Improving Quality of Seasoned Tasmanian Eucalypt Timbers

by

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A.L. Redman

Abstract

The initial purpose of this thesis was to optimise kiln predrying times, without increasing the levels of drying degrade, for 25mm thick regrowth *Eucalyptus obliqua* using KilnSched scheduling program.

The first trial conducted involved the daily measurement of moisture gradients to accurately determine the accuracy of KilnSched from measured behaviour. This trial was conducted over three weeks under mild conditions (20°C DBT, 19°C WBT). After this period of drying 100% of the backsawn boards dried showed signs of collapse and 90% of the quartersawn boards were collapsed. Surface checking severity was also unsatisfactory. It was evident that the timber was dried above the collapse threshold temperature.

A subsequent trial was conducted to determine the collapse threshold temperature of the timber. The results of the trial showed that half of the boards tested collapsed at a collapse threshold temperature of 10°C.

As a result of this discovery, the research aim was changed to reducing the severity of collapse, surface checking and internal checking degrade of regrowth *E. obliqua*, by pretreating the timber whilst in its green state prior to drying. Three pretreatment regimes were trialed. The regimes included two chemical pretreatments involving common table salt (sodium chloride) and a physical regime involving presoaking green logs in heated water. Sodium chloride was chosen due to its low cost and availability. The salt regimes consisted of both soaking green boards in a saturated salt solution, and packing green boards with a layer of salt between each row and wrapping in moist hessian. The salt regimes were conducted over nine weeks. The presoaked regime logs were soaked at 45°C over three days. Control boards were used to compare the pretreatments with untreated timber cut from the same stock.

Following the pretreatment regimes, the control and pretreated boards were randomly racked and kiln predried following a typical drying schedule used by the Tasmanian

timber industry for this species of timber. Upon completion of predrying, the boards were reconditioned and then final dried (following typical industry schedules) before they were investigated for levels of degrade.

Once final drying was complete, each board was dressed to a thickness of 25mm. There was no sign of residual collapse shrinkage on any board after reconditioning. Surface checking penetration data showed the salt solution regime produced the most desirable percentage of unchecked board faces on both sides of 17.8%. The presoaked regime produced the least favourable results at a dressed thickness of 25mm with no boards free of surface checking on both faces. At a dressed thickness of 19mm however, 61.9% of the presoaked regime boards were check free on both sides. This figure was significantly greater than the other regimes. The salt regime values were higher than their corresponding control values indicating an improvement in check free recovery due to the salt pretreatments. The increase in check free recovery for the presoaked regime at 19mm indicated that the checks did not penetrate as deeply as for the other regimes even though boards from the presoaked regime dressed at 25mm were all surface checked. This may be due to the presoaking reducing the level of internal stresses in the timber due to the heat treatment.

The severity of internal checking was greatly increased by the salt solution regime compared with its control (48.9% cf. 23.3%). Internal checking was slightly reduced by the salt/hessian regime. The level of internal checking for the presoaked regime was significantly less than the other regimes (2.4%). Again this may be attributed to reducing internal stress levels by the presoaking pretreatment.

Average EMC values for both the salt regimes were 2-3% higher than for the control packs and the presoaked regime. This was theorised to be attributed to the diffusion of the salt into the board surfaces of these regimes and the hygroscopic nature of salt.

Overall the presoaked regime was by far the best regime at increasing the levels of timber recovery through reducing degrade caused by internal checking and surface checking. The presoaked regime is both practical industrially, inexpensive and free of corrosive and dangerous chemicals.

As an extension to work previously conducted by this author (Redman, 1997), the final chapter of this thesis is based on the generation of moisture meter species correction calibrations for *E. obliqua*.

It was evident that the correction factors for resistance-type moisture meters used on *E.obliqua* deviate from those given in the Australian Standard. The cause of this deviation is most possibly due to the difference in meter electrode placement with respect to the timber grain direction as specified by the meter manufacturer.

The regression trendline for the resistance and capacitance type meters indicate a strong fit. The regression trendline for capacitance - type meter readings performed on *E. delegatensis* previously (Redman, 1997) was not a strong fit due to density effects.

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Contents

Chapter 1. Literature Review

1.1 The Structure of Hardwoods

Commercial species of timber are classified into two main groups, softwoods and hardwoods.

