 mm of the other.

Percentage of boards meeting the first three drying quality classes as specified in AS4787 (Standards Australia 2001) based on resistance moisture meter and oven dry measurements are shown in Table 4.4.2. Overall drying quality class to AS4787 was B, or C if MC gradient was included. Target MC for quality class calculations was 12%.

	Quality class AS4787		
	Target MC	MC gradient	Oven dry MC
A	70.5	50.5	86.3
B	28.4	30.5	11.6
C	0.0	15.8	1.1

Table 4.4.2. Percentage of boards meeting AS4787 drying quality classes for target MC and MC gradient (optional) using meter and target MC from oven dry.

Oven dry MC was measured on a short sample from each board. Mean was 12.1% with a standard deviation of 1.1%. Mean corrected MC1/3 from meter measurements was 12.6%.

Mean shrinkage in board width was 6.0% and in thickness (before machining) 4.2%. 2.1% of boards exceeded AS2796 (Standards Australia 1999) allowances for spring in flooring, while 10.5% exceeded the allowance for twist. No boards suffered internal check.

4.4.5. Discussion

The new version of **KilnSched** adequately modelled drying behaviour of the sample boards. No surface checking was predicted or observed. Moisture content modelling was, however, compromised by kiln conditions being left at the initial condition for 24 days. **KilnSched** cannot accurately model the effect of these high-humidity conditions for an extended period, as small fluctuations in kiln conditions cause absorption of moisture at the surface. Moisture content measurements toward the end of the trial indicated that model performance might be improved by further adjustments to the sorption isotherm model. However, gathering data to inform this would be a large task and is not justifiable at this stage. **KilnSched** was originally developed for drying check prone species at low temperature; spotted gum does not seem to be overly prone to surface checking and is dried at comparatively high temperature, so **KilnSched's** value as a schedule development tool for this species is limited at this stage.

Dried quality of the trial timber was generally very good. Final dried MC was higher than initially targeted as the trial was aborted early following a power failure during the Christmas shutdown. Quality class B was attained for target MC, and class C for MC gradient. Completing drying to the end of the schedule would have improved this. Degrade due to twist was high at 10.5%; this developed during drying and so could probably be reduced by schedule tuning, for example a conditioning treatment near the end of drying.

4.4.6. Conclusions

The new version of **KilnSched** adequately modelled the drying of spotted gum. Further improvements could be made but the work required is probably not justifiable at this point. Dried quality was good with virtually no drying induced degrade with the exception of twist, which degraded 10.5% of boards. Caution needs to be exercised in use of the model as it depends on a large number of both directly measured and assumed parameters, and the small sample used may not be representative of all the resource.

4.5. Queensland regrowth blackbutt, Eucalyptus pilularis

4.5.1. Materials

105 boards of backsawn regrowth blackbutt nominal 100 × 25 mm, 3.5 m long were sent from Boral Timber sawmill located at Herons Creek, NSW, to the DPI&F laboratories in Brisbane for measurement and drying.

Green measurements performed on each board were: length; Width; Thickness; Endsplit numbered end; Endsplit other end; Surface check top surface; Surface check bottom surface; Spring > 10 mm; Bow > 25 mm; and Twist >10 mm.

Ten boards were sampled for: initial moisture content (MC), Basic Density and Unconfined Shrinkage (Radial and Tangential). Shrinkage curves were fitted using three points: zero shrinkage at the initial MC; shrinkage and MC at fibre saturation point (FSP); shrinkage and MC at equilibrium MC (EMC). These results are shown in Appendix B.

4.5.2. Drying

Drying conditions for the trial are shown in Figure 4.5.1. Drying was monitored using a GPSE temperature/humidity datalogger. Unfortunately, due to a datalogger malfunction no conditions were recorded between days nine and eighteen (approximately) as evident from the graph.

Five of the boards sampled for basic density and initial MC from each batch were monitored throughout the trial for weight to give average MC, Figure 4.5.2. The other five were monitored for width, thickness and moisture profile (destructive slicing test). Measurements were carried out after 68(3), 193 (8), 360 (15), 513 (21) and 781 (32) hours (days) drying.

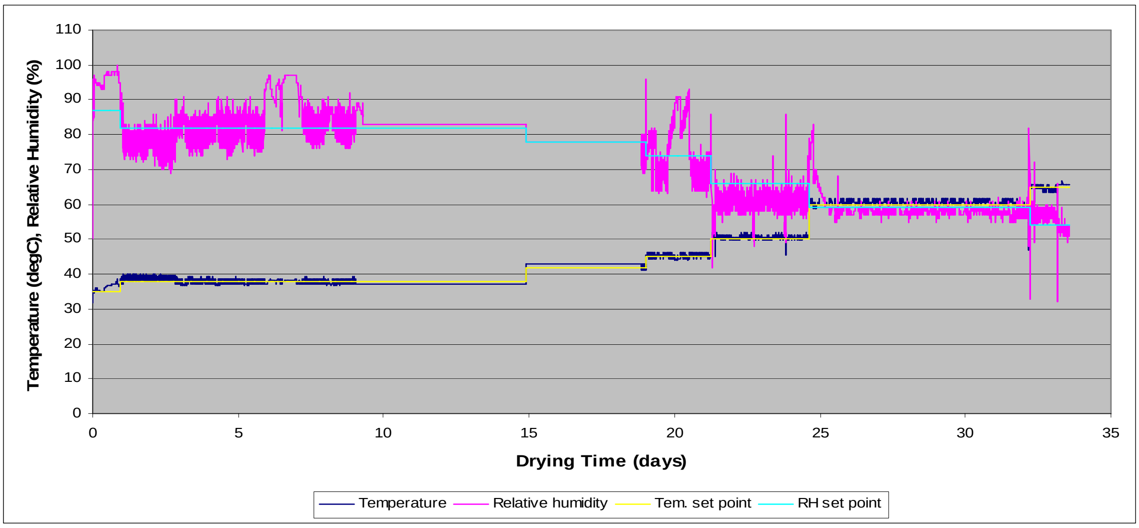

Figure 4.5.1. Recorded kiln conditions for blackbutt

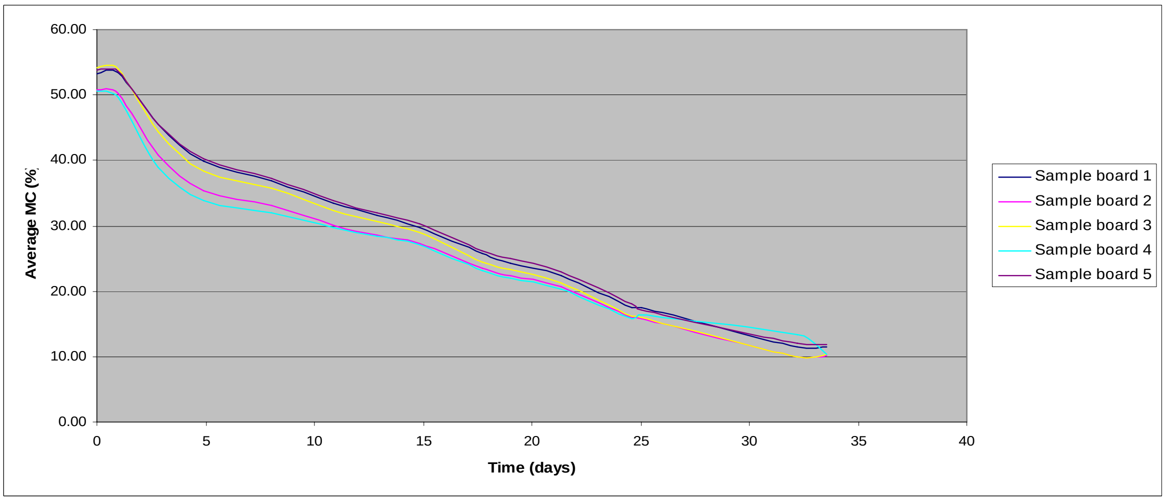

Figure 4.5.2. Moisture content of sample boards during drying

4.5.3. Modelling

The new version of **KilnSched** developed for blackbutt was used to model the recorded kiln conditions over the first 405 hours (days) of drying for each of the five boards monitored for MC profile. The diffusion coefficient was calculated by fitting the measured and modelled moisture profiles in the usual way. Examples of measured and modelled moisture profiles during drying from each of the two batches are shown in Figure 4.5.3.

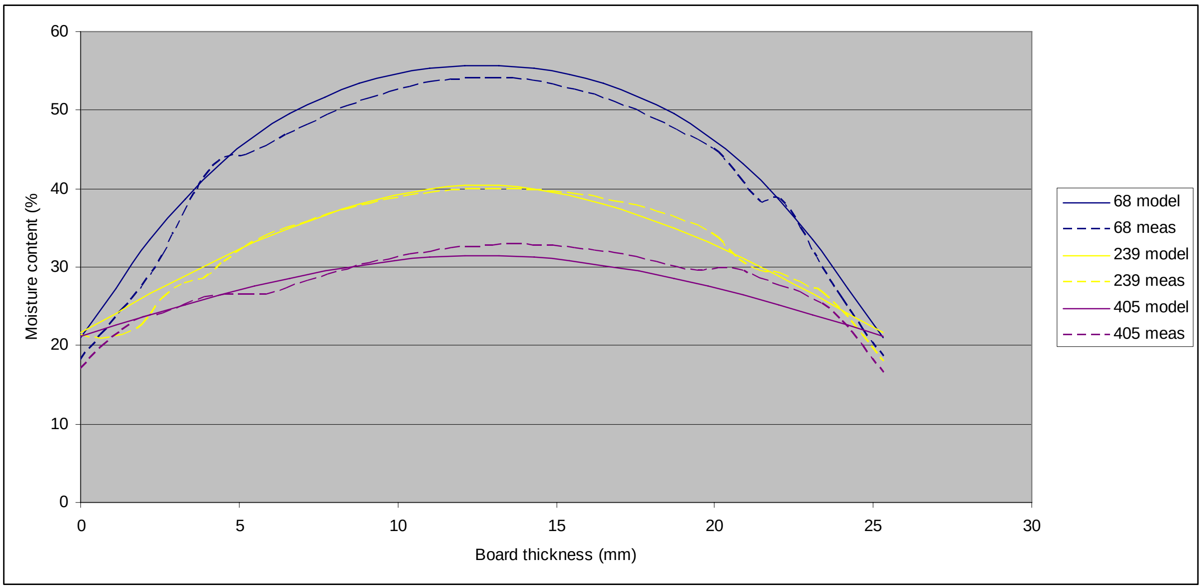

Figure 4.5.3. Moisture content profiles during drying for blackbutt sample board 3.

A comparison was made of predicted average MC during drying of each MC profile sample board and the average MC calculated from the measured MC profile at each measurement. Results are shown in Figure 4.5.4.

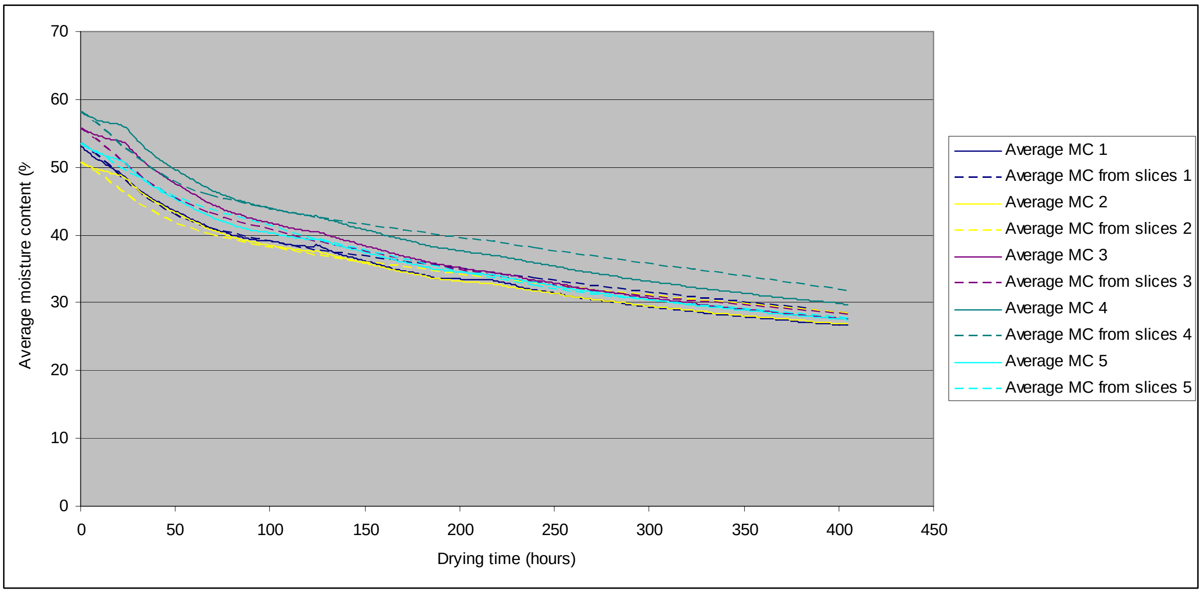

Figure 4.5.4. Average MC measured and predicted by model for blackbutt

The model predicted formation of surface c checking in one of the MC profile sample boards. Unfortunately, these were not observed for occurrence of defect, only the average MC sample boards. Of those, two were observed to have slight surface checking and one moderate at 68 hours. This is in general agreement with the model's prediction of surface instantaneous strain close to the level that would cause surface checking for the majority of boards, and in excess of that value for a small number of boards.

4.5.4. Dry evaluation

Following drying, 95 boards (105 less the 10 sample boards) were machined to 19 mm thickness and evaluated. Grading was carried out to AS2796 (Australian Standards 1999) on the best side only, disregarding distortion. Minimum grade length was 1200 mm with increments of 100 mm above that. In order of severity, the main reasons for downgrade were tight gum vein, insect hole and surface check. Results are shown in Table 4.5.1.

AS2796 grade	Select	Standard	High Feature
% of board length	58.6	32.5	8.9

Table 4.5.1. Percentage of overall board length in each grade (to AS2796)

Total board length lost to endsplit green and dry was 450 mm, 0.14% and 835 mm, 0.25% of total length respectively. Sixteen boards (17%) of boards were downgraded due to surface check. The total length downgraded due to surface check was 12,400mm, 3.8% of total board length. It should be noted that all surface checking was associated with boards having wavy grain. Sixty nine boards (73%) had wavy grain.

Percentage of boards meeting the first three drying quality classes as specified in AS4787 (Standards Australia 2001) based on resistance moisture meter and oven dry measurements are shown in Table 4.5.2. Target MC for quality class calculations was 11%.

	Quality class AS4787		
	Target MC	MC gradient	Oven dry MC
A	70.2	92.6	81.9
B	27.7	7.4	18.1
C	1.1	0.0	0.0

Table 4.5.2. Percentage of boards meeting AS4787 drying quality classes for target MC and MC gradient (optional) using meter and target MC from oven dry.

Oven dry MC was measured on a short sample from each board. Mean was 11.4% with a standard deviation of 1.2%. Mean corrected MC1/3 from meter measurements was 10.6%.

Mean shrinkage in board width was 6.31% and in thickness (before machining) 4.93%. No boards exceeded AS2796 (Standards Australia 1999) allowances for spring in flooring, while 6.4 % exceeded the allowance for twist. No boards suffered internal check.

4.5.5. Discussion

The new version of **KilnSched** closely modelled the drying behaviour of the sample boards. Surface checking was predicted in one of the MC profile samples with peak instantaneous strain 5% above the value taken to cause surface checking. Three of the average MC sample boards were observed to have mild surface checking at this time. Peak surface instantaneous strain occurred around this time for all sample boards, after which it dropped off significantly. Ideally, the schedule should have been slightly milder for the first three days and then accelerated more. Dried quality of the trial timber was generally very good. Quality class B was attained for target MC, and class A for MC gradient. Degrade due to twist was moderately high at 6.4%; this developed during drying and so could probably be reduced by schedule tuning. Stack weights may have reduced twist levels. Downgrade due to surface check was high (17% of boards) however checks were generally scattered on boards with severe wavy gain.

4.5.6. Conclusions

The new version of **KilnSched** adequately modelled the early part of drying of blackbutt when any surface checking is most likely to occur. Dried quality was generally good with the exception of twist, and surface check due to wavy grain. Further work could be made but is probably unjustifiable at this point. Caution needs to be exercised in use of the model as it depends on a large number of both directly measured and assumed parameters, and the small sample used may not be representative of all the resource.

4.6. Discussion of commercial and near-commercial scale trials

A summary of results from the commercial and near-commercial scale trials is shown in Table 4.6.1.

Modelling of drying and stress development was hampered to some extent by some drying occurring prior to the timber entering the kiln. Previously, the level of measurement applied to the timber for these experiments had only been applied at a very small experimental level (around 0.1 m^3). Expansion to this semi-commercial scale inherently added inaccuracy. Selection of boards, shipment, measurement, racking, rack transport and kiln loading all took much longer and all provided opportunities for the timber to dry in an uncontrolled manner. Kiln control and uniformity of conditions were inevitably to a lower standard than that possible in a small experimental kiln and experiments were subject to industrial limitations such as equipment breakdown and periodic shutdown in steam supply. In an industrial situation, switching off a predrier moderates drying conditions for the timber, so long as humidity conditions during cool-down and heat-up are controlled to conservative levels. Thus continuous predrying schedules developed with **KilnSched** should provide a good basis for industrially applied schedules, so long as sufficient safety margin is allowed for kiln control and variation in uniformity of kiln conditions.

Note that diffusion coefficients from the first and second trials (Appendices A and B respectively) are different; this is due primarily to changes in the model. It seems that deficiencies in the original model for some of these regrowth species were partly overcome by adjusting the diffusion coefficient. The actual value used for diffusion coefficient is not important in this case; what is important is the accuracy of resultant modelling.

		Initial MC, unconfined shrinkage % and corresponding MC at FSP and at EMC																		
		Tangential					Radial					Green sample board measurements						Model prediction		
Batch	No.	IMC	FSP MC	FSP St	EMC	EMC St	IMC	FSP MC	FSP Sr	EMC	EMC Sr	Thick (mm)	Width (mm)	Initial MC (%)	Basic Density (kg/m^3)	Checking observed (hours)	Diffusion coefficient (x10^{-7} m^2/hour)	Time to check (hours)	Peak surface ei	Time to peak ei (hours)
jarrah blue	17	102	40	0.1	10.0	6.5	102	40	0.1	10.0	4.0	29.0	112	105	565	172				
	26	84	40	0.4	10.0	7.0	84	40	0.4	10.0	4.5	27.8	113	90	617	385				
	53	93	34	0.6	10.0	5.5	93	38	0.7	10.0	5.8	27.9	113	90	614	385				
	80	70	29	0.3	10.0	5.5	70	29	0.5	10.0	5.0	28.7	113	73	688					
	89	60	40	0.4	10.0	6.0	60	39	0.4	10.0	5.5	28.6	112	70	693					
	18	86	35	0.5	10.0	5.0	86	35	0.1	10.0	3.5	29.7	111	99	553		2.8	NA	0.019	483
	27	100	38	0.3	10.0	6.0	100	38	0.3	10.0	5.5	29.4	113	96	570		3	655	0.021	655
	54	92	40	0.2	10.0	5.5	92	37	0.7	10.0	6.0	30.3	113	92	610	385	2.2	459	0.022	459
	81	59	33	0.4	10.0	7.0	59	40	0.4	10.0	6.0	30.8	113	67	735	625	1.7	456	0.024	456
	90	58	40	0.2	10.0	5.5	58	40	0.4	10.0	5.0	28.9	111	67	688		2.6	NA	0.019	484
	Mean	80	37	0.3	10.0	6.0	80	38	0.4	10.0	5.1	29.1		85	633		2.5			
messmate orange	11	90	C		9.3	4.6	90	30	0.4	10.4	5.0	28.3	107	100	516					
	42	82	C		6.7	5.2	82	29	0.3	5.8	4.8	28.4	107	94	582					
	65	82	30	0.1	10.4	3.7	82	44	0.3	11.6	3.8	26.6	134	91	585	625				
	76	75	C		7.5	7.6	75	35	0.5	11.7	6.1	28.6	83	77	613	794				
	85	87	35	0.5	7.8	5.7	87	35	0.5	7.6	4.1	28.7	135	90	563	385				
	18	97	38	1.1	8.2	5.8	97	38	0.1	5.1	3.3	29.7	135	106	519	794	1.7	NA	0.009	556
	33	88	45	0.6	11.2	6.0	88	35	0.6	13.0	2.5	28.5	108	95	548		1.3	NA	0.014	436
	57	93	33	0.9	6.8	5.4	93	34	0.1	6.3	4.0	28.8	109	99	504		2.3	NA	0.009	666
	74	82	32	1.0	6.4	7.3	82	32	0.6	12.0	7.7	30.6	108	84	582	385	1.7	330	>0.0334	>450
	84	66	35	0.5	6.4	5.7	66	35	0.4	9.0	6.9	28.7	108	74	608	385	1.7	426	>0.0223	>465
	Mean	84	35	0.7	8.1	5.7	84	35	0.4	9.3	4.8	28.7		91	562		1.7			

Notes: "C" indicates a shrinkage slice that collapsed

*Check time is sampling time that checking was first observed; checking formed between this time and the previous sampling time

Peak surface e_i>2% is indicative of surface check formation

Table 4.6.1. Summary results from commercial and near-commercial scale trial. Continued below.

		Initial MC, unconfined shrinkage % and corresponding MC at FSP and at EMC																		
		Tangential					Radial					Green sample board measurements						Model prediction		
Batch	No.	IMC	FSP MC	FSP St	EMC	EMC St	IMC	FSP MC	FSP Sr	EMC	EMC Sr	Thick (mm)	Width (mm)	Initial MC (%)	Basic Density (kg/m^3)	Checking observed (hours)	Diffusion coefficient (x10^{-7} m^2/hour)	Time to check (hours)	Peak surface ei	Time to peak ei (hours)
VicAsh	7	105	35	0.3	10.0	10.0	105	40	0.8	10.0	5.0	31.1	197	124	485	387	1.5	436	0.023	542
Gould	10	93	C		10.0	6.0	93	40	0.4	10.0	4.5	31.4	160	100	484	268	1.1	NA	0.018	367
pink	25	93	37	0.3	10.0	4.0	93	33	0.7	10.0	4.5	32.3	169	111	516	147	1	NA	0.02	539
	28	84	36	0.6	10.0	8.0	84	35	0.6	10.0	7.0	34.0	152	99	512	147	1.4	404	>0.0273	544
	45	100	42	0.8	13.4	4.0	100	44	0.6	10.0	6.5	31.6	174	102	526		1.7	392	0.028	526
	40	84	37	0.7	10.0	5.0	84	35	0.5	10.0	4.5	30.6	338	98	544					
	43	100	C		10.0	8.0	100	35	0.3	10.0	5.0	32.5	178	109	512					
	46	88	35	0.5	10.0	7.5	88	33	0.7	10.0	5.0	30.8	196	98	518	268				
	Mean	93	37	0.5	10.4	6.6	93	37	0.6	10.0	5.3	31.8		105	512		1.3			
VicAsh	17	118	45	0.6	10.0	8.0	118	38	0.1	10.0	4.0	33.5	141	131	485		2.3		>0.003	>544
DWTS	18	88	32	0.5	10.0	4.0	88	36	0.3	10.0	2.5	34.1	140	98	432		1		0.011	416
green	33	114	43	0.5	10.0	5.5	114	46	0.3	10.0	4.5	33.4	140	125	455		1.6	518	>0.0204	>544
	56	105	54	0.8	10.0	6.0	105	36	0.2	10.0	3.0	32.3	140	119	491	147	1.6		>0.0083	>544
	57	110	50	0.2	10.0	7.0	110	32	0.2	10.0	4.0	31.8	116	118	497	147	1.6		>0.0092	>544
	34	99	42	0.3	10.0	7.0	99	50	0.2	10.0	5.0	32.0	140	107	508	268				
	71	120	50	0.1	10.0	8.0	120	50	0.3	10.0	5.0	32.4	116	122	489	268				
	72	96	35	0.1	10.0	4.5	96	34	0.3	10.0	3.5	39.5	117	113	499					
	86	95	38	0.6	10.0	7.0	95	37	0.3	10.0	4.0	32.3	117	104	511	147				
	87	86	30	0.1	10.0	5.0	86	32	0.1	10.0	3.5	32.7	117	103	511	268				
	Mean	103	42	0.4	10.0	6.2	103	39	0.2	10.0	3.9	33.4		114	488		1.6			
VicAsh	Mean	99	40	0.4	10.2	6.4	99	38	0.4	10.0	4.5	32.7	158	110	499		1.5		0.0	489.0

Notes: “C” indicates a shrinkage slice that collapsed

*Check time is sampling time that checking was first observed; checking formed between this time and the previous sampling time

Peak surface e_i>2% is indicative of surface check formation

Table 4.6.1. Summary results from commercial and near-commercial scale trials. Continued from above.

		Initial MC, unconfined shrinkage % and corresponding MC at FSP and at EMC																		
		Tangential					Radial					Green sample board measurements						Model prediction		
Batch	No.	IMC	FSP MC	FSP St	EMC	EMC St	IMC	FSP MC	FSP Sr	EMC	EMC Sr	Thick (mm)	Width (mm)	Initial MC (%)	Basic Density (kg/m^3)	Checking observed (hours)	Diffusion coefficient (x10^{-7} m^2/hour)	Time to check (hours)	Peak surface ei	Time to peak ei (hours)
spotted gum (DPI&F)	1	57	26	0.3	13.5	5.5	58	34	0.3	14	2.8	31.1	107	61	779		1	NA		
	2	42	30	0.1	11.4	5.5	39	C				27.6	106	41	840		1.1	NA		
	3	55	31	0.1	13	4.6	53	32	0.1	13.9	2.1	29.8	107	54	750		0.9	NA		
	4	41	27	0.1	12.6	6.9	37	C				27.2	106	42	822		1.4	NA		
	5	45	27	0.4	11.5	5.1	46	35	0.1	14.3	2.6	30.8	107	49	854		1	NA		
	6	49	27	0.2	15.2	3.8	49	30	0.4	11.5	3.6	26.3	107	53	838					
	7	48	28	0.1	14.5	7.3	44	C				30.4	108	49	784					
	8	38	29	0.1	14.4	2.8	42	34	0.1	11.5	4.9	30.3	110	39	856					
	9	54	27	0.5	13.5	3.8	54	33	0.1	10.9	2.8	29.3	106	57	815					
	10	48	23	0.1	15.3	3.3	49	27	0.1	11.5	3.1	28.3	107	52	830					
	Mean	47.7	27.5	0.2	13.5	4.9	47.1	32.1	0.2	12.5	3.1	29.1		49.6	816.8		1.1			
blackbutt (DPI&F)	1	52.4	29	0.1	11.7	7	50.8	28	0.2	10	4.2	25.2	105	58	809		1.2	NA	0.017	66
	2	45.8	28	0.2	11.5	6.5	48.1	25	0.1	10.6	3.2	24.7	107	51	861		1.1	NA	0.044	68
	3	53.5	28	0.2	10.8	6.7	52.8	25	0.1	9.1	4	25.3	103	60	804		1.2	NA	0.007	85
	4	58.3	33	0.3	12.1	6.9	60.2	24	0.2	9.7	3.6	25.5	104	67	756		1.0	67	0.021	87
	5	48.7	30	0.5	9.7	7.1	56.9	C				24.9	104	59	806		1.1	NA	0.02	68
	6	55.5	29	0.4	12.1	8.3	56.6	C				25.8	105	60	766	68				
	7	52.2	25	0.3	9.7	6.3	52.5	24	0.2	10.7	4.2	25.0	104	57	812	68				
	8	53	26	0.4	11.3	4.1	54	28	0.1	11.9	2.8	25.2	103	57	817					
	9	45.3	26	0.5	9.7	6.6	47.2	C				24.9	105	54	842	68				
	10	55.8	35	0.5	11.2	7.8	51.9	25	0.1	10.7	3	28.3	102	57	818					
	Mean	52.1	28.9	0.3	11.0	6.7	58.5	25.5	0.2	9.9	3.8	25.5		57.9	809.1		1.1			

Notes: "C" indicates a shrinkage slice that collapsed

*Check time is sampling time that checking was first observed; checking formed between this time and the previous sampling time

Peak surface e_i>2% is indicative of surface check formation

Table 4.6.1. Summary results from commercial and near-commercial scale trials. Continued from above.

5. Sample predrying schedules and discussion

Generic schedules were calculated for each species using the new versions of **KilnSched** based on the mean species properties shown in Appendix B. Boards modelled were 28 mm thick, quartersawn for messmate and Victorian ash, backsawn for jarrah, spotted gum and blackbutt. The schedules for each species are shown in Tables 5.1-5.5; model-predicted average MC and surface instantaneous strain are shown in Figures 5.1-5.5. Modelling was only carried out for drying to just below FSP as these species are generally kiln final-dried at higher temperatures than **KilnSched** can reliably model, and most degrade occurs during drying to FSP.

Temperatures for the schedules have been selected as typical of those at which each species is dried with low occurrence of collapse (for collapse prone species). The temperature is not "optimised" in any other sense. Velocity is also set at values typical of that expected for predrying each species; 1.0 m/s for spotted gum and blackbutt and 0.5 m/s for the more refractory species. Humidity setpoints for each schedule were adjusted using an iterative process, so that predicted surface instantaneous strain remained below the value of 0.02 taken to correspond to formation of surface checking.

Setpoint changes have been restricted to two days following starting, 7 days after starting, then every 7 days thereafter. Temperature and wet bulb temperature steps have been restricted to whole degrees. Note that these restrictions are just for the sake of simplicity; these schedules are for demonstration purposes. Schedules can be varied every hour and temperature incremented infinitesimally. Note also that the model accepts schedules with either wet bulb temperature or relative humidity setpoints.

Time (days)	Time (hours)	Temperature (°C)	Wet bulb temperature (°C)	Relative humidity (%)	Velocity (m/s)
0	0	22	20	83.5	0.5
2	48	22	19	75.7	0.5
7	168	23	20	76.3	0.5
14	336	24	20	69.6	0.5
21	504	25	21	70.3	0.5
28	672	26	21	64.3	0.5
35	840	27	21	58.8	0.5
42	1008	28	21	53.7	0.5

Table 5.1. Sample schedule for jarrah

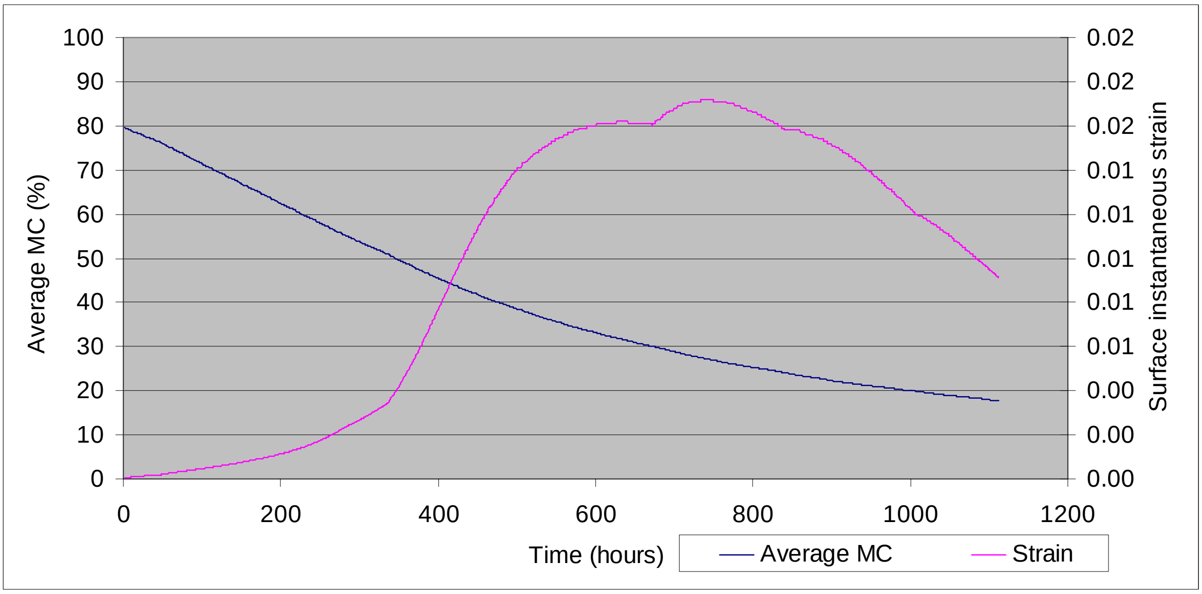

Figure 5.1. Predicted average MC and surface instantaneous strain for jarrah

Time (days)	Time (hours)	Temperature (C)	Wet bulb temperature (C)	Relative humidity (%)	Velocity (m/s)
0	0	22	20	83.5	0.5
2	48	22	20	83.5	0.5
7	168	23	20	76.3	0.5
14	336	24	21	76.8	0.5
21	504	25	22	77.3	0.5
28	672	26	22	70.9	0.5
35	840	27	22	65.0	0.5
42	1008	28	21	53.7	0.5

Table 5.2. Sample schedule for messmate

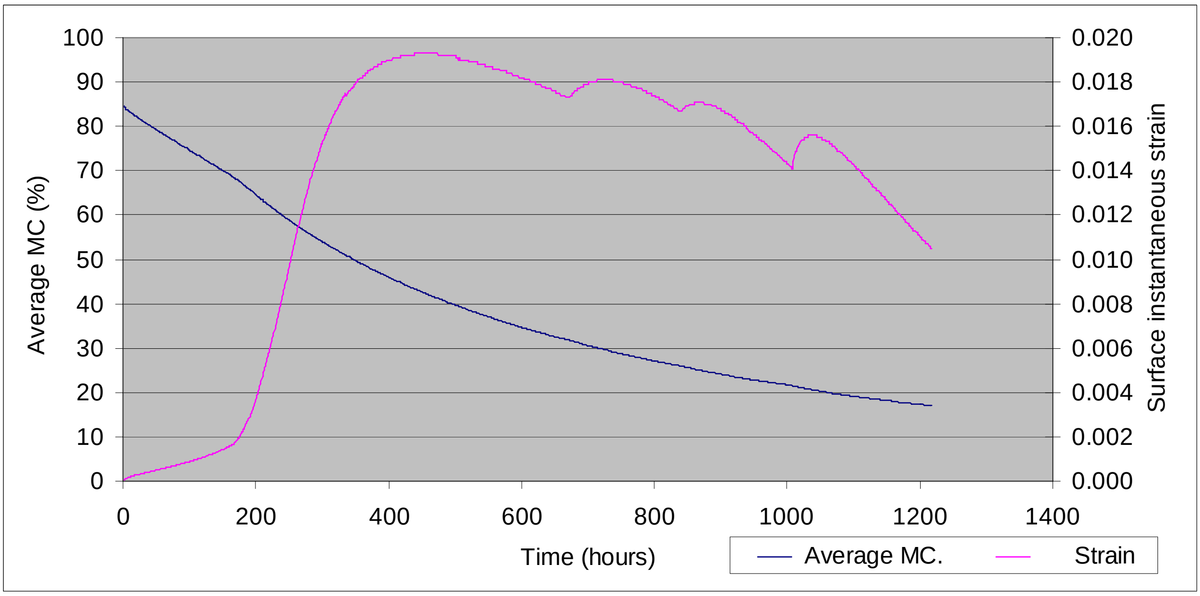

Figure 5.2. Predicted average MC and surface instantaneous strain for messmate

Time (days)	Time (hours)	Temperature (C)	Wet bulb temperature (C)	Relative humidity (%)	Velocity (m/s)
0	0	22	20	83.5	0.5
2	48	22	20	83.5	0.5
7	168	23	21	83.9	0.5
14	336	24	21	76.8	0.5
21	504	25	22	77.3	0.5
28	672	26	22	70.9	0.5
35	840	27	22	65.0	0.5
42	1008	28	21	53.7	0.5
49	1176	29	21	53.7	0.5

Table 5.3. Sample schedule for Victorian ash

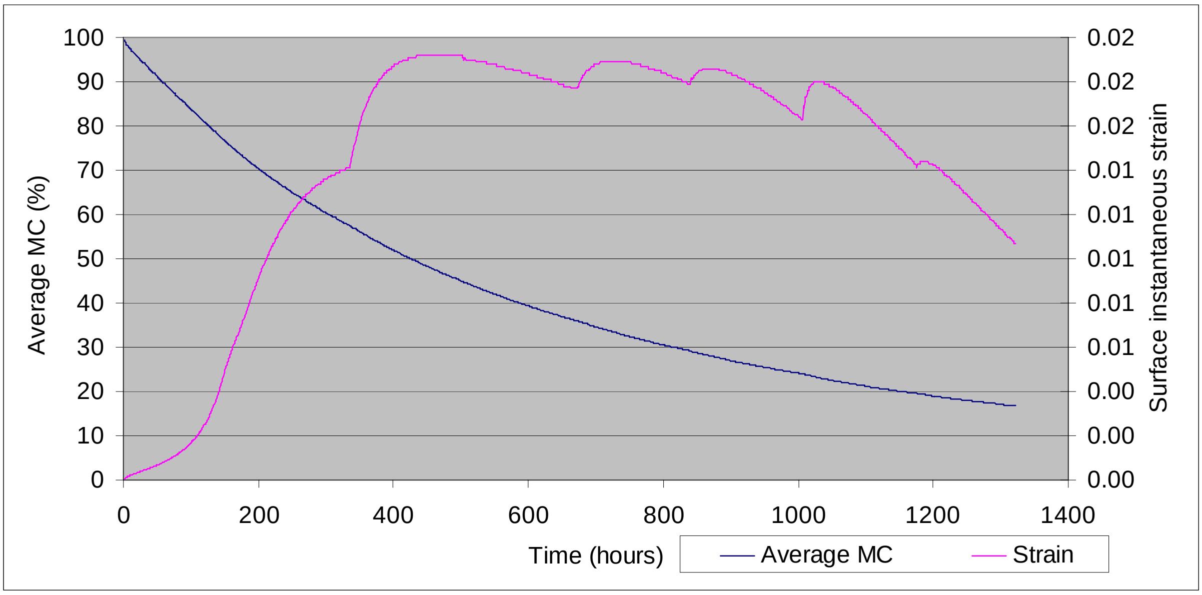

Figure 5.3. Predicted average MC and surface instantaneous strain for Victorian ash

Time (days)	Time (hours)	Temperature (C)	Wet bulb temperature (C)	Relative humidity (%)	Velocity (m/s)
0	0	35	33	87.2	1
2	48	37	35	87.6	1
7	168	40	37	82.5	1
14	336	45	42	83.6	1
21	504	50	46	79.7	1
28	672	60	51	62.3	1
35	840	70	60.0	62.1	1

Table 5.4. Sample schedule for spotted gum

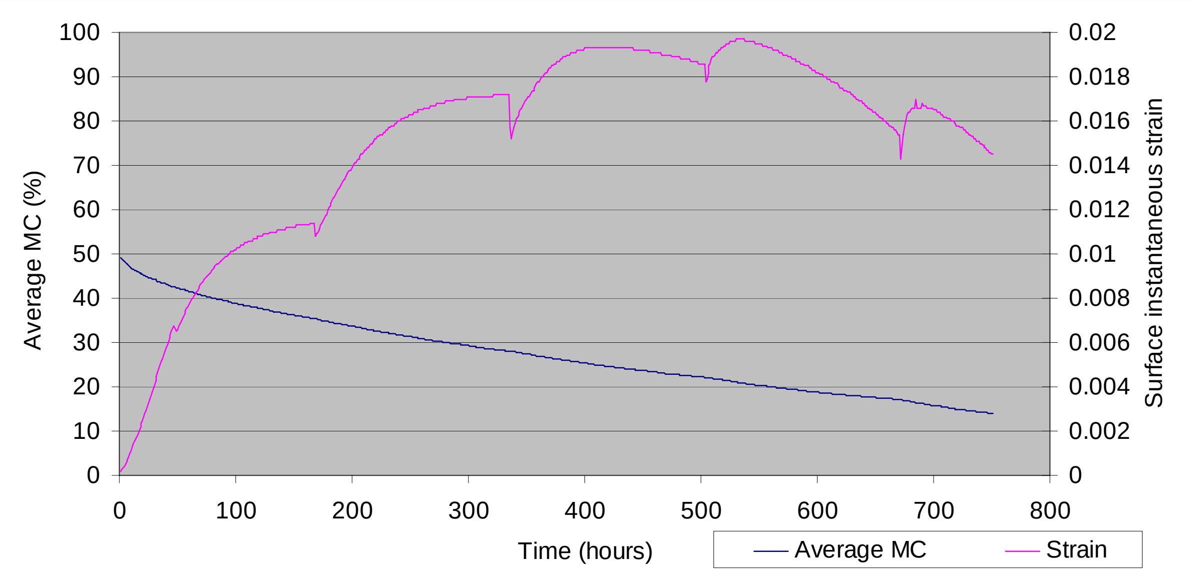

Figure 5.4. Predicted average MC and surface instantaneous strain for spotted gum

Time (days)	Time (hours)	Temperature (C)	Wet bulb temperature (C)	Relative humidity (%)	Velocity (m/s)
0	0	35	33	87.2	1
2	48	37	35	87.6	1
7	168	40	37	82.5	1
14	336	45	42	83.6	1
21	504	50	46	79.7	1
28	672	60	54	73.5	1
35	840	70	60	62.1	1

Table 5.5. Sample schedule for blackbutt

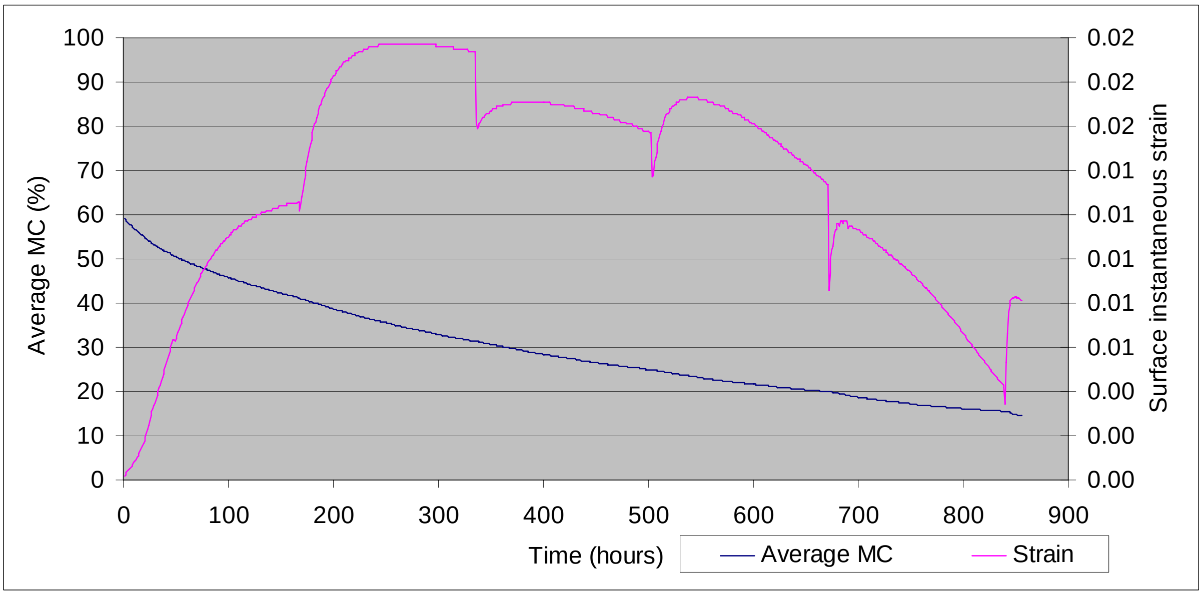

Figure 5.5. Predicted average MC and surface instantaneous strain for blackbutt

Experimental versions of **KilnSched** calculate diffusion coefficient by matching measured and predicted moisture content profiles though the board thickness. This process is not generally possible in a commercial environment due to the time, skills and equipment required to make the measurement on only one board. Surface moisture contents are extrapolated from the first three measured values into the board, hence are prone to measurement inaccuracy, particularly late in drying. For this reason, commercial versions of the model rely on a generic value of the diffusion coefficient. This can be set by the user in these versions in case the generic value does not fit the specific resource a mill is processing. It can be set by fitting predicted and measured average MC during drying. The difficulty in measuring diffusion coefficient means that it has only been practically possible in this work to measure it on a small number of boards for each species. Attaining a generic value representative of the whole resource is impractical; rather, users should ensure that the model uses parameters suitable for their particular feedstock.

Similarly, the user can alter basic density, initial moisture content and unconfined shrinkage parameters if the default generic values are found to be inaccurate for the mill's specific resource. Board thickness and type (backsawn or quartersawn) can also be altered. Note that **KilnSched** is a one-dimensional model; board width should be a minimum of approximately 4 × board thickness.

In the past, mills have found **KilnSched** valuable as a training tool as well as for schedule development (Michael Lee, Neville Smith Timbers, 2004 *pers. comm.*). Mill personnel can investigate the possible effects of their actions; for example, leaving a fresh rack of timber exposed in a windy area on a hot day. In this case, absolute accuracy of the model is less important than it is for schedule development.

Mill drying staff using **KilnSched** for schedule development need to use it with appropriate caution. **KilnSched** is principally a laboratory-developed tool; timber drying is a complex process involving the interaction of many parameters. A computer model can only ever be a simplification of such a situation with many inherent assumptions. Schedule changes, particularly acceleration of drying, should be introduced gradually along with careful observation of the dried quality that results.

The schedules presented here are examples only; it was not possible to trial them at an industrial scale due to practical constraints. **KilnSched** users should compare model predictions with actual drying performance and make incremental adjustments to schedules.

6. Recommendations and further work

Five computer models are supplied with this report. It is recommended that they be disseminated throughout the relevant parts of the processing industry free of charge with a simple user manual.

Useful improvements have been made to the original **KilnSched** model. Model predictions now more accurately match measurements. However, these modifications have by necessity been based on a small number of measurements, so generic species properties may need to be adjusted. Mills will get more accurate modelling by adjusting species properties to suit their particular feedstock.

Further improvements could be made to the models' accuracy by more measurements, particularly of sorption isotherms. However, the effort is probably not warranted at this stage as the species that would most benefit are relatively easy to dry quickly with low degrade (spotted gum and blackbutt).

The biggest improvement to drying quality of the collapse prone species studied would be by finding means of avoiding collapse degrade, either by identifying and segregating collapse prone material or controlling the drying process in some way that avoids collapse and internal checking.

If the new single-board **KilnSched** models prove to be accurate and useful in use, they should be extended to kiln-wide models. These account for the variability in the timber being dried and variation in drying conditions throughout the kiln (such as those resulting from fan reversal) to predict overall dried quality of a batch of timber, for example Pordage and Langrish (2000). Such a model could then help inform decisions on investment in drying equipment, by predicting drying time and quality for various products produced from particular drying regimes.

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8. Appendix A. Drying and modelling results from small-scale experimental trials

Data for the modelling below is shown in Table 2.8.1.