Hardwoods are those timbers arising from trees which are products of flower bearing seeds (angiosperms) while softwoods arise from trees which bear cones containing seeds which are not enclosed in a seed case (gymnosperms). Density and hardness do not contribute to the classification of hardwoods and softwoods.

The following discussion of the structure of wood includes only that relevant to hardwoods as the work conducted in this thesis is concerned primarily with the Eucalypt species that make up the group known as 'Tasmanian Oak' which are hardwoods. The following information was obtained and summarised from Siau (1984), Bootle (1983) and Butterfield (1980).

1.1.1 Physical Structure

The physical structure of wood is extremely non homogeneous by nature. This is reflected in timber properties such as density, moisture content and its general physical appearance. A mature tree is comprised of three main elements, namely, the crown or leaf system, the trunk or bole, and the root system.

The root system acts as an anchor for the tree as well as absorbing water and essential minerals from the soil.

The function of the tree crown is to manufacture food materials essential for tree growth. The leaves of a tree contain a green substance called chlorophyll which, with the action of sunlight, breaks down carbon dioxide. The oxygen is released back into

the air through the leaves while the carbon combines with minerals and water absorbed by the root system to form food substances.

The trunk of a tree is the most important element with regards to this thesis and is the section from which commercially available timber is derived. The trunk of a tree is made up of several different layers. From the outer circumference of the trunk to the center they are; the outer bark, inner bark, cambium layer, sapwood, heartwood and the pith.

The outer bark of the trunk is all dead tissue. It contains breathing pores known as lenticels which allow the flow of oxygen into the living tissue of the tree and the disposal of carbon dioxide into the atmosphere. The main purpose of the outer bark is to armor the tree and reduce water loss through evaporation.

The inner bark of a tree consists of thin, green, moist tissue which conducts food manufactured in the crown of the tree to the cambium layer.

The cambium layer consists of a very thin layer of cells that are responsible for all growth in trunk diameter. Growth takes place through the division of cells. The cambium layer forms new sapwood or xylem on the inside of the cambium and new inner bark or phloem on the outside. A new sapwood cell laid down at a particular distance from the ground and inner pith retains that position for the life of the tree, therefore inner bark cells move outward from the pith as the tree grows.

The sapwood is the newly formed wood that surrounds the heartwood. It is composed of living cells whose function is to conduct water and minerals from the roots to the leaves. The sapwood is usually softer and lighter in color than the heartwood. The inner sapwood gradually hardens and turns into heartwood as the tree grows. The sapwood is less resistant to decay and insect attack.

The heartwood is the fully matured part of the tree. The transition to heartwood is marked by the deposition of extractives and other extraneous material in the cells, and in the case of the Tas. Oak. species, by the accelerated production of tyloses. Tyloses

are cellular membranes which enter vessels (1.1.2.1) from adjacent parenchyma cells (1.1.2.2) through pit pairs and greatly increase the resistance of water flow through the heartwood. The death of the living cells then follows so that the heartwood is physiologically dead tissue. Its main function is to provide stability to support the tree.

The pith is the central core of the tree and is the dead tissue that represents the earliest growth of the tree as a sapling.

Most woody plants from temperate climates exhibit light and dark rings through the cross section of the trunk between the cambium layer and the inner pith. These growth rings are produced as trees grow periodically rather than continuously. Growth rings are usually associated with seasonal changes or dramatic climate fluctuations. Generally the lighter growth rings are associated with rapid spring and early summer growth. This is called the earlywood and is softer and has large thin-walled cells compared to the darker latewood growth rings. Latewood is usually associated with slower growth in late summer and autumn. It consists of wood made up of cells comparatively narrower in width with thicker, stronger walls.

1.1.2 Cell Structure

The basic cell structure of hardwoods consists of three cell formations produced on the inside of the cambium layer (xylem). These are the parenchyma cell (axial and ray), fibre and the vessel. Figure 1.1 shows a typical hardwood block magnified to × 250 with the various cell orientations and relative sizes shown. The LRT key represents the directions of the longitudinal, radial and tangential directions respectively.