8.1. Modelling for alpine ash

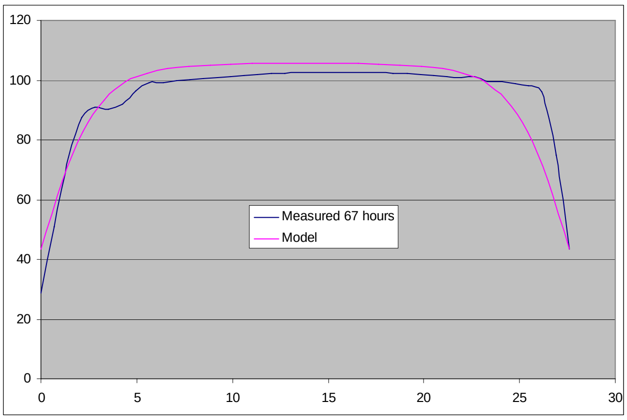

Figure 8.1.1. Measured and model predicted moisture content profile after 67 hours drying

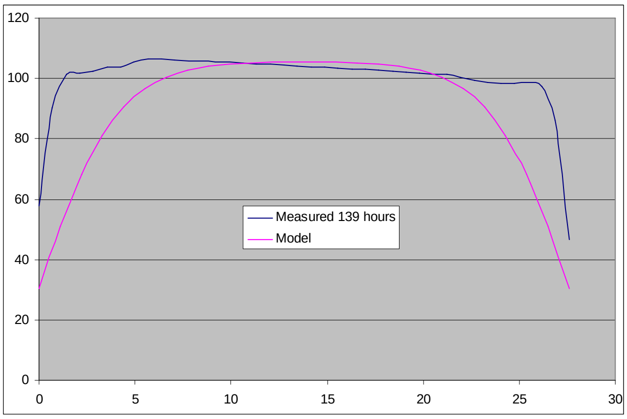

Figure 8.1.2. Measured and model predicted moisture content profile after 139 hours drying

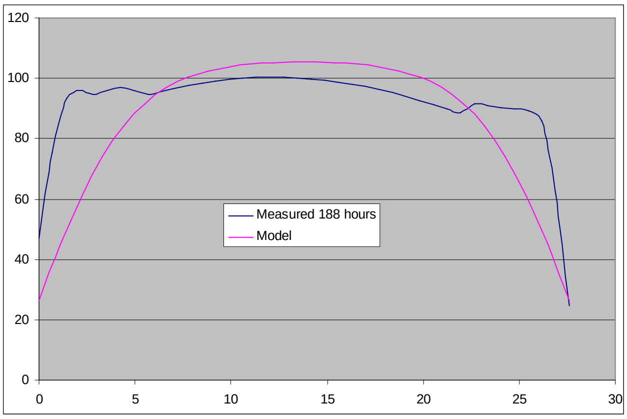

Figure 8.1.3. Measured and model predicted moisture content profile after 188 hours drying

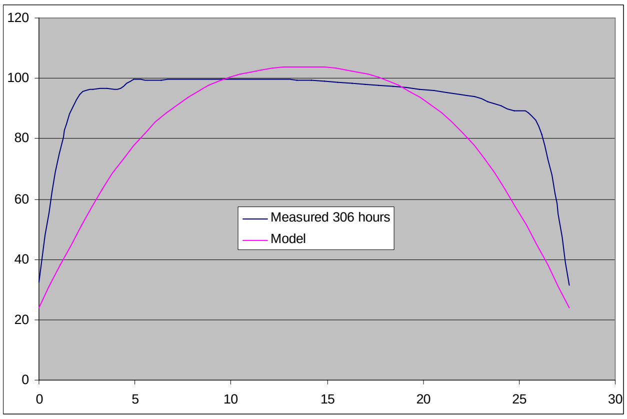

Figure 8.1.4. Measured and model predicted moisture content profile after 306 hours drying

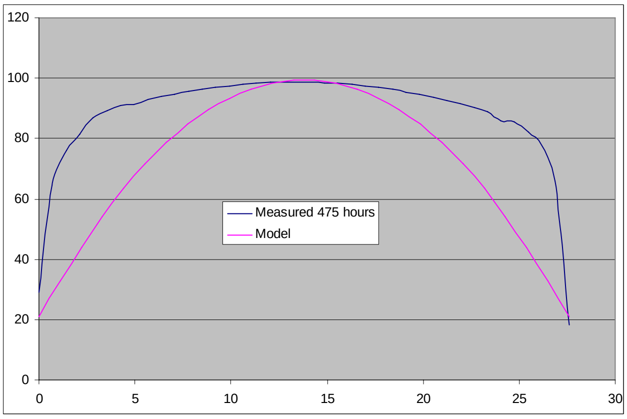

Figure 8.1.5. Measured and model predicted moisture content profile after 475 hours drying

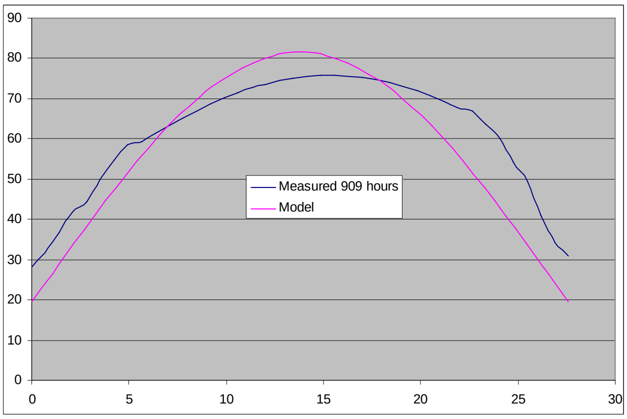

Figure 8.1.6. Measured and model predicted moisture content profile after 909 hours drying

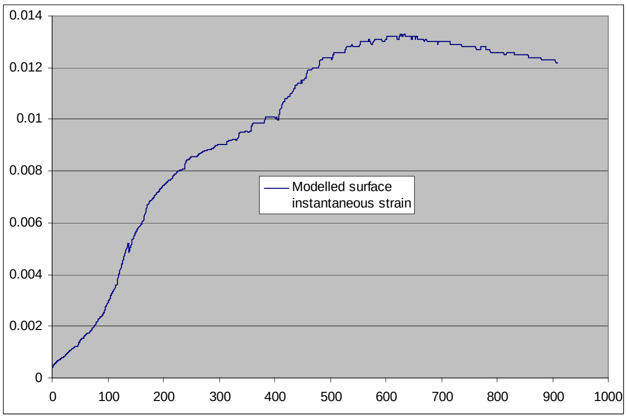

Figure 8.1.7. Model predicted surface instantaneous strain during drying. A level of 0.02 indicates formation of surface checking.

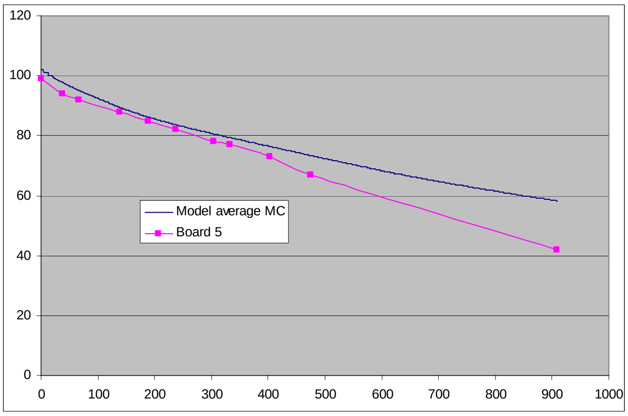

Figure 8.1.8. Measured and model predicted average moisture content during drying

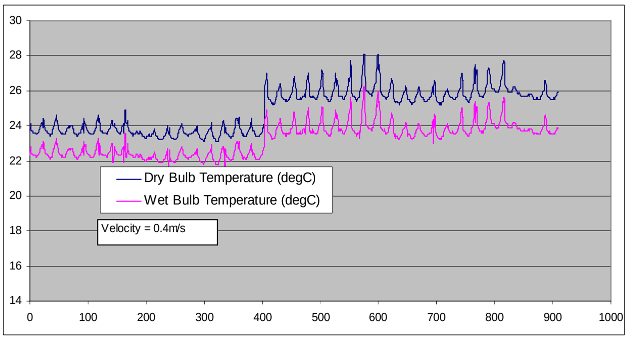

Figure 8.1.9. Recorded kiln conditions for drying trial

8.2. Modelling for blackbutt

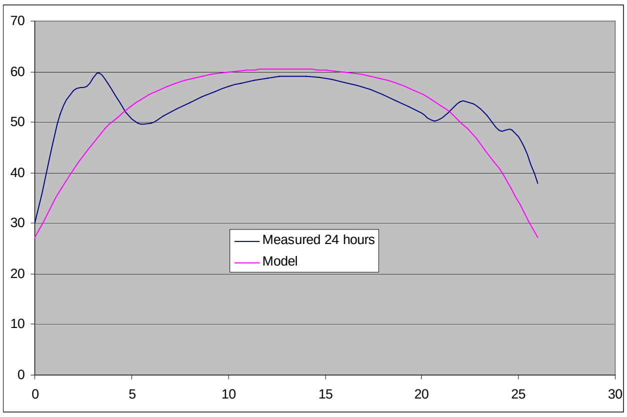

Figure 8.2.1. Measured and model predicted moisture content profile after 24 hours drying

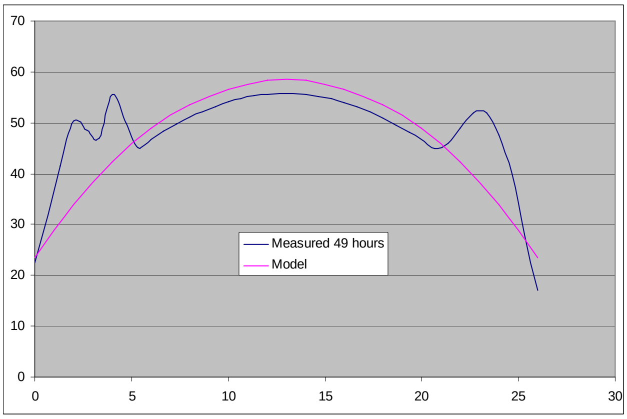

Figure 8.2.2. Measured and model predicted moisture content profile after 49 hours drying

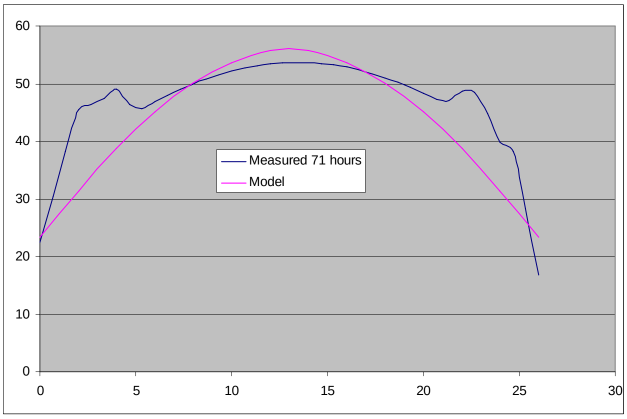

Figure 8.2.3. Measured and model predicted moisture content profile after 71 hours drying

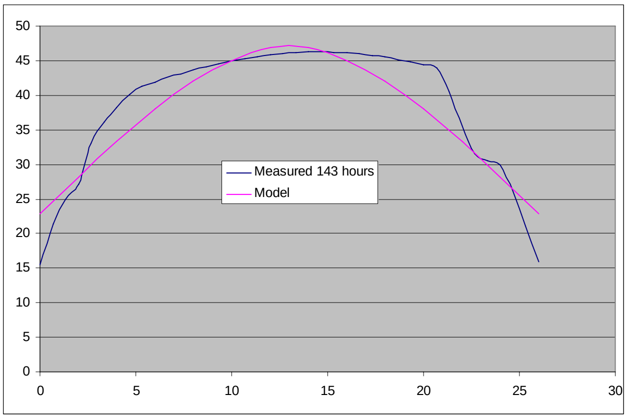

Figure 8.2.4. Measured and model predicted moisture content profile after 143 hours drying

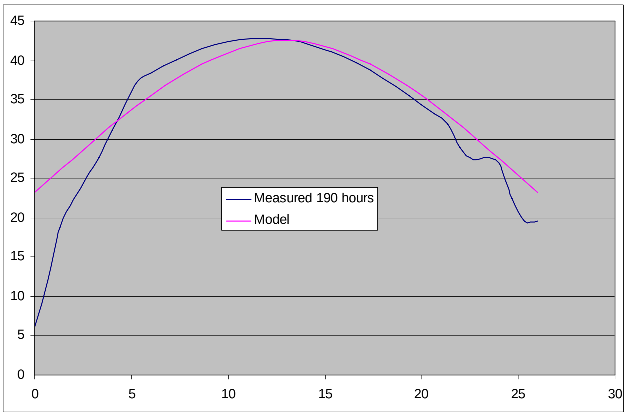

Figure 8.2.5. Measured and model predicted moisture content profile after 190 hours drying

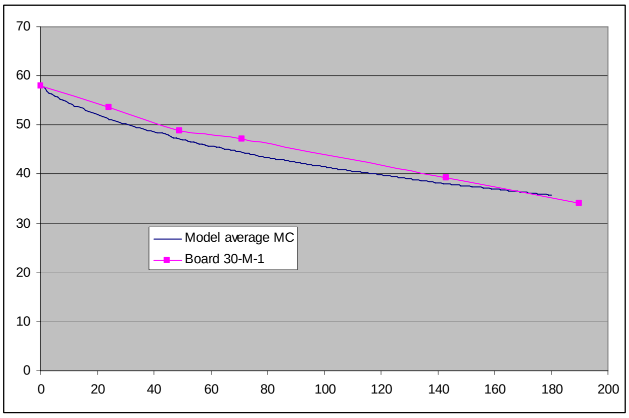

Figure 8.2.6. Measured and model predicted average moisture content during drying

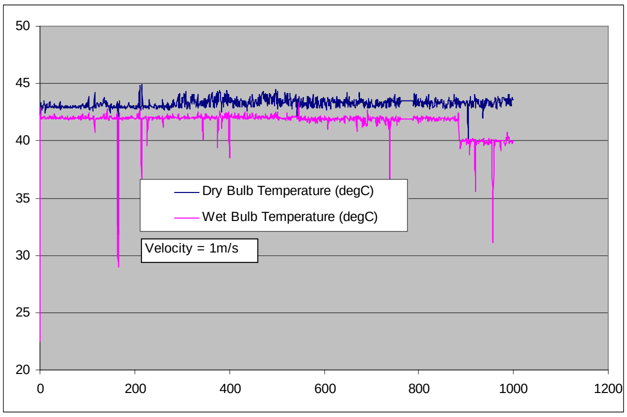

Figure 8.2.7. Recorded kiln conditions for drying trial

8.3. Modelling for jarrah

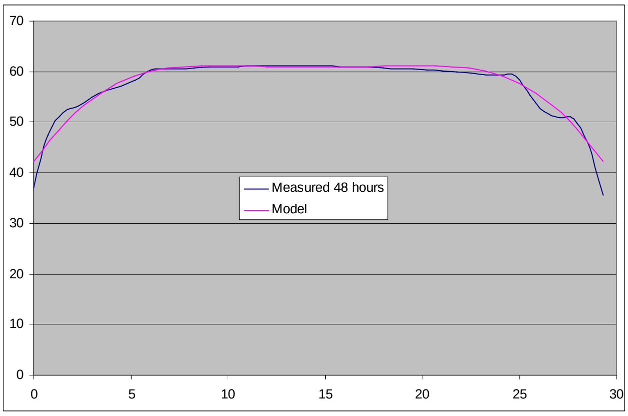

Figure 8.3.1. Measured and model predicted moisture content profile after 48 hours drying

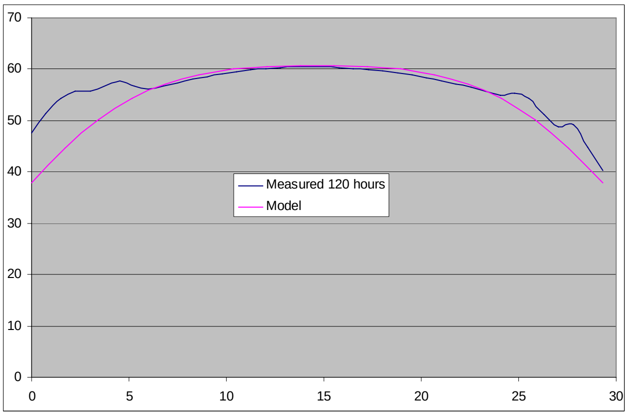

Figure 8.3.2. Measured and model predicted moisture content profile after 120 hours drying

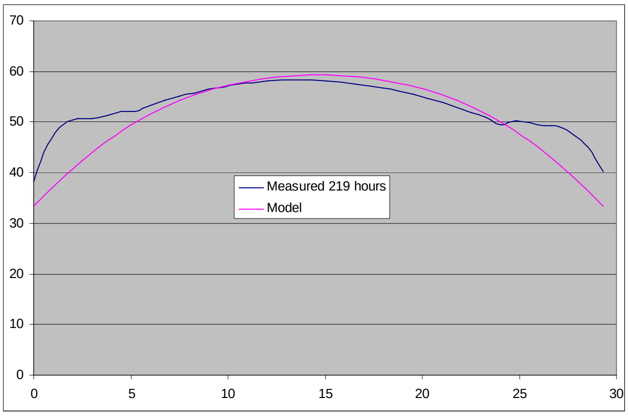

Figure 8.3.3. Measured and model predicted moisture content profile after 219 hours drying

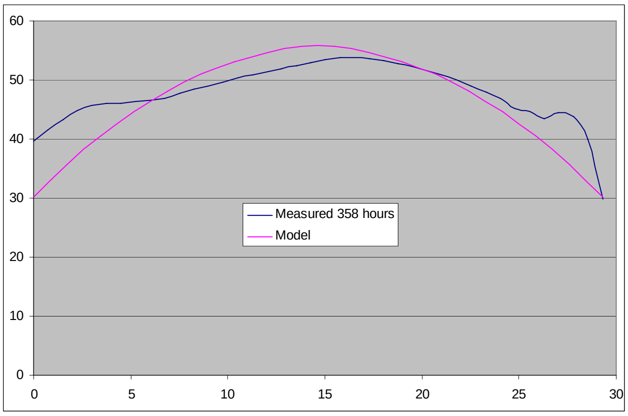

Figure 8.3.4. Measured and model predicted moisture content profile after 358 hours drying

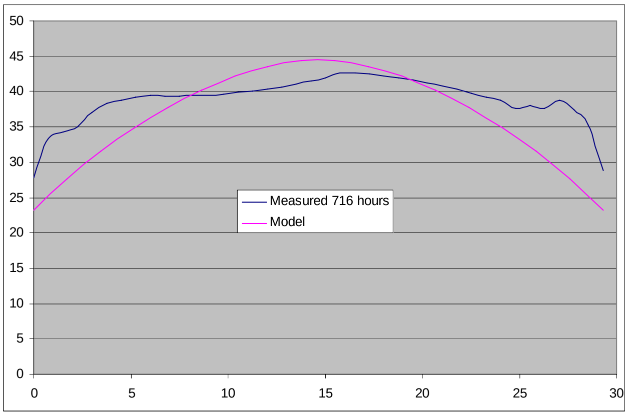

Figure 8.3.5. Measured and model predicted moisture content profile after 716 hours drying

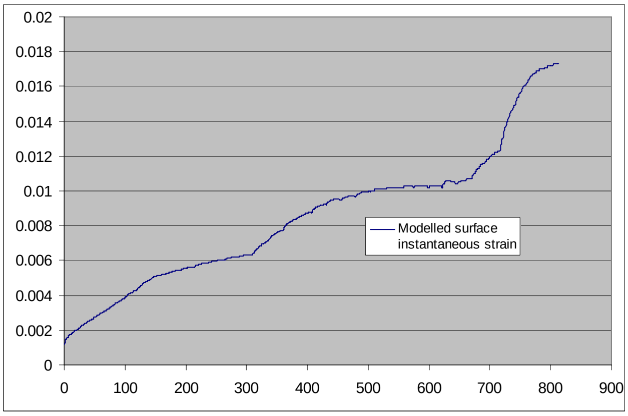

Figure 8.3.6. Model predicted surface instantaneous strain during drying. A level of 0.02 indicates formation of surface checking.

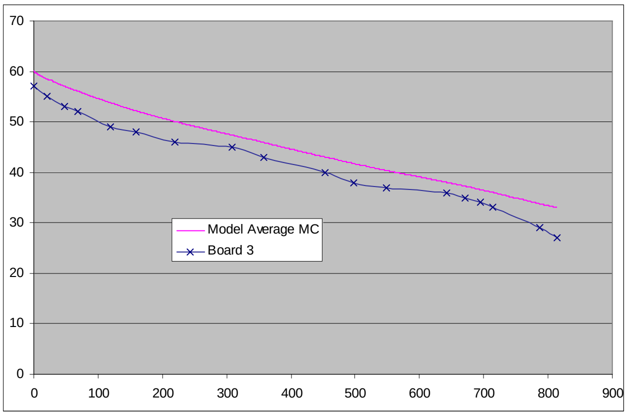

Figure 8.3.7. Measured and model predicted average moisture content during drying

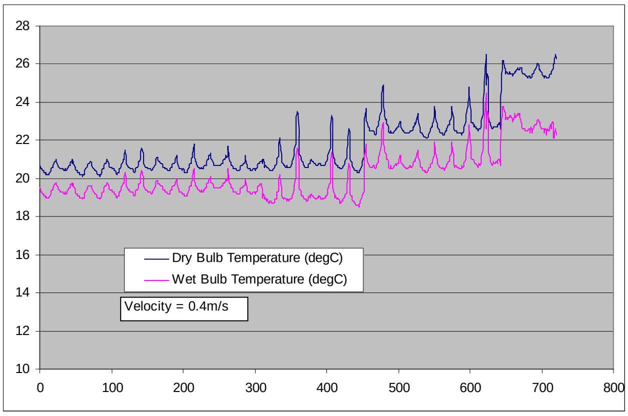

Figure 8.3.1. Recorded kiln conditions for drying trial

8.4. Modelling for messmate

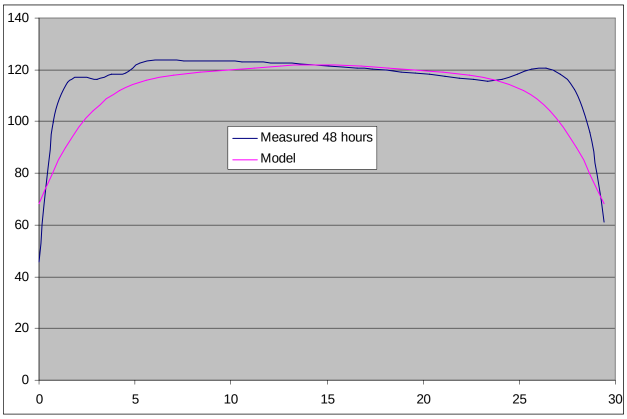

Figure 8.4.1. Measured and model predicted moisture content profile after 48 hours drying

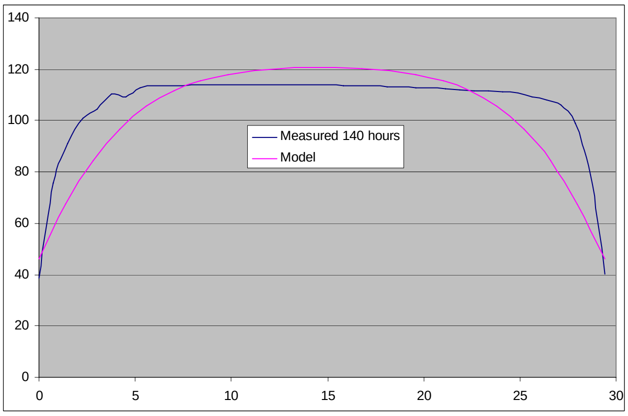

Figure 8.4.2. Measured and model predicted moisture content profile after 140 hours drying

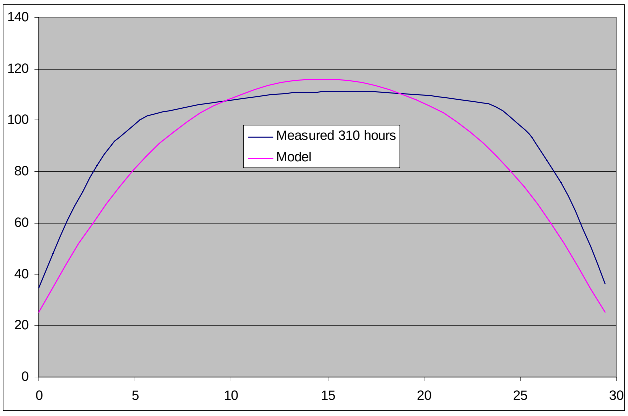

Figure 8.4.3. Measured and model predicted moisture content profile after 310 hours drying

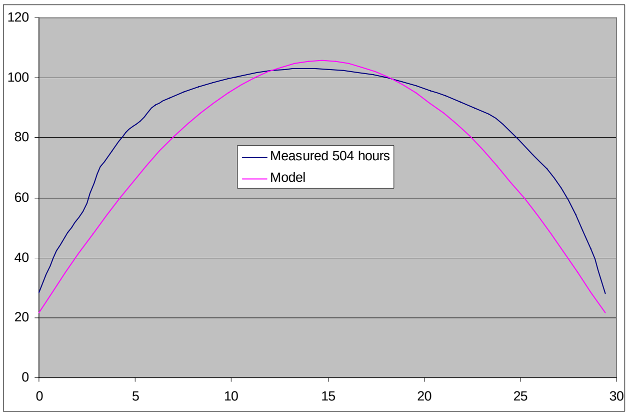

Figure 8.4.4. Measured and model predicted moisture content profile after 504 hours drying

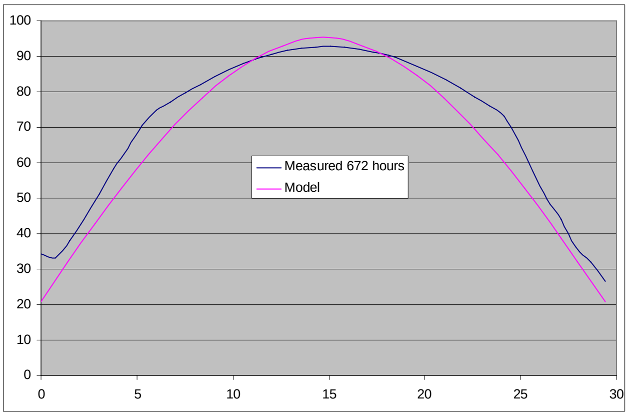

Figure 8.4.5. Measured and model predicted moisture content profile after 672 hours drying

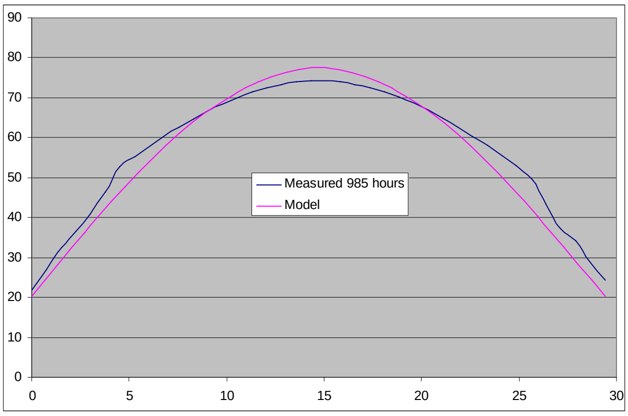

Figure 8.4.6. Measured and model predicted moisture content profile after 985 hours drying

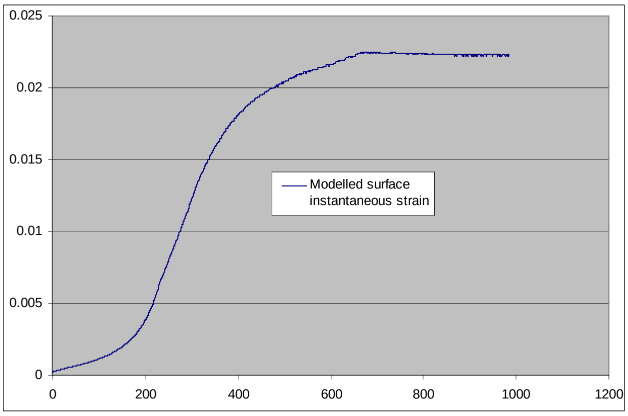

Figure 8.4.7. Model predicted surface instantaneous strain during drying. A level of 0.02 indicates formation of surface checking.

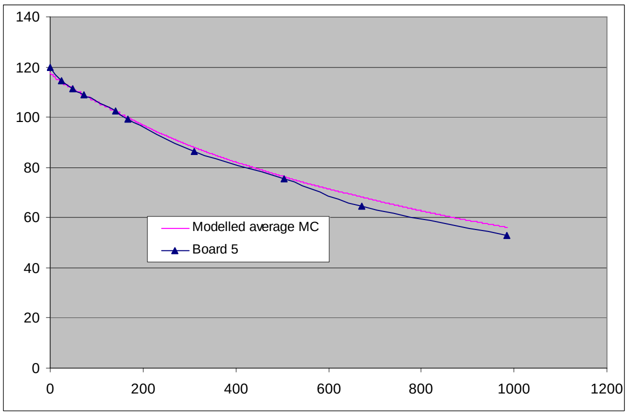

Figure 8.4.8. Measured and model predicted average moisture content during drying

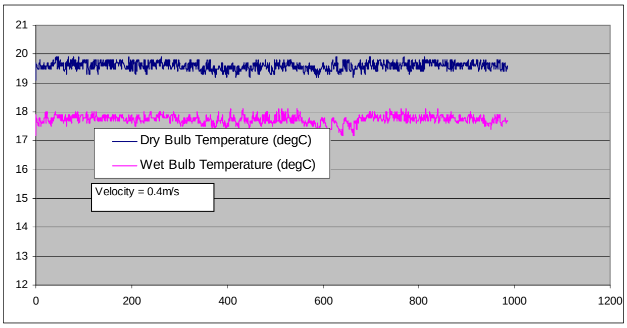

Figure 8.4.9. Recorded kiln conditions for drying trial

8.5. Modelling for mountain ash

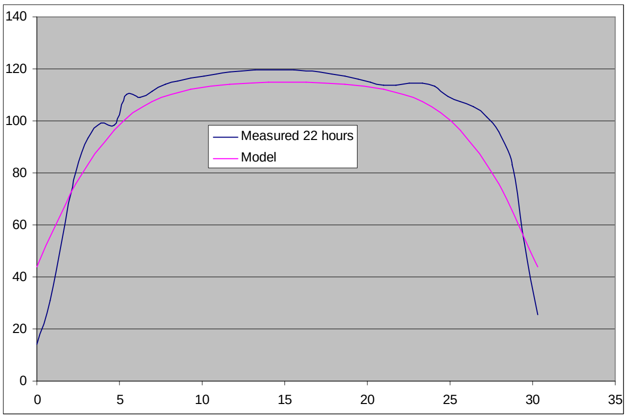

Figure 8.5.1. Measured and model predicted moisture content profile after 22 hours drying

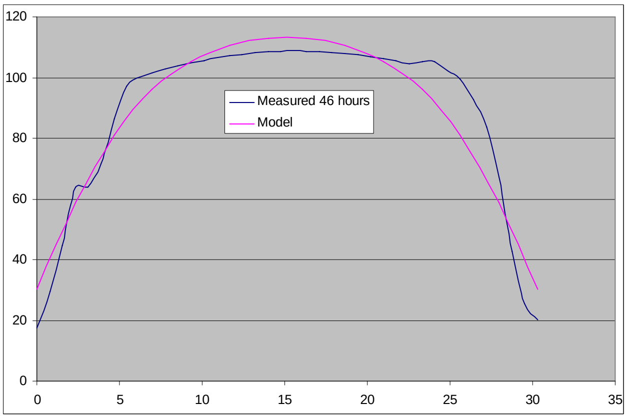

Figure 8.5.2. Measured and model predicted moisture content profile after 46 hours drying

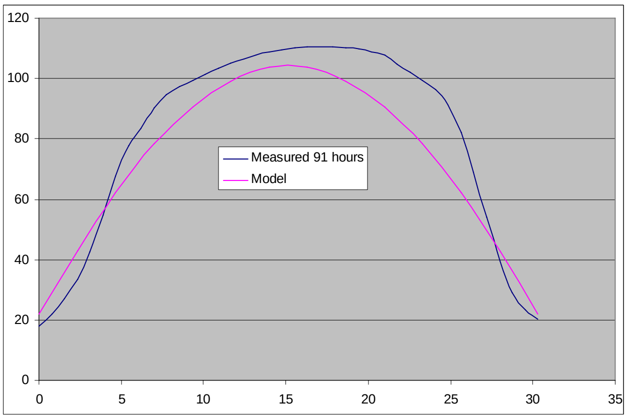

Figure 8.5.3. Measured and model predicted moisture content profile after 91 hours drying

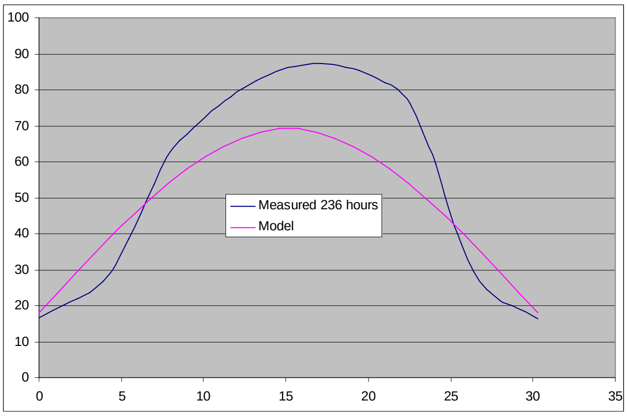

Figure 8.5.4. Measured and model predicted moisture content profile after 236 hours drying

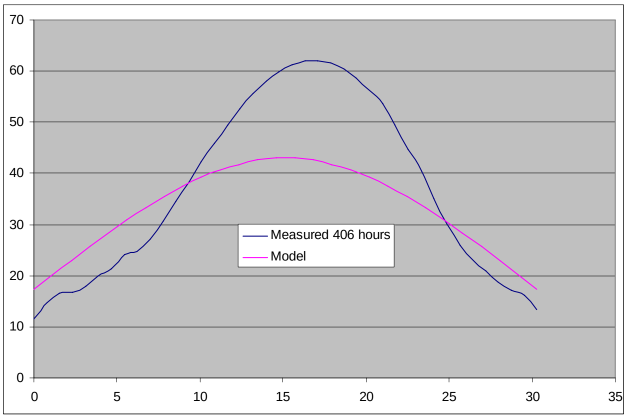

Figure 8.5.5. Measured and model predicted moisture content profile after 406 hours drying

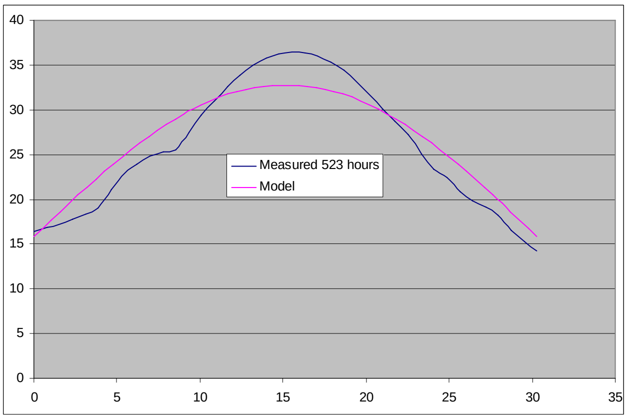

Figure 8.5.6. Measured and model predicted moisture content profile after 523 hours drying

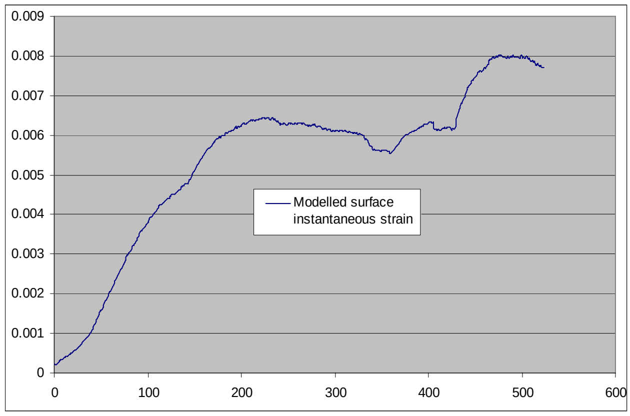

Figure 8.5.7. Model predicted surface instantaneous strain during drying. A level of 0.02 indicates formation of surface checking.

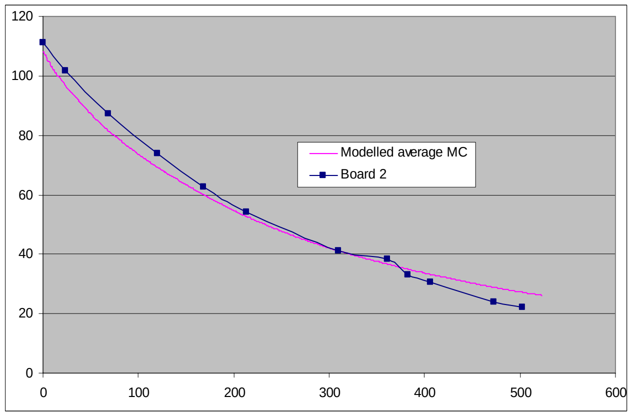

Figure 8.5.8. Measured and model predicted average moisture content during drying

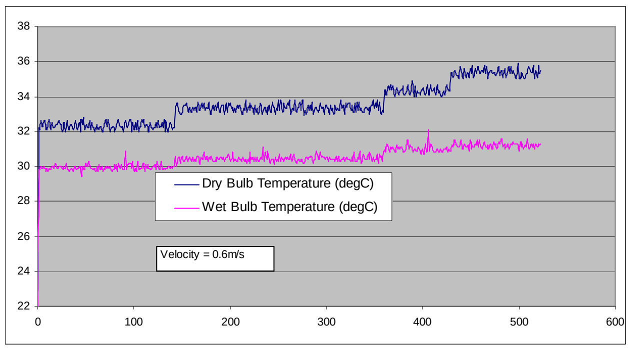

Figure 8.5.9. Recorded kiln conditions for drying trial

8.6. Modelling for spotted gum

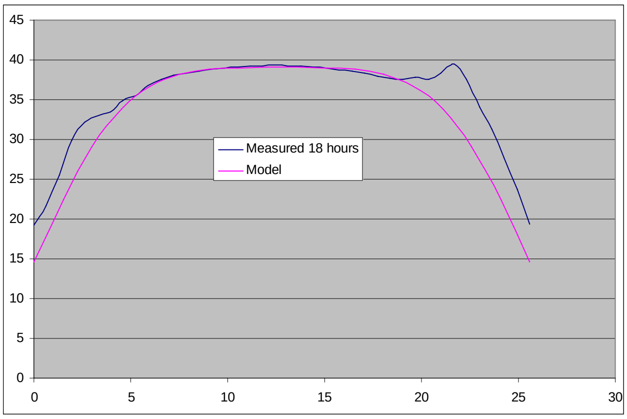

Figure 8.6.1. Measured and model predicted moisture content profile after 18 hours drying

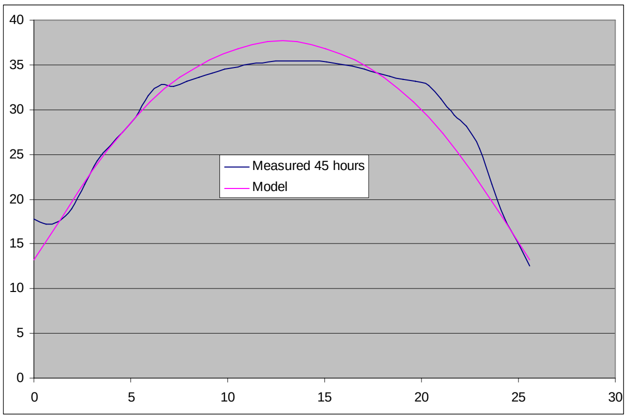

Figure 8.6.2. Measured and model predicted moisture content profile after 45 hours drying

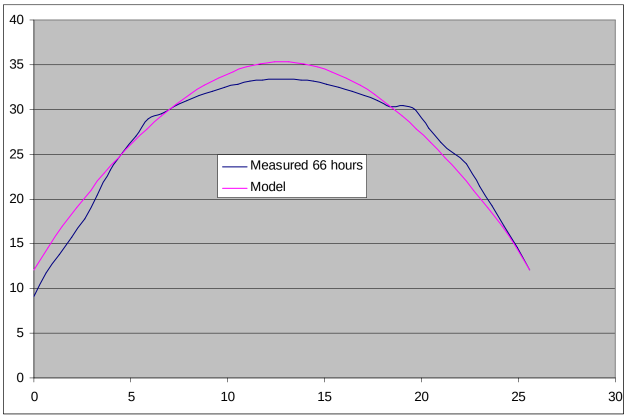

Figure 8.6.3. Measured and model predicted moisture content profile after 66 hours drying

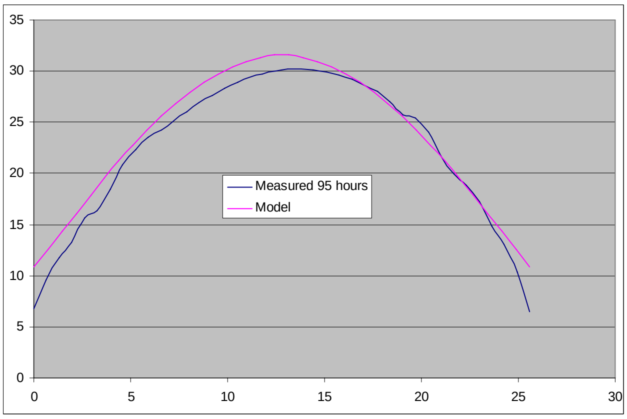

Figure 8.6.4. Measured and model predicted moisture content profile after 95 hours drying

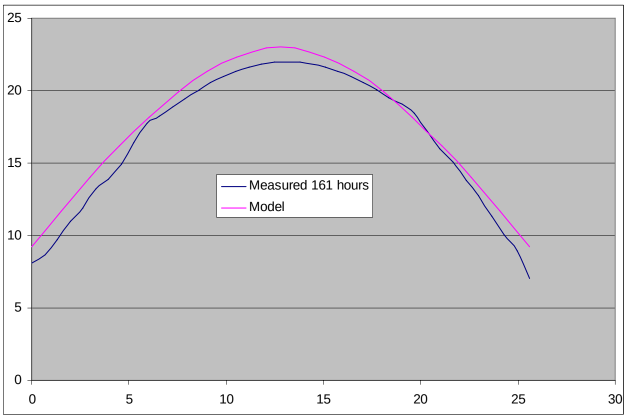

Figure 8.6.5. Measured and model predicted moisture content profile after 161 hours drying

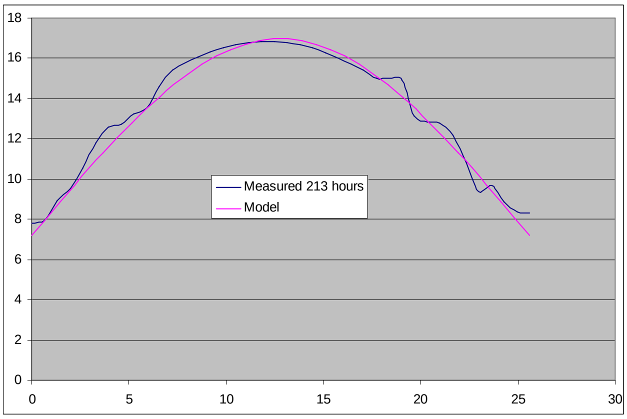

Figure 8.6.6. Measured and model predicted moisture content profile after 213 hours drying

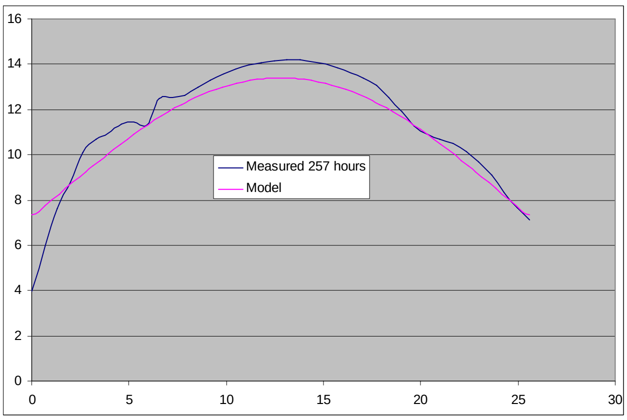

Figure 8.6.7. Measured and model predicted moisture content profile after 257 hours drying

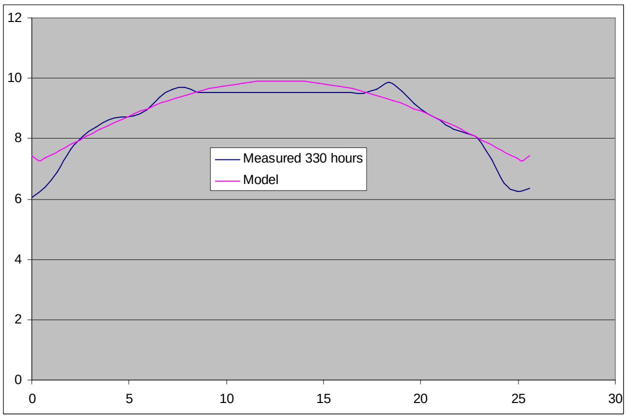

Figure 8.6.8. Measured and model predicted moisture content profile after 330 hours drying

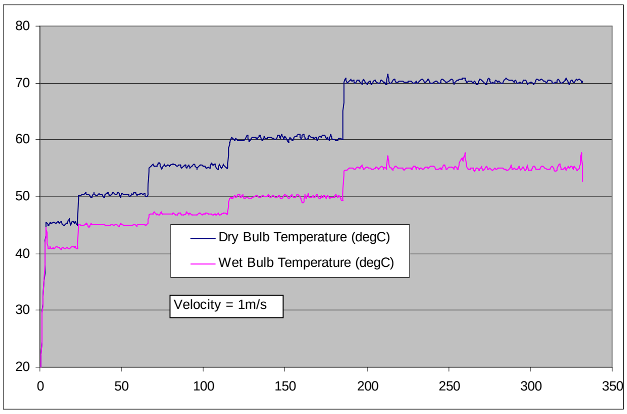

Figure 8.6.1. Recorded kiln conditions for drying trial

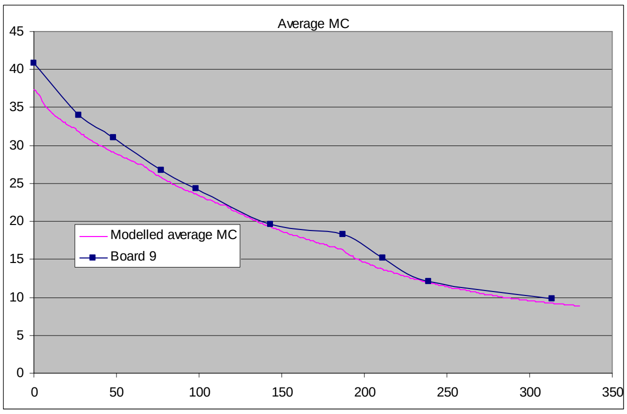

Figure 8.6.9. Measured and model predicted average moisture content profile during drying

9. Higher–temperature final drying of regrowth spotted gum

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Department of Primary Industries and Fisheries

October 2005

9.1. Introduction

Following current common industry practice, spotted gum (*Corymbia maculata*) is pre-air dried to a moisture content between 15 and 18 % before final kiln drying commences. Final drying temperatures rarely exceed 80 ºC.

Conventionally, high temperature drying refers to drying over 100 ºC. For the purposes of this study, the term 'higher temperature' drying is used to describe drying above 80 ºC.

The objective of this component of the project was to investigate the effect of higher temperature final drying on the dried quality and drying time of regrowth spotted gum.

9.2. Method

The chosen method is based on findings of the literature review appended to this report (9.5 Appendix A).

Regrowth spotted gum material was sourced through Boral in Kyogle, NSW. The nominal dimensions of the boards were 100 × 25 × 4200 mm. Boral staff selected 50 mixed sawn (backsawn, quartersawn and transitional) pre-air dried boards based on our specifications. The material was specified to be dried to15-20% MC (measured on site with a calibrated resistance–type moisture meter); with little or no signs of surface checking, collapse, gum pockets, spiral grain and insect attack, with less than 50 mm of end split and end check, and minimal signs of distortion.

The research consisted of four trials. Each trial consisted of 40 boards cut into four 900 mm lengths (the maximum length that can fit in the experimental kiln). Each trial consisted of matched sections from the original 4200 mm length boards.

Before drying commenced, the average initial moisture content/moisture gradient, and air dry density, for the 4200mm length boards, were calculated in accordance with Australian/New Zealand Standards AS/NZS 1080.1:1997 and AS/NZ 1080.3:1981, respectively. The oven dry method was used to determine moisture content and moisture gradient. The residual drying stress and internal check measurements were made in accordance with Australian/New Zealand Standard AS/NZS 4787:2001.

Prior to drying each 900 mm boards was measured for distortion (twist, spring, bow, cup) in accordance with Australian Standard AS 2796.3:1999, surface checking; end split; end check; and collapse in accordance with AS/NZS 4787:2001. Occurrences of surface checking, end split and end check were marked on the trial boards before drying. This was to ensure that these defects were not mistaken as a cause of kiln drying. End checks, unlike end splits, do not penetrate through the board thickness.

For each drying trial, the trial boards were racked in the research kiln 5 boards wide × 8 boards high. A row of 'dummy boards' were placed on the air inlet side of the stack as well as the top of the stack to eliminate the effects of harsher drying on the outer shell of the stack.

The four trials consisted of one conventional drying trial and three higher–temperature drying trials each running at different dry bulb temperatures (90ºC, 110ºC, and 130ºC). The drying schedule moisture content change and end points were measured with a load cell measuring the weight loss of the stack.

The energy consumed by each kiln trial was measured. It is a combination of the energy used by running the heater elements, boiler elements and fan.

The conventional drying trial (trial1) is based on Campbell's (1980) drying schedule for spotted gum. The higher temperature drying trials are based on Boone's (1979a, 1979b, 1980) recommendations from previous studies (see 9.5 Appendix A).

The endpoint average moisture content target for each trial was 10% and the equalising EMC target for each trial was 12%.

The following schedules were adopted:

Average MC	DBT deg. C	WBT deg. C	Relative Humidity	EMC %
20-15	70	55	45	6.5
15-10	70	50	35	5

Table 1–Conventional trial

Trial #	DBT deg. C	WBT deg. C	Relative Humidity	EMC %
2	90	65	35	4
3	110	85	38	4
4	130	max~100deg	35	3

Table 2–Higher temperature trials

For all trials, the heat up period, under saturated conditions, was 4 hours.

A natural cool down period occurred after drying with the fans turned off and the vents slightly open.

The equalising period was 24 hours, excluding a 4-hour heat up period. The equalising conditions were 60/54.5ºC (DBT/WBT) to give an approximate 12% EMC condition.

The air velocity was controlled at 3 m/s for trial 1 and 5 m/s for the higher temperature trials.

After kiln drying, distortion (twist, spring, bow, cup), surface checking, end split, end check, and collapse were measured in accordance with the aforementioned Australian standards. A 300 mm section was removed from each trial board numbered 1-20 to measure average moisture content, moisture content gradient and residual drying stress. Internal check was investigated at this stage on the cross sections of the freshly sawn ends of the trial boards. The remaining twenty 600 mm sections were end coated on the freshly sawn faces prior to equalising.

After equalising, measurements of collapse, residual drying stress, moisture gradient, average MC, and shrinkage were repeated. Further measurements of distortion and surface defects at this stage were deemed irrelevant due to the removal of 300mm from the sample boards prior to equalisation.

The remaining twenty (numbered 21-40) trial boards were evenly dressed to a thickness of 19 mm. Surface checking degrade levels were then re-assessed.

After the completion of each of the four trials, matched boards were photographed and compared visually for signs of discoloration.

9.3. Results

9.3.1. Energy Consumption and Drying Times

Energy consumption (kWh) was calculated by the kiln control software. The software takes into account the total length of time each energy consuming device (fans, heater and boiler) are switched on during the trial and the power ratings for each device. The fan speed is also taken into account so that energy consumption decreases with decreasing fan speed. Although this is not an exact energy consumption measurement made using a power meter, it can be used as a comparative measure between trials.

Excluding the four-hour heat up time, the percentage of time taken for trials 2, 3, and 4 compared with the control trial 1 are 48.3%, 36.5% and 12.5% respectively (table 3). The reduction in drying time was significant especially considering the relatively similar levels of power consumed.

The energy consumed by equalising was similar for each trial.

	Kiln Drying		Equalising	
Trial #	Energy (kWh)	Time (hrs)	Energy (kWh)	Time (hrs)
Trial1	64.26	24.3	61.61	28
Trial2	55.26	13.8	62.79	28
Trial3	62.85	11.4	61.57	28
Trial4	60.37	8.3	60.06	28

Table 3 – Energy consumption and drying time

9.3.2. Moisture Content

Average moisture content results before drying, before equalising and after equalising, were calculated (table 4). The standard deviation figures prior to equalisation (pre-equ MC%) indicate that the variability in average moisture content of the samples was exacerbated as the temperature increased (0.77 to 1.32% MC). The variability was considerably reduced by the equalising process as indicated by the standard deviation figures for each trial after equalisation (post-equ MC%).

The average moisture content variability after drying and equalising for each trial fall into the highest quality class A as specified by AS/NZS 4787:2001 (see 9.6 Appendix B for class classifications).

The moisture gradients for each drying stage, shown in Table 5, contain the average, maximum and minimum moisture content differences between case and core. In accordance with AS/NZS 4787:200, the average moisture content gradient quality classes after equalisation is ‘B’ for trial 1 and ‘C’ for the higher temperature trials. Class A is generally sought after in industry for flooring and joinery applications.

Trial #	Pre-Dry MC % Ave.	Max.	Min	Std.Dev.	Pre-Equ. MC % Ave.	Max.	Min	Std.Dev.	Post-Equ. MC % Ave.	Max.	Min	Std.Dev.	Qual. Class
Trial 1	15.5	16.8	14.5	0.69	11.4	13.3	10.1	0.77	11.5	13.1	10.0	0.80	A
Trial2	15.4	16.5	14.5	0.57	10.2	12.3	8.1	0.96	10.7	12.9	9.4	0.84	A
Trial3	15.4	18.9	14.5	1.01	10.9	12.5	8.8	1.04	11.4	12.9	8.8	0.90	A
Trial4	15.5	19.6	14.5	1.09	9.1	11.5	5.9	1.32	9.7	11.4	7.7	0.98	A

Table 4 – Average moisture content data

Trial #	Pre-Dry Ave.	Max.	Min	Pre - Equ. Ave.	Max.	Min	Post - Equ. Ave.	Max.	Min	Qual. Class
Trial 1	1.6	2.8	0.4	2.1	2.7	1.5	1.6	2.0	1.2	B
Trial2	1.6	2.8	0.4	3.9	4.2	1.5	2.0	2.6	1.4	C
Trial3	1.6	2.8	0.4	3.8	5.6	2.3	2.4	3.7	0.9	C
Trial4	1.6	2.8	0.4	4.0	5.3	3.1	2.2	3.4	1.2	C

Table 5 – Moisture content gradient data

9.3.3. Surface Checking, End Checking and End Split

Surface checking data (table 6) is represented as the percentage of boards check free. The first part contains the percentage of boards check free on both faces initially, before equalising and after dressing. Next is the percentage of dressed boards check free on one face only. Finally, the percentage of dressed boards check free on both faces that were check free initially, are shown.

Unfortunately, due to the large variation in initial levels of surface checking present in the boards, particularly trials 1 and 4, comparison of surface checking data shown in table 6 can not be accurately realised.

Trial #	Both Faces Initial	Both Faces Pre-Equ.	Both Faces Dressed	1 Face Dressed	Initial to Dressed
Trial1	50	12.5	55	95	89
Trial2	60	12.5	70	100	80
Trial3	47.5	15	40	80	78
Trial4	17.5	5	35	60	67

Table 6- Surface checking–percentage of boards check free

End split and end checking data is shown in table 7. The percentage of boards exhibiting end split from each trial was negligible. Any end checking measured was always associated with surface checked boards. The percentage of end checked boards from trial 1 to trial 4 increased. However, the length of end checking was not significantly increased over the four trials. This is evident from the end check quality class (AS/NZS 4787) results. Each trial falls into class B. This means that 90% of boards from each trial exhibited no more than 50 mm end check length.

Trial #	End Split % of Boards	End Check % of Boards	End Check Quality Class
Trial1	2.5	17.5	B
Trial2	0	37.5	B
Trial3	0	55	B
Trial4	2.5	75	B

Table 7 – End split/check data

9.3.4. Distortion

Distortion measurements are presented in table 8 as the percentage of sawn boards permissible for furniture components as specified by AS 2796.3:1999. The average percentage growth of each distortion type before and after drying is also given. A negative value represents an average decrease in distortion after drying.

The results do not show considerably high levels of distortion before and after drying for each trial. Twist showed the highest level of increasing during drying than other forms of deformation.

	Pre-Dry				Post-Dry			
	Twist	Spring	Bow	Cup	Twist	Spring	Bow	Cup
Trial 1	95	100	100	97.5	87.5	100	97.5	92.5
Trial2	95	100	100	92.5	90	100	97.5	90
Trial3	92.5	100	100	95	87.5	100	100	92.5
Trial4	87.5	100	100	97.5	82.5	100	100	100

Table 8 –Distortion–percentage of boards permissible

9.3.5. Residual Drying Stress

Drying stress was measured and classified into quality classes, in accordance with AS/NZS 4787:2001, before drying, before equalising and after equalising. The class results show that residual drying stress was increased for the higher temperature drying trials before and after equalising.

	Pre-Dry	Pre-Equ.	Post-Equ.
Trial 1	A	C	A
Trial2	A	B	B
Trial3	A	C	C
Trial4	A	C	C

Table 9 – Stress–quality class rating

9.3.6. Other Measurements

No visually evident discoloration was evident between matched dressed boards from the first three trials. There was some slight darkening of material from the fourth trial (figure 10).

Figure 10 – End matched samples showing colour – trial1 bottom to trial4 top

No collapse was evident on any sample throughout all trials.

No internal checking was evident throughout all trials.

9.4. Conclusions and Recommendations

The reduction in drying time for the high temperature trials was significantly reduced as final drying temperature increased for relative levels of energy consumption. As the main component of energy consumed in drying timber is equated to water removal, and as the initial moisture content of each trial was relatively similar, so too were the levels of energy consumed.

It was unfortunate that due to the large variation in initial levels of surface checking present, particularly between trials 1 and 4, comparison of final surface checking data can not be accurately realised. It is however interesting to note that the initial and final levels of surface checking between trials 1 and 2 were relatively similar. A very high percentage of the boards were check free on one face for both these trials. This is of particular importance to the flooring industry where boards are moulded with the best face in service.

Average moisture content variability and moisture content gradients increased from trials 1 to 4. The average moisture content variability was negligible, as the material measured from each trial was still in the highest quality class (AS/NZS 4787:2001). This was not the case for the moisture content gradient variability. Generally, industry expectations for moisture content gradient for flooring and joinery applications is of the highest standard quality (class A). The control trial 1 did not make this class (class B) and the higher temperature trials fared even worse (class C).

Residual drying stress levels are governed by moisture content gradient levels. Generally, comparatively higher final moisture content gradients result in higher residual drying stresses. This was certainly the case with these trials. The levels of drying stress progressively become worse from trials 1 to 4 as does the average moisture content gradient. For the higher temperature drying trials, either a longer equalising process, or an equalising process incorporating higher relative humidities (conditioning), would prevent high moisture content gradients and residual drying stresses from occurring.

The results do not show significantly high levels of distortion before and after drying for each trial. The levels of cup and twist were decreased for trial 4. This may be due to the higher temperature of this trial relieving these distortion types through the softening of wood tissue.

Slight discolouration was evident in material dried in trial 4 (130°C).

No collapse or internal checking was evident on any sample board throughout all trials.

In light of the outcomes from Trial 2, this author believes that there is sufficient evidence to repeat that particular drying protocol at a research scale initially and then at a commercial scale. With similar levels of drying degrade; slightly exacerbated moisture variation and stress levels, and a drying time just under 50% of the control trial, the final drying regime of Trial 2 has significant potential to be used in industry practice. Incorporated in further trial work would be an optimised equalising or conditioning phase to produce a final product of the highest dried quality standard.

9.5. Appendix A – High Temperature Drying Literature Review

The following is a review of definitions, previous research and aspects regarding high temperature drying of timber. Although softwoods and hardwoods are mentioned in this review emphasis is given to high temperature drying of hardwoods.

9.5.1. Introduction

High temperature drying of timber is not a new idea. A patent for an apparatus for seasoning timber using superheated steam was granted in 1867. In the 1920’s and 1930’s kilns capable of operating at high temperatures were reported in the Pacific Northwest and in Europe (Cassens 1979). As these kilns corroded excessively and did not produce quality material, especially with hardwoods, their presence in industry was short lived. The development of the prefabricated aluminium kiln contributed to the advancement of high temperature drying. Problems with thermal degradation of masonry and brick kilns were greatly minimised.

High temperature drying is defined as the kiln drying of wood at dry bulb temperatures of 100ºC or higher. The two processes most used involve (1) a mixture of steam and air, and (2) superheated steam. The process most commonly used for both softwoods and hardwoods uses a mixture of steam and air (Boone 1979a). For this process air is heated in the kiln in the conventional manner and any steam present (except for low-pressure steam for humidity control) is moisture expelled from the wood. The process is controlled by the dry bulb, and to some extent the wet bulb, as in a conventional kiln. The wet bulb temperature in this process remains below 100ºC (Lowery & Krier et al. 1968).

In the superheated steam process, steam occupies the kiln to the complete exclusion of air. The kiln or chamber is completely sealed except for a single outlet that controls pressure build-up. Superheated steam is supplied through coils with the steam giving up its superheat without condensing. The superheated steam process as defined by Lowery & Krier et al. (1968) is when the wet bulb temperature is maintained at 100ºC. In drying temperatures over 100ºC in super-heated steam the wet bulb temperature is always 100ºC (Sharma, Bali et al. 1960).

Sharma, Bali et al. (1960) state that ‘the vapour in an air-vapour mixture maintained above 100ºC inside a chamber is super-heated vapour since its temperature is above the saturation temperature corresponding to its partial pressure in the heated steam because its saturation temperature is lower than that of steam at normal atmospheric pressure, namely, 100ºC. It therefore seems desirable to use the term “super-heated steam drying” only for drying in an atmosphere of pure super-heated steam to the exclusion of air.

Kollmann (1961) and Lowery & Krier et al. (1968) list the following advantages and disadvantages of high temperature dryers.

Advantages:

1. Dryers only require temperature control as the EMC of wood falls rapidly with the temperature in atmospheric pressure in superheated steam.
2. Drying times are shorter than conventional kiln drying.
3. Fewer kilns are required to dry a given volume in a given time due to (2).
4. The high temperatures favourably influence the hygroscopic behaviour of wood. This is because when wood is dried at high temperatures, the EMC for adsorption lies below that of wood dried at lower temperatures, and its tendency to swell or to shrink is reduced.

Disadvantages:

1. With an increase in temperature the colour of the wood surface becomes darker (discolouration).
2. At high temperatures, resin emerges from resinous woods. The solvents in the resin evaporate and the resin acids crystallise, which produces an unsightly surface and effects machining.
3. If the wood contains loose knots, these usually drop out during superheated steam drying.
4. If the kiln fails during drying warp, collapse and splitting may be exacerbated.
5. The final dried moisture gradient is normally far steeper over the cross section of timber dried by this method than conventional drying. Generally an equalisation phase should follow a superheated steam run to reduce moisture gradients.
6. The formation of substantial quantities of organic acids compared with conventional drying requires greater care when choosing materials for the construction of a high temperature drying kiln.
7. An increased fire risk coincides with high temperature drying.

Lowery & Krier et al. (1968) summarises the three stages of high temperature drying as observed by several investigators.

The first stage of drying (constant rate period) occurs only if the initial moisture content of the wood is above fibre saturation point. Evaporation takes place at the surface and the drying rate depends on the external drying conditions, temperature, relative vapour content, and the velocity of the drying medium. The drying rate can be calculated by using the rate of heat transfer, because heat and mass transfer must be equal during this stage. During this stage the timber temperature does not exceed the wet-bulb temperature (100ºC) in pure steam at atmospheric conditions.

When the timber can no longer supply water so that the free water is present over the entire surface, the drying rate slows down and the surface temperature starts to rise above the wet-bulb temperature. This marks the second drying stage (falling rate period). It is believed that a zone of evaporation forms inside the timber and that this zone moves towards the interior of a board from the surface as drying progresses. The increasing distance from the surface increase the resistance to heat and moisture flow, explaining the falling drying rate that is observed.

When the wettest portion of the timber falls below the fibre saturation point, the third drying stage (also falling rate period) begins. This continues until all of the timber is in equilibrium with the drying atmosphere or when the drying process is terminated.

9.5.2. High Temperature Drying of Hardwoods - Research

The following section is an account of research conducted by others in the area of high temperature drying of hardwoods.

Drying Trials

Cuevas (1974) studied the effects of high temperature drying on two species of Australian hardwood species. The species studied were blackwood (*Acacia melanoxylon*) from Tasmania and alpine ash (*Eucalyptus delegatensis*) from Victoria. Blackwood is a non-collapse prone species while alpine ash is renowned for its susceptibility to collapse. The sample boards used were end sealed of dimension 25 × 100 × 500 mm.

Drying temperatures of 130ºC, 150ºC, and 180ºC and air velocities ranging from 5 to 10 m/s were selected as drying variables. The effect of restraint during drying on warp development as determined from twist, spring, bow and cup measurements was also investigated. The laboratory kiln used consisted of an electrically heated tunnel kiln with a maximum temperature of 240ºC and airflow of 14 m/s. The air was not humidified and hence no control of the wet bulb temperature was applied. The drying times, shrinkage, distortion and collapse intensity were assessed and compared with those obtained for conventionally dried timber.

Attempts to dry alpine ash from green under the high temperature regimes produced unsatisfactory results. However, when the wood was partially air dried to a moisture content of 30-40%, 25 mm thick boards were successfully dried to 10% moisture content in 1.5 hrs, 2 hrs, and 2.5 hrs at temperatures of 180ºC, 150ºC and 130ºC respectively, at an air flow of 10 m/s. Distortion of the test boards was comparable to conventionally dried material and mechanical restraint during drying had no appreciable effect however this may be due to the small lengths being dried.

The material showed no evidence of internal checking although surface checks were evident in material dried at 150ºC and 180ºC. Lowering airflow to 5 m/s reduced surface checking. Discolouration did occur however under high temperature conditions with the intensity increasing with rising temperature.

Cuevas (1974) produced successful results from high temperature drying of blackwood. Boards 25 mm thick were successfully dried without degrade from the green conditions (100 to 160% moisture content) to 10% moisture content at 130ºC and 180ºC in 12 and 4 hours respectively. The effect of airflow on drying rate was also investigated. The results showed that by decreasing the air flow from 10 m/s to 5 m/s increased the drying time by ½ hour and by increasing the airflow from 10 m/s to 12 m/s reduced the drying time by ½ hour. The drying time for conventional drying of this material requires 12 to 14 days.

Some minor internal checks were evident in the boards dried at 150ºC and 180ºC. Distortion was minimal and shrinkage was greater in thickness than in width for both backsawn and quartersawn boards. Reconditioning for two hours resulted in 50% recovery of the shrinkage in thickness. Discolouration of the boards was again evident at the higher temperatures, with the effect on the surface being more pronounced.

Fung (1976) similarly investigated high temperature drying of regrowth mountain ash (*Eucalyptus regnans*). Regrowth mountain ash are fast grown trees of lower density than that of mature trees. At high initial moisture contents of 40-50%, high temperature drying of this material was unsatisfactory, resulting in internal checking, excessive shrinkage due to collapse and increased discolouration. However, Fung (1976) successfully dried 25 mm thick boards from 30% to 15% moisture content with negligible degrade in two hours at 130ºC DBT, 52ºC WBT and 10m/s air flow. Discolouration of the material was very slight.

Twelve commercially available American hardwood species were kiln dried under high temperature conditions by Boone (1984). The species investigated were: white ash (*Fraxinus americana*), basswood (*Tilia americana*), beech (*Fagus grandifolia*), black cherry (*Prunus serotina*), blackgum (*Nyssa sylvatica*), cottonwood (*Populus deltoides*), American elm (*Ulmus americana*), hard maple (*Acer saccharum*), soft maple (*Acer rubrum*), Pecan-hickory (*Carya* sp.), sweetgum (*Liquidamber styraciflua*), yellow-poplar (*Liriodendron tulipifera*). The thickness of the samples dried was 25 mm for each species and two kiln drying schedules were employed. The schedules trialled were:

- 110ºC on green off saw material to 6 to 8 % moisture content in 50 to 55 hours using superheated steam and,
- Combination of conventional temperature drying from green to approximately 20% MC then dried to 6 to 8 % moisture content at 110ºC requiring a total of 100 to 250 hours.

Positive results from this study were very much dependant on species. When dried by the first schedule, basswood, yellow-poplar, white ash, sweetgum, and soft maple dried with only minor levels of drying defect. Black cherry, hard maple, beech, and pecan-hickory had sufficient defects to be unsuitable for this treatment. American elm, cottonwood, and blackgum showed intermediate levels of drying defects. The combination schedule reduced the drying degrade, but increased the kiln drying time over high temperature alone. The most common form of degrade was internal checking followed by warp and collapse.

High temperature drying of several American hardwoods was investigated by Richards (1958). Red oak (*Quercus rubra*), white oak (*Quercus alba*), hickory (*Carya* spp.), beech (*Fagus grandifolia*), blackgum (*Nyssa sylvatica*), sweetgum (*Liquidamber styraciflua*) and yellow-poplar (*Liriodendron tulipifera*) were the hardwoods selected for this study. The cross section dimensions of the boards investigated for each species were 150 × 6 mm, 150 × 12.5 mm, 150 × 19 mm and 150 × 25mm. The samples were 460 mm long and end sealed. The samples were dried in a fan forced drying oven at a temperature of 110ºC. No mention of humidity control or use of steam is given.

The results of this study showed 25 mm thick boards of yellow poplar, beech, blackgum, hickory and sweetgum could be dried in a short time without excessive visible defect. Hygroscopicity of the timber was noticeably decreased by the treatment. Some improvement in dimensional stability was observed. Case hardening was evident, but it was felt that this could be controlled via intermittent and or final steaming. Mild collapse was evident in most species with red oak, white oak and sweetgum severe collapse. Richards (1958) recommends that controlled air seasoning be used prior to high temperature drying of hardwoods. Red oak, white oak and sweetgum displayed such severe internal checking that it seems impractical to dry normal timber thicknesses of these species at high temperatures Richards (1958).

Sharma, Bali et al. (1960) performed high temperature drying trials on three Indian hardwoods namely, kuthan (*Hymenodictyon excelsum*), kanju (*Holoptelea integrifolia*) and balki (*Anogeissus latifoloia*). In all cases the timber thickness was 25 mm. Drying temperatures of 108ºC and 102ºC were trialled with decreasing humidities being employed as drying progressed.

Drying rates were considerably increased in high temperature drying. Case hardening stresses and moisture gradients in high temperature dried timber were found to be of the same order as for conventional kiln drying at lower temperatures. Intermittent steaming, especially during the later part of the schedules, effectively reduced moisture gradients. Warp and discoloration of timber was severe in all charges dried at high temperature, except in the case of kanju, which was successfully seasoned. Warp may have been more severe than it should have been as vast differences in air flow distribution inside the drying chamber was observed. Surface checking was found to be no more severe than in conventionally dried material. Sharma, Bali et al. (1960) suggests that high temperature drying may be applicable to other hardwood species that do not contain very high moisture content in the green condition.

Stress/Strain Analysis

Cech (1964) used the ‘slicing technique’ to investigate the development of drying stresses during high-temperature kiln-drying of 25 mm thick yellow birch (*Betula alleghaniensis*). The drying temperature used was 104ºC on both green off-saw material and partially air-dried material. The temperature was controlled electrically and humidification was provided by low pressure steam. Results showed the general pattern of strains was the same in both green and partially air-dried material. The lower initial moisture content in partially air-dried material altered strain values and collapse development. Substantially lower tensile set (which is the cause of casehardening) was developed in the shells of the green material than in the partially air-dried specimens. However, the maximum compression set in the core of the green material was about four times as large as in the partially air dried material. This greater compression set resulted in significantly greater shrinkage.

Air Flow Analysis

Kollmann (1961) showed that the influence of air velocities during high temperature drying is greater than for conventional drying. Observations showed that increased air flows below 40% MC for conventional drying was not significant. This compares to air flows rates losing their significance for timbers with an average MC of 20% and below for high temperature drying. Due to the high heat transfer rates required to maintain the rapid drying rates possible in high temperature drying, especially during the first stage of drying, the air flow velocity is of much greater importance than for conventional drying. Salamon (1969) suggests that proper air circulation must be selected to prevent the development of severe casehardening stresses, to maintain the drying medium in the high temperature range on the exit side of the stack, and to be economically suitable.

End Point Prediction

One problem that many researchers face when performing high temperature drying trials is to accurately and quickly determine the end point moisture content of specimens without disturbing the equilibrium of the kiln drying conditions. Jai, Hsiung et al. (1993) investigated the relationship between the temperatures of timber-centre and kiln-air, and moisture content changes during high-temperature kiln drying.

The tests were performed on 30 mm and 50 mm thick Mahogany (*Swietenia macrophylla*) and China-fir (*Cunninghamia lanceolata*). Both species were kiln dried at 112ºC in a mixture of steam and air. The timber central temperature was measured and continuously logged using a data logger and thermocouple sensor. The results of the study showed that a correlation exists for the difference between timber-centre and kiln-air as a guide for estimating the final average moisture content of the wood during high-temperature kiln drying. Jai, Hsiung et al. (1993) concluded that, a final average moisture content of 6% for the above species occurs when the central temperature of the samples reaches 111ºC or 1ºC below that of the drying (air) temperature of 112ºC. It is suggested however that these results may be species dependent.

Jai, Hsiung et al. (1995) repeated the above study on Lemon scented gum (*Eucalyptus citriodora*) and Taiwan incense-cedar (*Calocedrus formosana*) at a drying temperature of 110ºC. The results of this study indicated that this method for determining end point moisture content is not suitable for species which are susceptible to severe internal checking such as Lemon scented gum. As was found in the previous study a depression of 1ºC between the timber-centre and kiln-air medium was found to co-exist with an end point moisture content of 6%, for 30 mm and 50 mm thick incense-cedar.

Conventions

Boone (1979a) outlines common features or rules associated with high temperature drying of softwoods and hardwoods as follows:

- For best results stack widths should be narrow, i.e. 1.5m.
- A rapid heat up of the kiln (less than 4 to 5 hours) is important. Some suggest live steam to minimise surface drying of hardwoods during the heatup period.
- High air flow is important – at least 4m/s and 5to 6m/s is better.
- The wet bulb may be under partial control, no control, or fully under control as in conventional drying. It is difficult to maintain wet bulb temperatures above approximately 90ºC without an extremely tight kiln. Also the maximum EMC attainable is around 7%. Research with hardwoods indicates that control of wet bulb is preferred to keep stock from drying below 3 to 4%. This is preferable to letting the EMC fall to 1% or even 0% with no control.
- A cooling period is required if equalising and/or conditioning is to follow the high temperature phase. This is required to control wet bulb depression if both dry bulb and wet bulb temperatures are below 100ºC.
- If final MC tolerances are outside those required an equalising period is necessary. Variations between and within pieces is much greater with high temperature drying than conventional drying.
- Depending on final use, a stress relief conditioning period may be necessary.

Conclusions

From this review, it is evident that high temperature drying has its merits and also its downfalls. As far as drying timber faster than conventional drying high temperature drying is favourable. However, successful high temperature drying of hardwoods is shown to be species dependent as well as dependant on the initial moisture content of the timber. Discoloration is also a major issue in terms of drying degrade. Some level of wet bulb control and fast fan speeds are important factors in optimising both drying time and degrade.

High temperature drying is still in its infancy in Australia as far as hardwoods are concerned. High temperature drying shows promise, but it is not yet a system or technique to be used for all species at any or all moisture contents.

9.5.3. References

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9.6. Appendix B - Class Classifications

The following drying quality class classifications have been extracted from Australian/New Zealand Standard AS/NZS 4787:2001 –Timber – Assessment of drying quality.

Class A – caters for specific end uses and very specific requirements for drying quality.

Class B – applies where tight control over drying is required to limit ‘in service’ movement resulting from changes in equilibrium moisture content.

Class C – applies where higher drying quality is required and the final use environment is clearly defined.

Class D – applies when the final use environment is more clearly defined but again the drying quality requirements are not considered high.

Class E – applies when the final use and drying quality requirements are not high.

10. Influence of steam on drying rates of regrowth spotted gum

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June 2004

10.1. Executive Summary

This report describes the results of three experiments that were conducted with the aim of investigating the effect of mid cycle high humidity treatments on the drying rate of spotted gum (*Corymbia maculata*) boards 100 mm × 26 mm.

The basis for the experimental design was to test the suggestion that the evolution of compression stresses in wood during later stages of drying reduced potential drying rate. It was further theorized that stress relief through wetting might diminish this effect.

In the first experiment of the series, it was shown clearly that for a commonly used industrial drying schedule for spotted gum (i.e. maximum 70°C Dry Bulb Temperature -DBT), compression stresses peaked between 15% and 11% moisture content (MC).

In the second and third experiments, high humidity treatments were applied to samples of spotted gum for a period of 30 minutes at 15% and 11% MC respectively.

Two matching samples of 15 boards each were used in each experiment, with one set removed prior to high humidity treatment and therefore remaining untreated.

Differences in drying rate were tested as differences between mean MC for each matching sample.

Neither experiment produced significantly different drying rates among matching treated and untreated samples.

The conclusion drawn has been that for the drying schedule chosen for the experiments, mid cycle high humidity treatment did not produce different drying rates after the treatment period.

10.2. Introduction

The objective of this component of the project was to investigate higher temperatures and humidity treatments on the dried quality of regrowth spotted gum.

The conventional industrial approach to drying sub-tropical hardwoods such as spotted gum involves pre air-drying to approximately fibre saturation point (FSP), followed by kiln drying to between 10% and 11% moisture content (MC).

The most significant quality issue that concerns industrial processors is moisture content mean and variance, (which is most critical to flooring manufacturers). It is also widely recognised that spotted gum can be dried at elevated dry bulb temperatures (70°C DBT) without checking degrade or collapse under controlled humidity conditions. Dried moisture content variation is usually controlled by applying equalisation treatments (6°C Wet Bulb Depression (WBD) ~ 11% Equilibrium Moisture Content (EMC)) at the end of a drying cycle.

Attempts by industrial processors to dry at higher temperature have resulted in higher energy costs, which are not returned by proportionally faster drying. Some processors have chosen to dry wood at very low operational cost using solar/gas systems providing heat to 50°C

DBT. Under these circumstances no final equalisation treatment is required however drying time is long e.g. 14+ days.

The principal challenge for schedule development is therefore to improve drying time while maintaining tight control of moisture content, without adding cost.

100 mm × 26 mm spotted gum boards require 5 to 7 days at 70°C DBT to kiln dry, depending on pre dried MC. For air-dried material this is normally between 16% and 25%. Industrial processors report slow drying at low moisture contents in the kiln, despite application of considerable temperature increases (up to 85°C DBT).

Slow drying has been anecdotally contributed in part to the evolution of mechanical stresses in a board during drying. Literature (Skaar 1988) states that wood restrained in tension will equilibrate at a higher EMC compared to unrestrained wood. Similarly EMC can be depressed under compression. This behaviour may cause slow drying under high levels of case compression stress during drying.

The series of experiments described here were aimed at measuring the response of drying rate to high humidity cycles applied mid cycle, aimed at reducing drying stress and allowing faster drying rates.

10.3. Methods and Materials

10.3.1. Experimental Design

In order to design a set of experiments that are relevant to current industrial practices, the following points were taken into account:

- Drying at dry bulb temperatures above 80°C can result in higher cost and discoloration (darkening) of the drying stock compared to lower temperature (<=80°C) drying;
- The design of kiln drying experiments should emulate basic current industrial processes e.g. DBT of 70°C and applied to air dried stock;
- The experimental parameters of interest are kiln drying time and MC variation.

In any well-designed experiment, a single dependent variable should be isolated and measured in terms of the influence of an independent variable. For this series of experiments, drying time (dependent variable) was measured in terms of the influence of different humidity treatments (independent variable). This was achieved by measuring end point moisture content for matched samples of boards after they were dried in exactly the same way except for mid cycle high humidity treatment. This was achieved by removing one set of matched samples from the kiln while the other is treated.

A criticism of this approach is that end point MC must be measured at the end of the drying cycle and prior to final equalisation or other conditioning treatments, because these treatments will mask end point MC differences between matched samples. This was not considered to be a problem here as the variable being investigated is drying rate, and dried quality is being measured as the mean and variance in end point MC.

Three experiments were designed as follows:

Experiment 1

A pilot study to examine the evolution of stress and drying rate for a conventional drying cycle to determine timing of mid cycle steam treatment. A sample of 20 pieces were dried according to current industrial practices i.e. 70°C DBT

Experiment 2

A second experiment examining the drying rate for matched samples (15 boards each sample, a total of 30 boards) dried in a single charge, with one sample steamed mid cycle (at 15% MC average), and the second not steamed. Drying rate was measured as the difference in final MC for the two groups of samples.

Experiment 3

A repeat of experiment two varying only the MC at steaming to 11%

10.3.2. Equipment

Experiments were conducted in a 0.13 m^3 experimental kiln. Drying conditions and load mass were measured at 5-minute intervals. Stress evolution was measured as cup distortion of a thin board sealed on one face (Perre 1996). The apparatus is shown in Plate 1. Displacement was measured using a resistance-based transducer. The sample thickness for displacement measurements was 15 mm.

Plate .1 Apparatus for measuring cup distortion of a drying board.

10.3.3. Drying Schedule

The schedule applied in these experiments mimics standard production approaches with the exception that many commercial operators pursue final equalisation at 6 °C WBD and 70°C DBT which equates to 11% EMC. This is to control the wide variation in MC that occurs in air-dry stock.

Final steaming was chosen for Experiment 1 to provide data on the effects of steaming and the performance of the stress measurement apparatus (Figure 1). The change point to steaming was 11% MC. Note final conditioning treatments have no influence on the experimental objective, which is to measure drying rates.

Steaming was conducted at 1°C WBD and 70°C DBT, to avoid darkening of the wood at high temperatures and to closely match current production kiln performance.

10.3.4. Material

Samples of re-growth spotted gum boards 100 mm × 26 mm were collected from sawmills in northern New South Wales and Southeast Queensland.

The material was selected from air-drying stock to include an operational range of moisture content for air-dried material.

10.4. Results and Discussion

10.4.1. Experiment 1

The drying record showing dry and wet bulb temperature, drying time, moisture content and drying stress evolution is shown in Figure 1. Note the evolution of stress is shown un-scaled as ohm resistance. High resistance values imply cupping of the sample board with the concave side up, or dry surface and wet core.

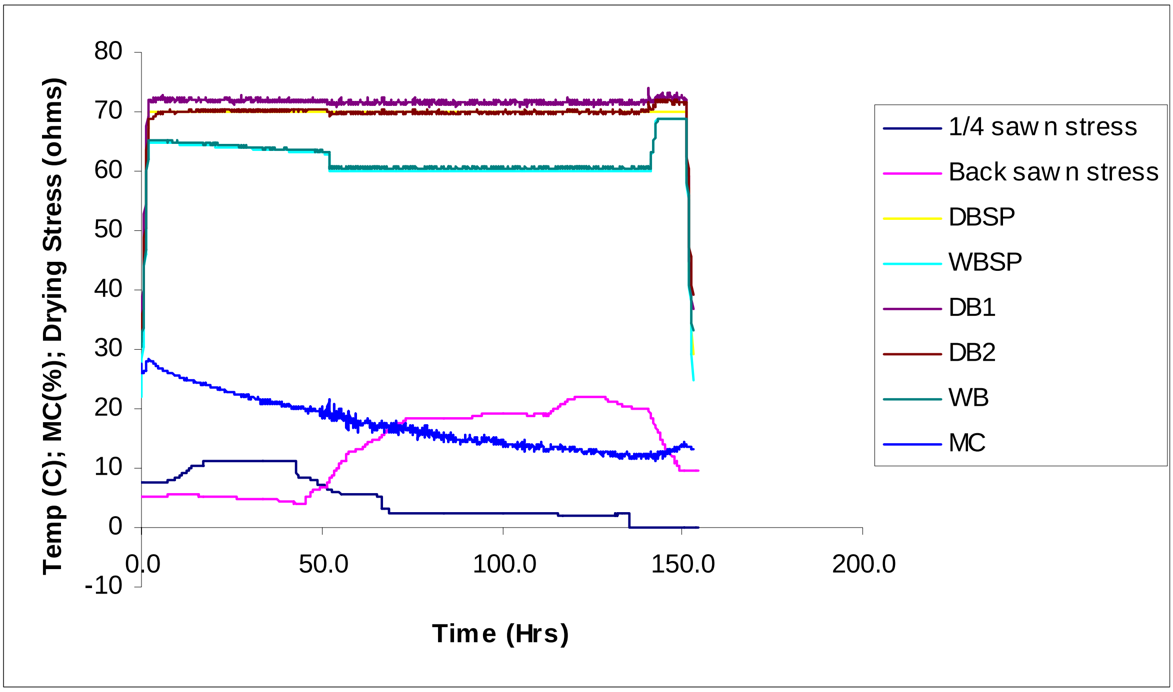


Figure 1. Drying record experiment 1

Note the traces marked 'quarter sawn' (dark blue) and 'back sawn' (pink) show the evolution of stress for each sawing orientation. For the quarter-sawn sample, the transducer signal unfortunately failed just prior to steaming. Despite this, Plate 2 shows the quartersawn sample finished flat, suggesting the transducer signal will have returned to the start value which was the trend at the time of failure.

The drying record for Experiment 1 shows:

- The quarter-sawn sample exhibited expected behavior, cupping concave up initially and then down after stress reversal.

- Tension stress in the quarter sawn sample peaked early at approximately 24% MC and started to fall at 20% MC.
- The onset of stress reversal in the quarter sawn sample occurred at 18% MC and had peaked at 17%.
- The back sawn board exhibited unexpected behavior, with initial readings showing surface compression rather than tension stresses. The reason for this can only be attributed to an interaction between the distribution of moisture during early drying and the orientation of sawing.
- Tension stress in the back sawn sample begins to build at approximately 18% MC and grows to a peak at 12%.
- The introduction of steam caused both boards to relax and attain final shape, which is shown below in Plate 2.

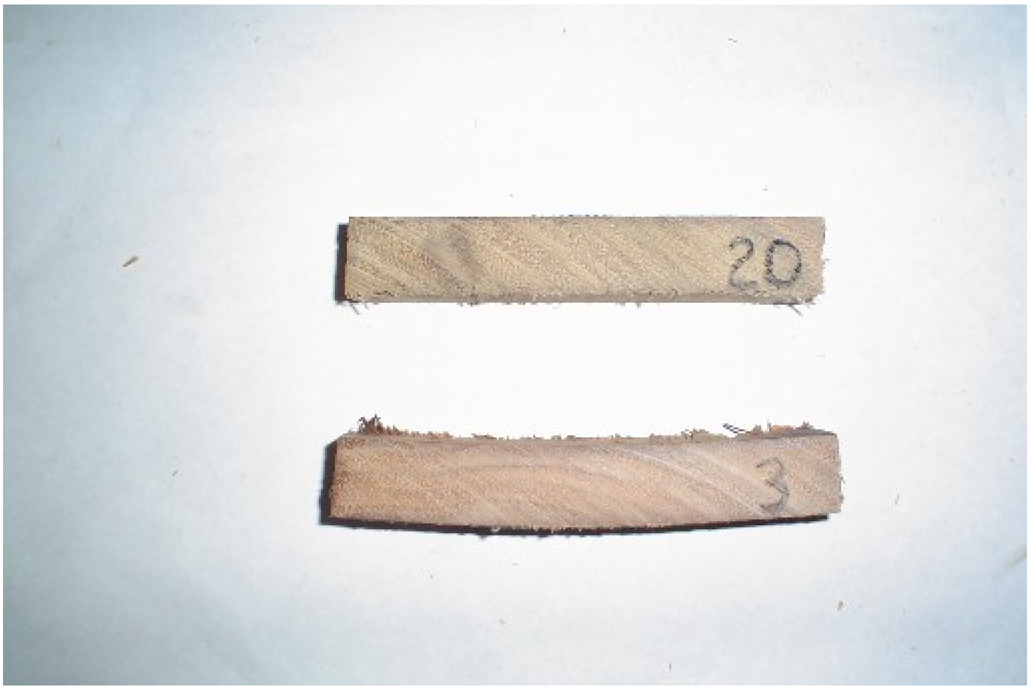


Plate 2. Final sectional shape of stress measurement samples. Note sealed face is down. Quarter sawn board is top piece. Note residual cupping in back sawn piece below and indicated in experimental results shown in Figure 1

The key conclusions from this experiment contributing to subsequent experiments are:

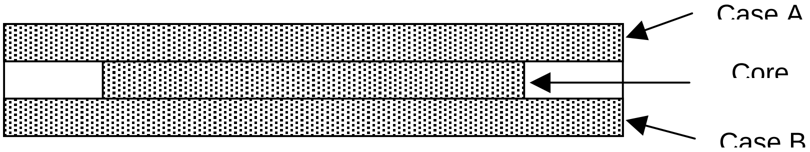
- That peak surface compression stresses are present when wood moisture content is between 17% and 12% during kiln drying, and that high humidity treatments should be tested within this range.
- That wetting wood by applying high humidity conditions late in the drying cycle causes significant relaxation of drying stresses.

Table 1 below, Figures 2 to 6 summarise further results derived from Experiment 1.

Sample	Moisture Content (%)					
	Initial	Whole Section	Case A	Case B	Core	Case - Core
Max	32.5	16.3	15.9	16.3	18.8	3.7
Min	15.4	10.9	11.3	10.8	10.0	-4.4
Mean	24.0	13.2	13.2	13.0	14.0	-0.9
StDev	5.4	2.9	2.9	2.4	2.2	0.4
1	16.0	10.9	11.8	10.8	10.8	0.5
2	23.1	15.1	15.9	14.1	14.0	1.0
3	26.2					
4	32.5	11.1	12.8	11.1	10.7	1.3
5	23.0	14.4	14.5	14.4	10.8	3.7
6	16.0	12.2	12.8	12.0	11.6	0.8
7	22.7	12.6	12.1	12.4	13.9	-1.6
8	27.7	15.5	14.0	14.8	18.8	-4.4
9	25.4	12.5	12.9	12.4	13.3	-0.7
10	15.4	12.2	12.5	12.6	12.1	0.4
11	25.1	13.3	13.1	13.7	13.5	-0.2
12	18.9	12.2	12.6	12.4	14.3	-1.7
13	20.4	11.3	11.3	11.6	10.0	1.5
14	23.2	13.7	12.5	12.8	15.8	-3.2
15	31.7	11.5	12.9	13.8	15.9	-2.6
16	29.9	16.3	15.7	16.3	18.3	-2.3
17	28.2	13.9	12.9	13.1	15.2	-2.2
18	32.0	13.3	12.4	12.4	14.7	-2.3
19	25.0	15.4	15.0	13.6	17.7	-3.4
20	18.4					

Table 1. Summary of results for Experiment 1.

Note the sample-cutting patterns to assess MC gradient (Case – Core) is shown below in Figure 2. Samples were 100mm × 26mm. Case value is calculated as the mean of A and B samples.



F*igure 2. Cutting pattern used to produce case and core moisture content test samples.*

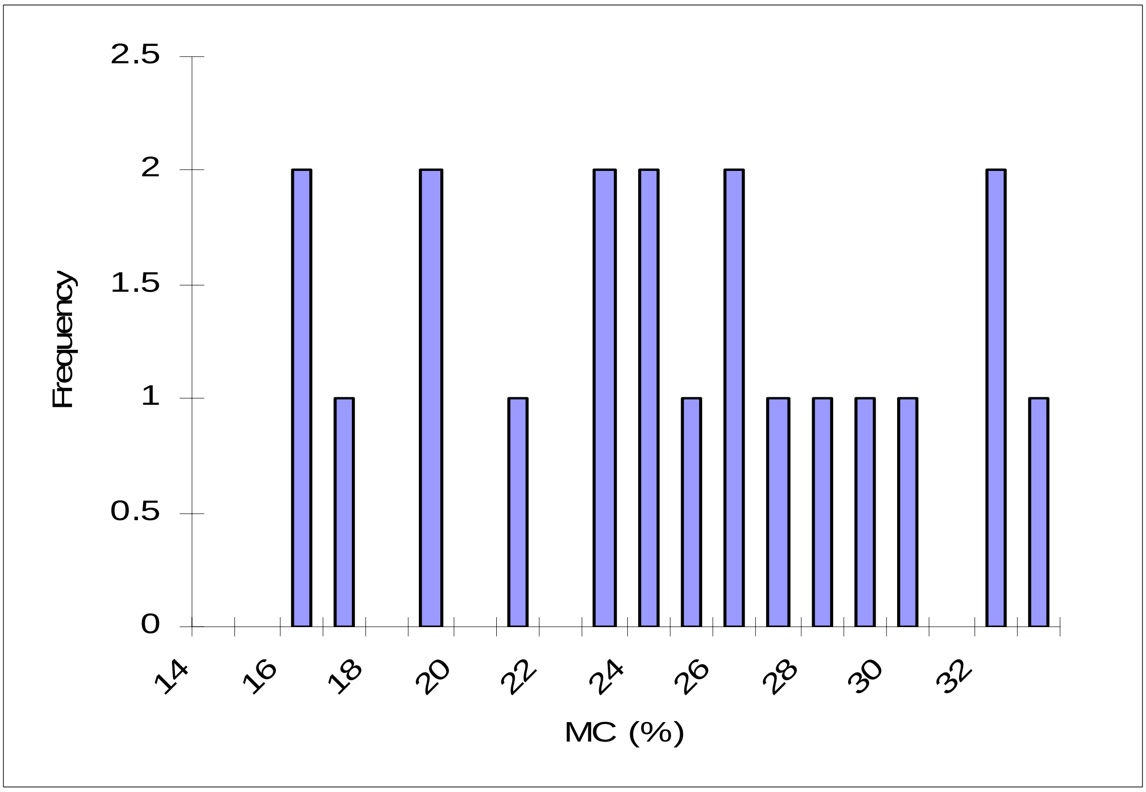


Figure 3. Initial moisture content distribution in Experiment 1.

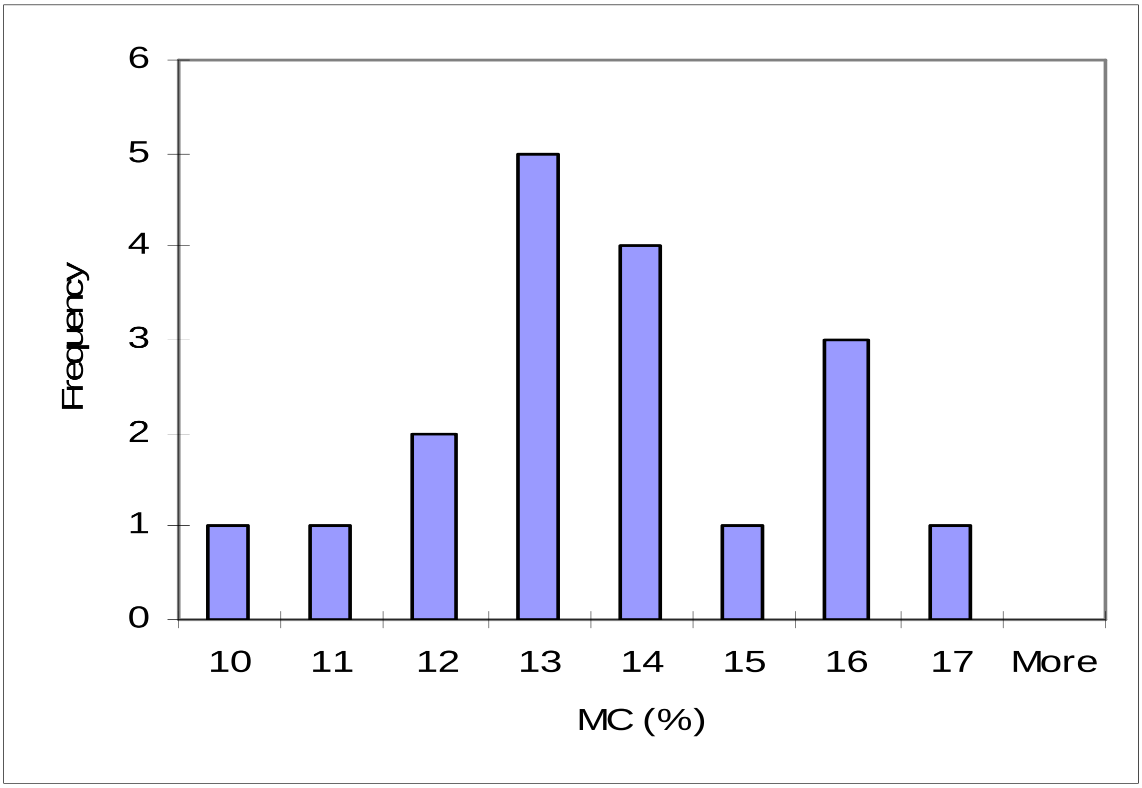


Figure 4. Final Moisture content distribution for whole cross sections in Experiment 1

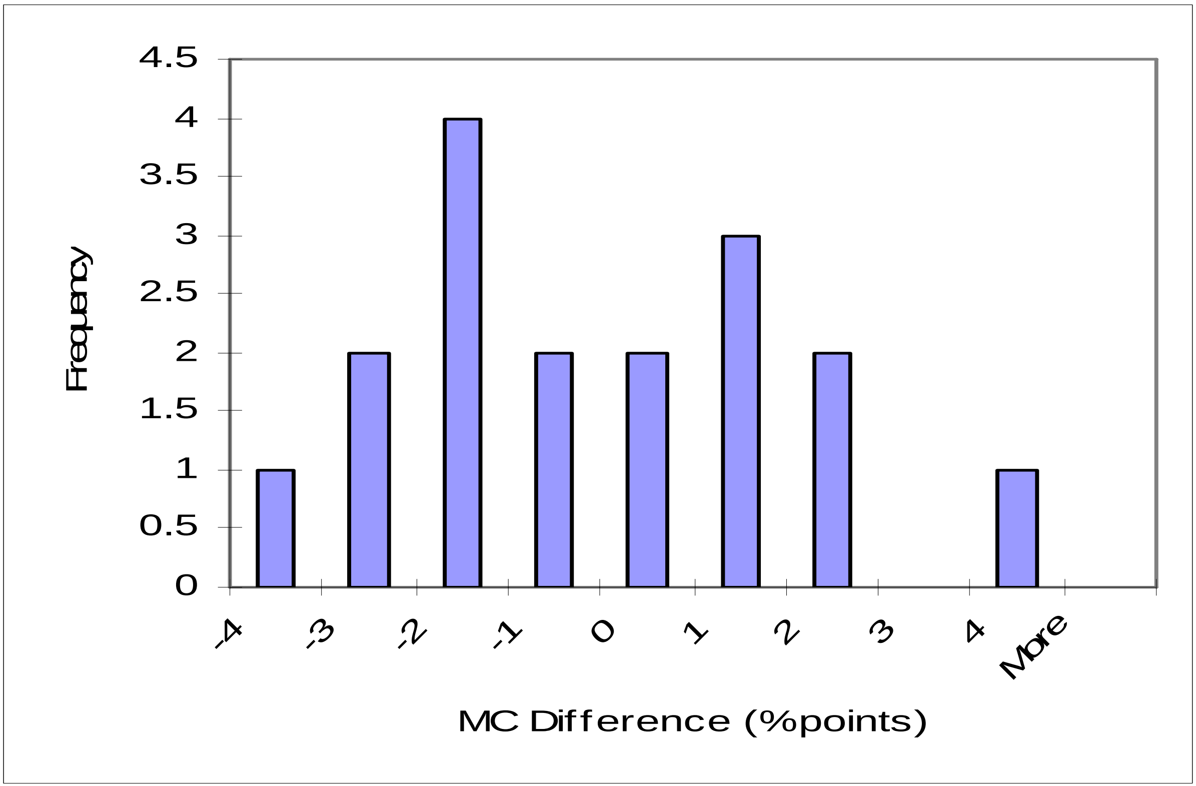


Figure 5. Distribution of 'case minus core' moisture content differences in Experiment 1

Plate 3. Stress prong test results immediately after cutting in Experiment 1

The results shown in Table 1, Figures 3 to 5 have also shown that:

- The initial moisture content of the experimental sample shown in Figure 3 reflect current industrial pre drying practices;
- The drying time of 150 hours is within the range of industrial practice, however the end point range of final MC shown in Figure 4, is high at 11% to 16%
- The variation in the 'case to core' moisture content results shown in Figure 5, indicate the majority of samples were still wetter in the core after steaming. Seven were wetter in the case than the core indicating over steaming. This suggests the change point to final steaming was too early and should have been lower at 10% or 9%.

10.4.2. Experiment 2

To test the effects of high humidity or steam treatments on drying rate, Experiment 2 used two matched sets of 15 boards each, which were dried together in the same charge. Note that initial moisture content was slightly lower, (mean 17%MC) compared to Experiment 1.

Based on the data from Experiment 1, at 15% MC (an estimate of peak compression stress), one set was taken from the kiln and each board weighed then stored in plastic wrap. The matching set was steamed for 30 minutes at 70°C DBT and 1°C WBD.

After steaming the un-steamed set was returned to the kiln, and the charge dried to an average of 10% MC, at 70°C DBT and 50°C WBT. All boards were measured 24 hours after the drying schedule was completed.

The results of Experiment 2 are summarised in Table 2 and Figures 6 to 8.

Sample	Moisture Content (%)								
	Initial	Steamed				Unsteamed			
		Whole Section	Case A	Case B	Core	Whole Section	Case A	Case B	Core
Max	20.9	10.7	9.8	10.0	15.1	11.2	9.2	9.3	13.9
Min	15.4	7.5	7.4	7.3	8.2	7.4	6.7	7.1	7.3
Mean	17.2	8.5	8.6	8.4	11.0	8.5	7.9	8.3	10.4
StDev	1.4	0.9	0.6	0.7	1.9	1.0	0.8	0.6	1.8
1	17.0	8.0	8.4	8.4	11.7	7.9	8.0	8.1	11.2
2	17.5	8.4	8.9	8.3	11.8	8.2	6.7	7.6	7.3
3	16.7	7.9	8.0	8.4	11.5	7.6	8.4	8.2	11.2
4	17.1	9.2	8.5	8.7	11.6	8.9	8.4	8.3	10.6
5	16.2	8.4	9.3	8.2	9.2	8.9	8.9	8.0	10.9
6	16.5	7.7	8.2	7.8	8.8	7.8	7.1	8.8	9.2
7	15.4	8.0	8.9	7.5	9.2	8.5	7.7	8.7	9.5
8	17.0	7.7	7.4	7.9	9.0	7.6	6.9	7.4	8.8
9	17.6	8.7	8.5	8.5	11.5	8.9	8.6	8.4	11.4
10	17.9	9.1	9.0	9.1	11.5	8.4	8.0	8.2	11.1
11	16.3	8.6	8.6	8.6	12.2	8.7	8.9	8.6	12.4
12	15.6	8.1	8.2	8.1	10.9	9.2	8.3	8.6	12.0
13	17.3	7.5	8.0	7.3	8.2	7.4	6.8	7.1	7.9
14	19.2	9.9	9.5	9.6	15.1	7.5	7.1	8.5	8.3
15	20.9	10.7	9.8	10.0	13.4	11.2	9.2	9.3	13.9

Table 2. MC results summary for Experiment 2

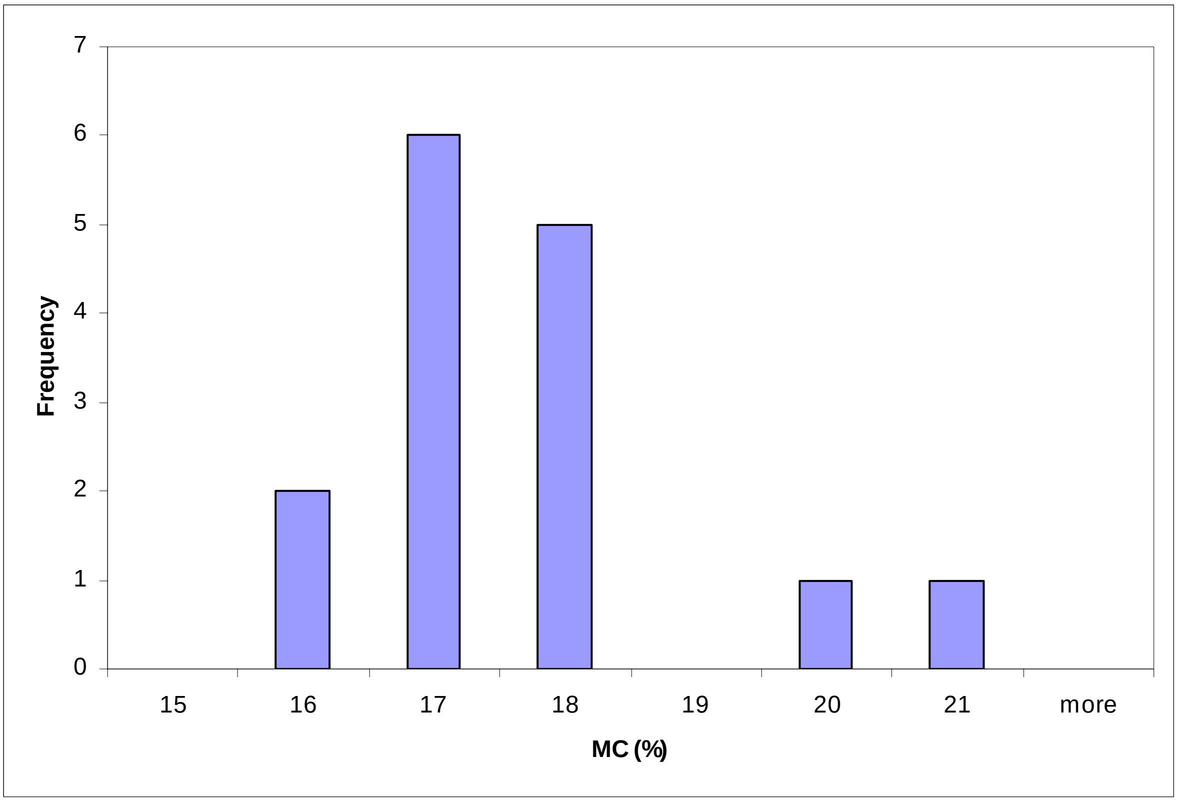


Figure 6. Initial whole section MC distribution (n=20) in Experiment 2

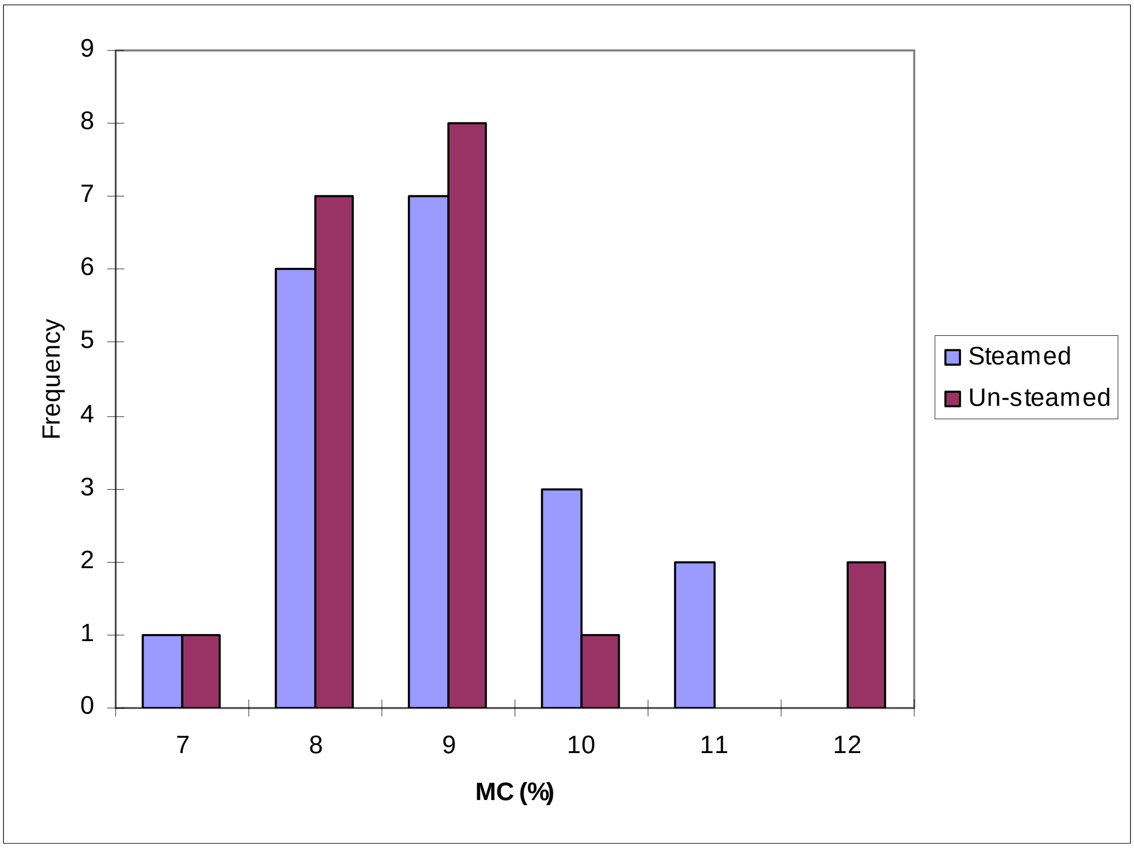


Figure 7. Final whole section MC Distribution in Experiment 2

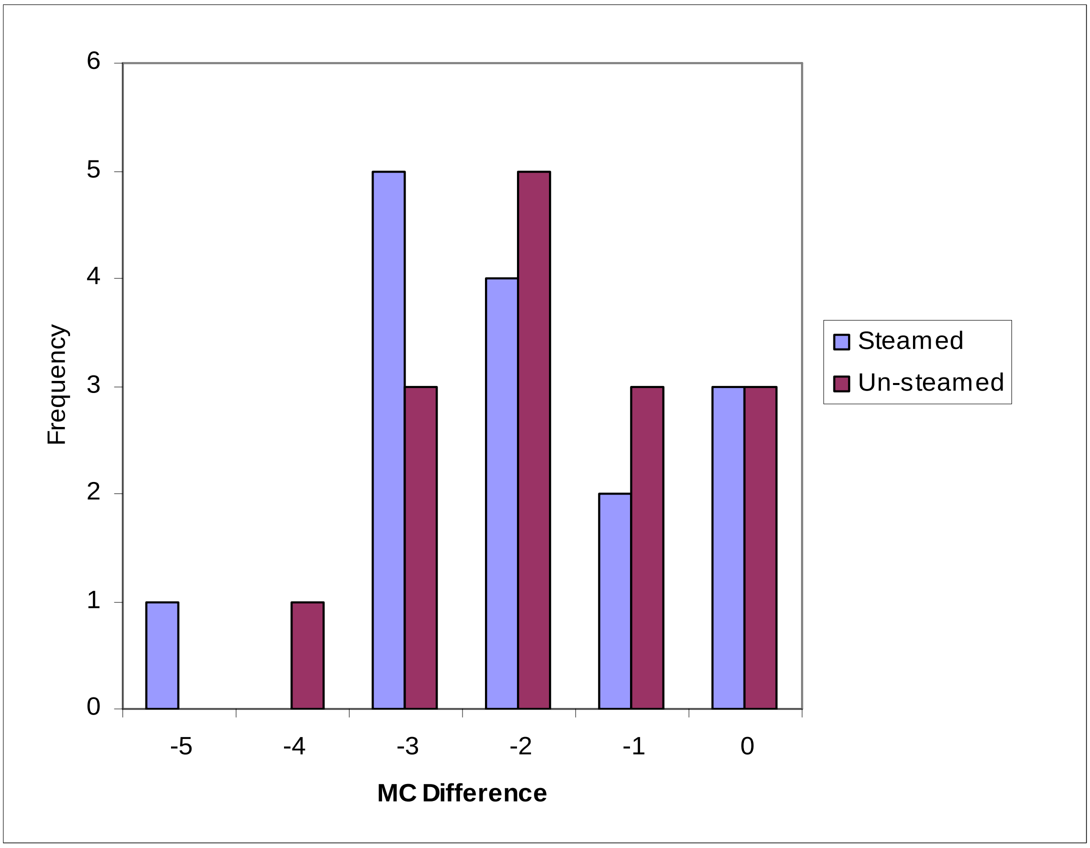


Figure 8. Distribution of difference case minus core in Experiment 2

T - Tests for differences between means of final whole sample MC (Figure 7), and case core variation (Figure 8), show samples are not significantly different.

The results of Experiment 2 show:

- Final moisture content was not different between steamed and un-steamed samples.
- Case to core variation was also not different between steamed and un-steamed samples.
- Applying high humidity treatments relatively early in the kiln drying cycle (15% MC) did not influence drying rates between steamed and un-steamed samples.

10.4.3. Experiment 3

To further test the effects of steam on drying rate, Experiment 3 used two matched sets of 15 boards each, which were dried together. Based on the data from Experiment 1, at 11% MC (later in drying and during high surface compression stress), one set was taken from the kiln, each board was weighed and then stored in plastic wrap. The matching set was steamed for 30 minutes at 70°C DBT and 1°C WBD.

The sample for this experiment was also matched to the sample for Experiment 2. The material had been wrapped and stored until required for Experiment 3.

After steaming, the un-steamed set was returned to the kiln, and the charge dried to an average of 10% MC at 70°C DBT and 50°C WBT. All boards were measured 24 hours after the drying schedule was completed.

The results are summarised in Table 3 and Figures 9 to 11.

Sample	Moisture Content (%)								
	Initial	Steamed				Unsteamed			
		Whole Section	Case A	Case B	Core	Whole Section	Case A	Case B	Core
Max	18.3	10.3	9.3	10.0	13.4	9.9	9.2	9.6	14.1
Min	13.0	7.2	6.8	7.2	8.4	7.5	7.1	7.2	8.2
Mean	15.4	8.8	8.3	8.4	10.9	8.8	8.2	8.4	11.1
StDev	1.4	0.9	0.7	0.9	1.5	0.8	0.7	0.8	1.7
1	17.6	9.3	8.4	9.3	12.3	9.4	8.5	8.1	12.0
2	14.8	7.8	7.4	7.5	9.4	9.3	8.7	9.1	11.9
3	14.5	9.5	8.6	9.1	11.8	8.9	8.9	8.2	11.6
4	15.0	7.2	6.8	7.2	8.8	8.2	7.9	7.8	10.0
5	14.9	8.6	7.8	8.0	10.6	7.5	7.1	7.2	8.2
6	16.7	9.4	8.8	9.0	12.0	8.8	8.2	8.6	10.7
7	15.7	9.3	9.3	9.9	11.9	8.8	8.8	8.2	11.6
8	15.9	7.9	7.7	7.4	10.1	9.7	9.0	9.6	14.1
9	14.2	9.2	8.8	9.4	12.2	9.8	8.4	9.5	13.5
10	13.5	7.8	7.9	7.9	8.7	8.2	7.3	8.8	9.4
11	15.9	8.1	8.1	7.3	8.4	8.0	7.9	7.5	9.1
12	15.6	9.3	8.2	8.8	12.1	8.8	8.2	8.6	12.0
13	14.6	8.3	8.5	7.6	10.5	7.6	7.3	7.3	8.8
14	15.6	9.9	9.1	8.9	11.5	8.5	8.1	8.4	10.6
15	18.3	10.3	9.3	10.0	13.4	9.9	9.2	9.6	12.4

Table 3. MC results summary for Experiment 3

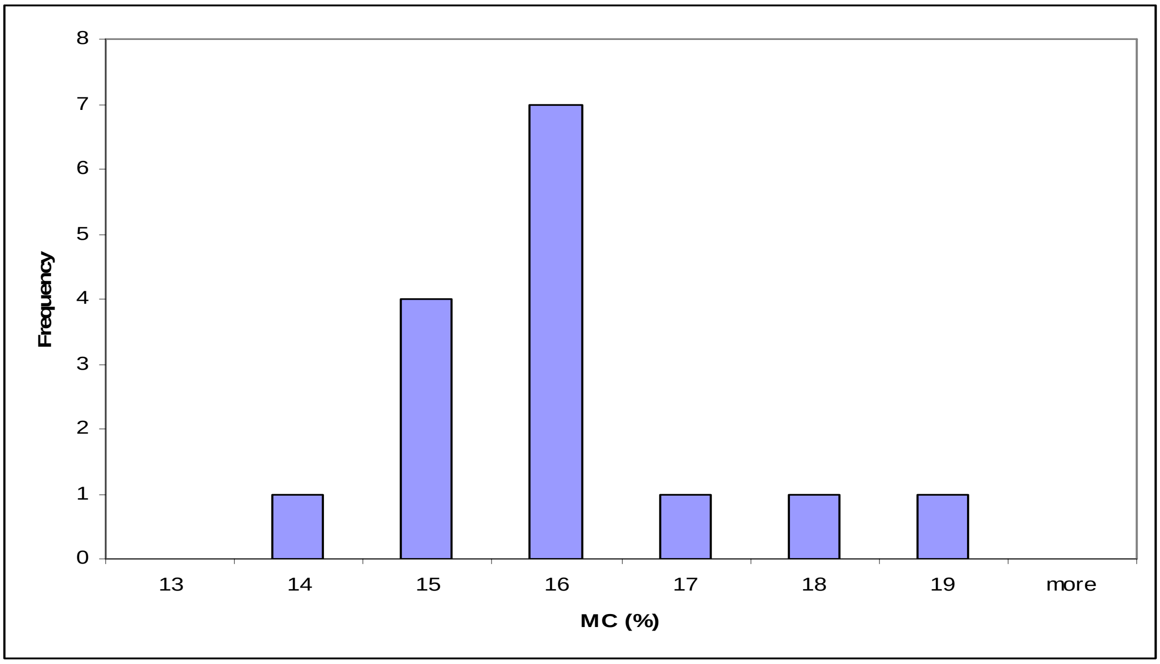


Figure 9: Initial whole section MC distribution (n=15) in Experiment 3

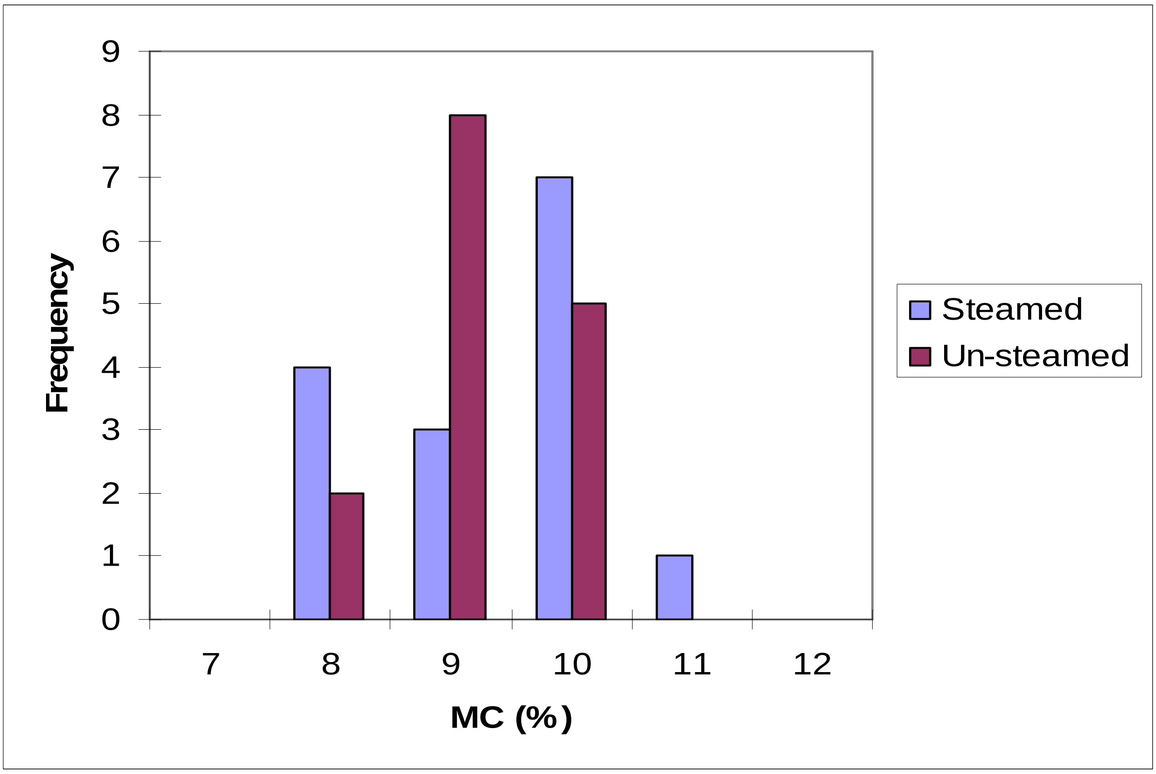


Figure 10. Final whole section MC Distribution in Experiment 3

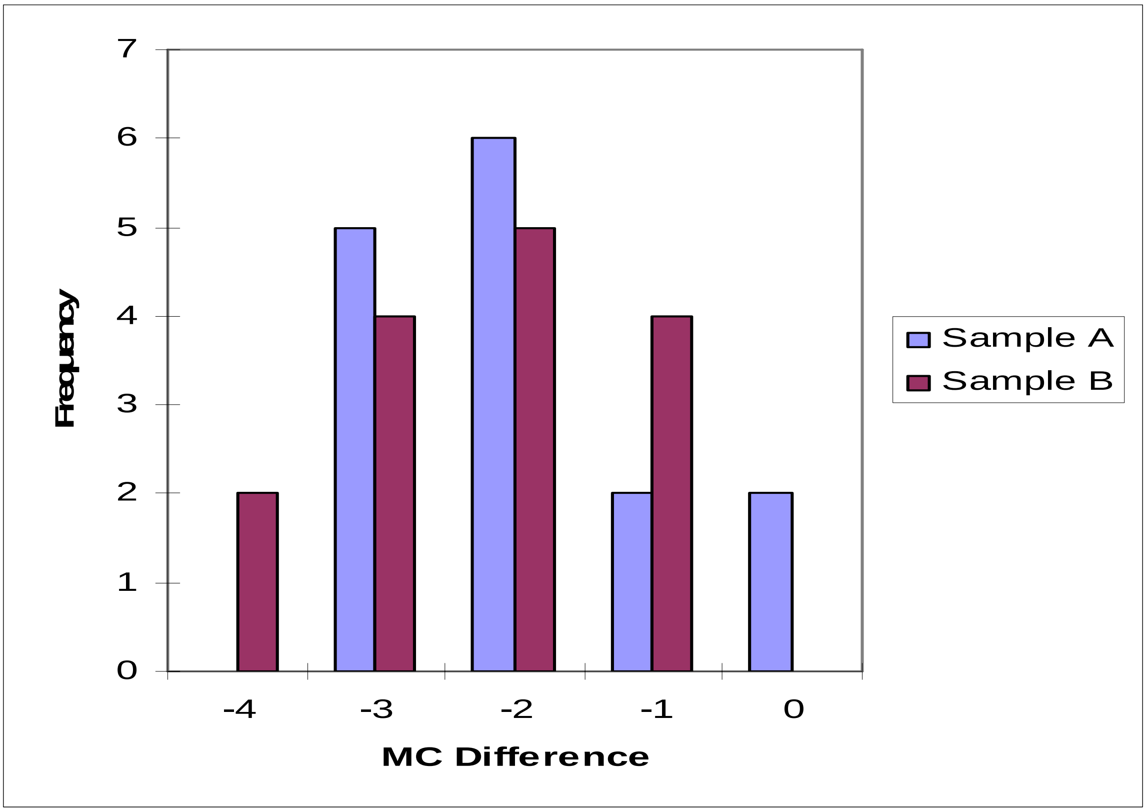


Figure 11. Distribution of difference case minus core in Experiment 3

T - Tests for differences between means of final whole sample MC (Figure 10), and case core variation (Figure 11), show samples are not significantly different.

Experiment 3 has shown:

- No significant difference was found, between steamed and un-steamed samples in terms of final MC and case core variation.
- Compared to Experiment 2 the variation in final MC was slightly less, possibly indicating an influence of steaming later in the drying period or at a lower MC.
- Similarly, the difference in 'case MC minus core MC' indicated a trend whereby steamed samples finished with lower variation.
- The timing of steaming adopted in Experiments 2 and 3 show that no significant differences in drying rate emerge by steaming early or later during the period of peak compression stress.

10.5. Conclusion

The drying experiments reported here show that within the bounds of the experimental conditions (i.e. drying at 70°C DBT), steaming during final drying when the case zone of a cross section is in compression does not significantly influence drying rate compared to matched samples that were not steamed.

Similarly, the timing of steam treatments (at 15% MC or 11% MC) did not effect drying rate compared to un-steamed matched samples.

Further work on the subject could include investigations into the effect of steaming at higher temperatures and or longer durations, on drying times and dried quality.

10.6. References

Skaar C. 1988 "Wood Water Relations" Springer Verlag Series on Wood Science

Perre P. 1996 "Flying Board Experiment" Australian Forest Products Conference

11. Economic evaluation of different timber drying systems for drying spotted gum and blackbutt

Martin Davies and Graeme Palmer

Department of Primary Industries and Fisheries

November 2005

11.1. Introduction

For the hardwood sawn timber industry, drying is the single processing step that adds the greatest value. For-example, at the time this report was prepared, green sawn structural timber was selling at \$645.34 /m^3, while rough-sawn dry boards suitable for manufacturing flooring were selling for \$1191.70 /m^3. One of the reasons drying adds such value is that the process costs about \$150 /m^3; however, there is significant variation in this cost between processors and methods. Therefore, processors who operate with higher efficiency, have greater profitability than their competitors.

This report outlines the results of an analysis of the costs of drying two hardwood species by a variety of methods. The primary aim of this analysis was to determine the viability of controlled pre drying in combination with kiln drying, compared with drying from green off saw in a kiln. In addition to this, the analysis was extended to cover a variety of approaches and to compare these in the same way.

The species selected for the analysis were blackbutt (*Eucalyptus pilularis*) and spotted gum (*Corymbia maculata*), sawn to 25 mm and 40 mm thick.

The kiln drying systems modelled were:

- conventional kiln drying above 70°C using LP gas fuel on a small scale,
- conventional kiln drying above 70°C using wood waste as fuel on a large scale,
- conventional kiln drying below 70°C using LP gas fuel on a small scale,
- solar LP gas hybrid kiln drying below 70°C on a small scale,
- dehumidifier type kiln drying below 70°C on a small scale,
- vacuum kiln drying on a small scale.

Pre drying scenarios included

- exposed air drying with conventional kiln final drying,
- covered pre drying in the air with conventional kiln final drying,
- pre drying in a large kiln chamber and conventional kiln final drying on a large scale using wood fuel.

11.2. Methods

The analysis method utilised spreadsheets to define the different process scenarios under test. The spreadsheets were designed to account for as many of the costs incurred by drying that could be reasonably included, with data drawn from current manufacturers and processors willing to contribute. The key purpose of the spreadsheets was to isolate various inputs and to expose the sensitivity of total cost to these inputs.

The design of the spreadsheets is generic; however, it can not account for all potential business contexts. Issues such as cash flow position, tax position or available capital are not included as these are too enterprise specific to be useful to the analysis. Despite this the relevant costs incurred by drying are included. For example, a facility to include interest payments on borrowing and depreciation over varying periods is included.

11.2.1. Inputs

Drying costs were analysed by modeling an array of drying systems using spreadsheets, which allowed the input costs to be changed and the total cost estimated. In this way, the changes in drying costs were observed over a range of input values and the sensitivity of cost to various inputs estimated. The input values that were used to model drying costs are summarised below.

Financial variables

- Interest rate – on borrowing or to calculate cost of opportunity
- Loan period – for borrowing – assumes principal (P) is paid in amounts of P/T each year over the loan term (T) plus interest on outstanding loans
- Depreciation period – used to calculate straight-line depreciation over the term.
- Cost of stock – used to calculate the cost of opportunity on stored stock value, eg. air drying stock, and losses to drying degrade using a devaluation rate.
- The percentage reduction in value due to degrade
- Operating hours per year – used to calculate productivity: the product of days in the year and hours per day in operation.

Kiln capital costs for various designs

- The cost of land and site works for an air-dying yard
- The cost of sheds for a covered air-drying yard
- The cost of a predrying chamber
- The cost of a conventional kiln chamber that can be heated above 70°C (High Temp)
- The cost of a conventional kiln chamber that can be heated to a maximum 70°C (Low Temp)
- The cost of a vacuum kiln
- The cost of a small-scale heat plant using LP gas for fuel and hot water for heat transfer
- The cost of a large-scale heat plant using wood waste for fuel and steam for heat transfer
- The cost of Solar /LP gas hybrid heat plant
- The cost of a dehumidifier heat plant
- The cost of a heat plant to be used with a vacuum dryer
- The cost of a steam-generating system for small-scale operations able to control wet side relative humidity (RH) to 2°C wet bulb depression (WBD)
- The cost of a steam-generating system for large-scale operations able to control wet side RH to 2°C WBD

The values in the spreadsheet are formed from the sum of components. The numbers used have been drawn from publications only after consultation with manufacturers. Where multiple chambers share equipment, costs are dispersed linearly to provide an average cost per kiln.

Process specifications

- The number of predriers to be used in the analysis
- The number of kilns supported in a small-scale operation or a large-scale operation or where vacuum dryers are used
- Maximum operating temperature and minimum wet bulb depressions for various types of kilns
- The nominated end point of drying – used to calculate energy usage
- Airflow specified as the kilowatts required per square meter of stack void space independent of air speed and the price of one fan for two speeds (high and low).
- The number of fans in a chamber for high and low air speed and in a vacuum drier.
- The dimensions of wood drying stacks.

Energy prices

- The cost of LP fuel gas
- The cost of electricity
- The cost of wood fuel. Note heat value of wood is calculated as the cost of production divided by the energy content of wood at 50% MC.
- The saving offered by solar collection as a proportion of total energy as suggested by manufacturer
- An energy loss factor for each type of kiln

Labour

- The wages of an operator, a loader driver and a boiler attendant
- The cost of labour appears constant for many types of systems
- Where production is small, labour is part time and operators have duties elsewhere in the process.
- On average one person handles approximately 50k m^3 per annum of product and usually at least two persons (operator and loader) are required. At large scale a boiler attendant is required however these three can handle around 150k m^3 per annum.

Other plant

The annual cost of a loader which is usually shared in small operations. Handling rate 100k m^3 per annum

Consumables

- Fuel and oil
- QA Equipment
- Instruments and sensors

- Furnace maintenance
- Maintenance of heat transfer systems for small and large scale operators, solar system operators, and vacuum system operators

Material character

- As the basic density and green moisture content

Drying times

- For each of two species (spotted gum and blackbutt)
- For pre drying and final drying or for drying from green to final in a single step
- Operating at high and low temperature
- Under Vacuum

11.2.2. Spreadsheets

Two files or workbooks were built with Microsoft Excel. One refers to a single-stage approach to drying – dry from green in a single process (Drying Economics 1 Stage1.xls). The second refers to two stages of drying – pre dry and final dry in two different types of processes (Drying Economics2 Stage 1.xls).

For two-stage drying, only conventional kiln final drying has been included in the analysis.

Each file comprises a "Summary" sheet outlining the results of calculations, which we discuss last, "Miscellaneous" sheet, which contains the variety of input data as discussed above, and a series of sheets describing different drying processes.

The "Miscellaneous" data sheet is the only sheet that is changed by users, and other sheets refer to this sheet to calculate cost.

For the single-stage drying process, individual sheets describe different types of drying process. Sheet names summarise the processes and the variety considered by the project e.g.

- "ConvGasRHCtrld" = Conventional temps (70 – 100) fuel gas heated with RH controlled using steam input. This represents an "Incomac" or "Nardi" type using a fuel gas fired boiler.
- "ConvWoodRHCtrld" = Conventional temps (70 – 100) wood fuel heated with RH controlled using steam input. This represents the same as above except fired by wood fuel
- "LowTGasRHUnctrld" = Low temperatures (40 – 70) fuel gas heated without RH control and therefore not requiring a boiler. A hot water heat exchange system is assumed. Other systems such as air to air or direct fired may have been considered; however, these are so few in industry, they were not included.
- LowGasSolarRHUnctrld" = Low temperatures (40 – 70) fuel gas heated with solar energy collection as a supplement, without RH control and therefore not requiring a boiler. A hot-water heat exchange system is assumed. Solar only system can be examined by varying the solar advantage parameter to 100%
- LowTDehumid = Low temperatures (40 – 70) electric powered heat pump
- Vacuum and Steam = Drying under vacuum with steam to provide heat

For two stage drying three approaches were tested:

- Air Dry + ConvGasHCtrl = Uncontrolled air drying combined with small scale conventional drying kilns as described above
- "Covrd Air Dry + ConvGasRHCtrl" = Air drying under a roof in an open sided shed combined with small scale conventional drying kilns as described above
- Pre Dry +ConvGasRHCtrl = Predrying in a dedicated large kiln combined with large scale conventional drying kilns.

11.3. Results and Discussion

11.3.1. Comparing Drying Methods

A comparison of average cost of drying for all species and thickness for each drying method is shown in Table 1. These results (the output of the model) are based on current costs and times gathered from kiln manufacturers, parts suppliers and wood processors. Each scenario is sized to reflect current commercial or industrial scales.

This table shows clearly the cost savings associated with two stage systems compared to single stage systems. This is due to lower capital and operating costs associated with pre drying compared to drying in a kiln. This is especially the case for air drying where energy costs for heating and air flow are not incurred.

In respect of single-stage drying, the least expensive option is the conventional LP gas heated kiln, drying at high temperature. This method of drying reflects the benefits of higher throughput and simple inexpensive machinery. The higher cost systems are those with lower throughput; while the highest cost processes are those using expensive energy sources.

Conventional kiln drying that uses LP gas at high temperature is shown to be less expensive than conventional kiln drying that uses wood fuel. This is because the capital cost of installing a wood fuel power plant is high compared to other systems. These results assume that the operation consists of 5 kilns requiring a 1 MW heat plant. However, if the operation is scaled up to more than 10 kilns with a 3 MW or greater heat plant, the wood fuel scenario outperforms the LP gas. This is because of the cost of depreciation on capital dispersed over larger production. Therefore, wood fuel systems service a specific large scale market segment.

Method	Average Cost of Drying ($\$m^3$)
Conventional kiln drying above 70^{o}C using LP gas fuel on a small scale.	100.30
Conventional kiln drying above 70^{o}C using wood waste as fuel on a large scale.	149.50
Conventional kiln drying below 70^{o}C using LP gas fuel on a small scale.	228.51
Solar LP gas hybrid kiln drying below 70^{o}C on a small scale.	209.24
Dehumidifier type kiln drying below 70^{o}C on a small scale.	298.67
Vacuum drying kiln on a small scale.	102.93
Exposed pre drying in the air and conventional kiln final drying.	52.73

Covered pre drying in the air and conventional kiln final drying.	61.39
Pre drying in a large kiln chamber and conventional kiln final drying on a large scale using wood fuel.	85.90

Table 1. A comparison of the cost of drying as an average of each species and sawn-wood thickness for each method

The high cost of drying from green off saw in a dehumidifier is associated with high cost of electric energy compared to LP gas or wood fuel, and the inability to recover energy needed to maintain high relative humidity early in drying. In a heat pump electrical dehumidifying timber-drying system the average cost of heat energy is $96 /m^3 compared to $42 /m^3 in a conventional high temperature system that uses LP gas.

For the vacuum drying case, the assumed drying time was half of conventional systems. This assumption is based on the best information available but is not proven commercially. The vacuum kiln scenario was included because this technology is emerging, and generates interest for the industry. Based on this analysis, the technology has considerable commercial potential.

Vacuum type dryers provide a significant saving due to more efficient use of energy. They operate at low temperatures for relatively short time. Therefore, these dryers are able to relatively quickly provide a good use of capital at a comparatively low unit cost of drying. If this is coupled with a significant reduction in drying associated degrade such as might be captured drying collapse prone timbers, then vacuum drying option will prove to be competitive

11.3.2. The impact of Degrade

One of the objectives of this report was to compare the cost of drying hardwood green off saw, to a two stage process involving controlled predrying. It can be seen from the results presented in Table 1 that the two stage process is the most cost effective. However, the selection of a drying method should consider potential losses to degrade.

For most processors in the subtropical region of eastern Australia, air-drying is a common practice. If a comparison is made between the cost of uncontrolled or exposed air drying and drying in a kiln green off saw (Fig 2), degrade losses of as little as 10% by drying in the air will erode any savings compared to drying from green.

A reduction to 5% degrade from 10% drying in the air, attained by covered drying returns a 12% reduction in cost. Clearly, any significant degrade in the yard is quickly accounted for by investing in reducing degrade, and drying green off saw can be justified if degrade in pre drying is high. For many processors, available log resources will not support large pre driers, and severe summer climatic conditions will provide conditions for cost effective drying green off saw.

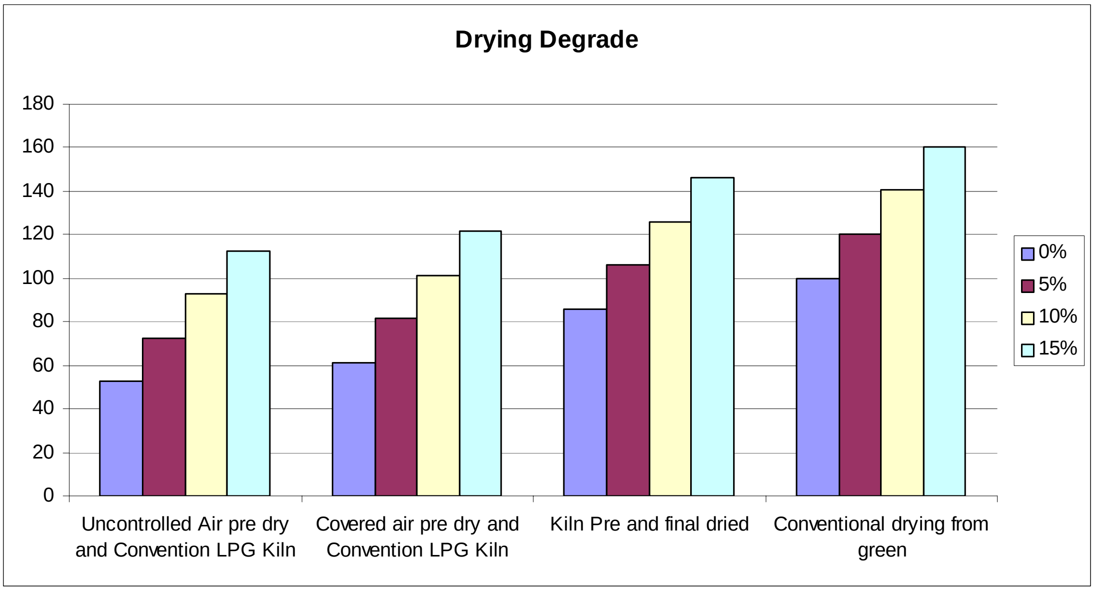


Figure 2. Cost associated with drying for 4 drying methods and 4 degrade levels.

11.3.3. Capital and Operating Costs

Direct comparisons between methods are not easily justified as the systems vary considerably in terms of process capacity. Indeed for many operators, insufficient volumes of wood are available to support large-scale controlled pre drying or wood fuel energy use. It is more relevant to consider the performance of the system in terms of operating costs and required capital.

Table 2 shows the cost of each scenario modelled, the capital cost per unit drying capacity and the capital cost per cubic meter produced. It is notable that the lower temperature options offer the lowest set up costs and therefore occupy a market niche within smaller operators. Table 3 below also shows the advantage of solar hybrid heating in terms of reduced operating costs, and therefore performs the best within the low capital market niche.

Table 3 shows that if the depreciation periods are increased from 10 to 20 years the total cost of production is significantly reduced. Indeed, longer depreciation periods may be justified in the case of wood drying kilns, and in this case, operating costs are the major contributor to total cost. Under these circumstances, energy cost and productivity become the most important parameters.

Type	**Heating**	**Capital Cost of Case $**	**Capital/m^3 capacity $/$m^3$**	**Capital/m^3 production $/$m^3$**
Conventional temperature	Fuel gas	867,000	2006.94	82.64
Conventional temperature	Wood waste	4,090,000	9467.59	389.84
Low temperature	Fuel gas	504,000	3888.89	617.65
Low temperature Solar	Solar/Fuel gas hybrid	534,000	4120.37	654.41
Low temperature Dehumidifier	Heat pump / Electric	534,000	4120.37	654.41
Vacuum Steam	LP Gas	1,674,000	12916.67	341.91

Uncontrolled Air pre dry and Convention LPG Kiln	Fuel gas	879,500	969.47	139.72
Covered air pre dry and Convention LPG Kiln	Fuel gas	1,379,500	1520.61	219.15
Kiln Pre and final dried	Wood Waste	3,501,667	1157.96	166.88

Table 2. A comparison of the cost of drying as an average of each species and sawn-wood thickness for each drying method

Type	**Heating**	**Depreciation $\$/m^3$ over 10yrs**	**Depreciation $\$/m^3$ over 20yrs**	**Operating Costs $\$/m^3$**
Conventional temperature	Fuel gas	100.30	93.02	81.62
Conventional temperature	Wood waste	149.50	115.16	76.70
Low temperature	Fuel gas	228.51	174.25	104.11
Low temperature Solar	Solar/Fuel gas hybrid	209.24	154.98	84.84
Low temperature Dehumidifier	Heat pump/Electric	298.67	241.18	167.81
Vacuum Steam	LP Gas	102.93	76.97	48.73
Uncontrolled Air pre dry and Convention LPG Kiln	Fuel gas	52.73	45.37	28.68
Covered air pre dry and Convention LPG Kiln	Fuel gas	61.39	52.26	33.35
Kiln Pre and final dried	Wood Waste	85.90	67.52	40.39

Table 3. Operating and depreciation costs for each drying methods

11.4. Conclusions

The analyses described in this report show a clear advantage of two stage drying systems versus single step drying in terms of costs of production. The costs difference is associated with savings in energy and capital associated with low temperature pre drying, which is less expensive than using an expensive drying kiln able to dry at high temperatures.

A consideration of degrade rates was also used to show the advantages of investment in controlling initial drying and concluded that drying green off saw in a kiln can be readily justified if alternative pre drying systems such as air drying, cause even low levels of degrade (~10%).

The analysis has also shown niches exist in the market for wood drying equipment based on available capital and resource volumes despite widely varying drying costs.

The costs associated with drying timber vary greatly from processor to processor, even if they are using the same systems. Therefore, the report is not comprehensive and local contexts generate different cost outcomes. Specific cost comparisons can be made however using the system of spreadsheets that has been constructed, which are available to interested individuals.

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