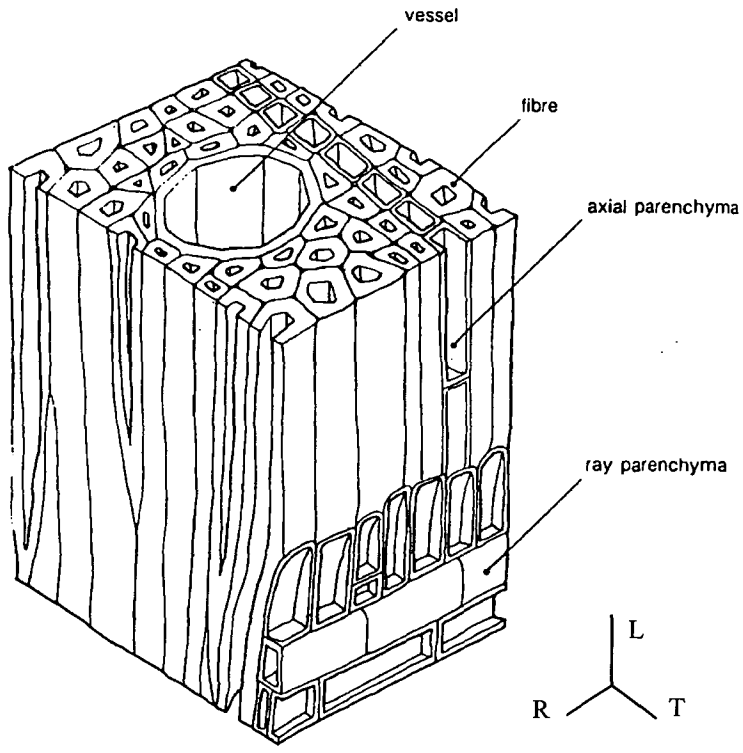

Figure 1.1 - Diagram of a hardwood cube (magnification × 250), cell pits have been omitted. Diagram extracted from Butterfield and Meylan (1980).

1.1.2.1 Fibres

Fibres make up the bulk volume of most hardwoods. Their primary role is to provide mechanical support for the tree. They are axially elongated cells that taper at each end to a point with generally a smaller mid-diameter than the other cell types. Their secondary walls are usually sparsely pitted and considerably thicker than those of the vessel elements and axial and ray parenchyma cells. Normally they have no living contents at maturity. The proportion of fibres present, fibre diameter, and the average thickness of their cell walls largely govern the density of a hardwood. Fibres overlap longitudinally and the lumens of adjacent fibres are connected by pits. Although pits are present in fibres of the Tas. Oak group they are filled or occluded with various extractives.

1.1.2.2 Vessels

Hardwoods are sometimes called *porous woods* because of the vessels or 'pores' that are sometimes visible to the naked eye in clean cut transverse faces. The vessels perform the major water carrying functions in the living tree. The grouping of vessels and their mid-diameter varies considerably from one species to another. The diameter of the vessels of any given species varies within each growth increment. Vessels, built up of individual vessel elements joined end to end provide a pathway for the conduction of water and dissolved mineral salts from the roots to the leaves.

Material moving through vessels passes relatively freely between individual 'end to end' cell elements through perforations in their walls. Perforations are virtually unobstructed openings in the end walls forming *perforation plates.* Extensive intervessel pitting is also present between vessel walls.

1.1.2.3 Parenchyma Cells

Parenchyma cells have thin walls with numerous pits and are generally brick shaped. They act as a form of storage tissue and are scattered in strands, patches or bands amongst the vessels and fibres. Unlike other wood cells, parenchyma cells remain alive for some years after completion of their development. Ray parenchyma is present in horizontal bands called medullary rays that radiate from the pith towards the bark.

1.1.3 Chemical Composition

Apart from extractives wood cells consist primarily of three substances, cellulose, lignin and hemicellulose. Carbon dioxide from the atmosphere is combined with water obtained from the roots to photosynthesize simple sugars. When these sugars are conveyed from the leaves to the wood cells, they are changed into more complex cellulose, hemicellulose and lignin.

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Cellulose consists of thousands of glucose molecular units chained together end to end to form polymers of simple sugars called polysaccharides. Cellulose exists in both crystalline and non-crystalline (amorphous) states. The percentage of cellulose present in wood is reported by Siau (1984) to be remarkably constant, namely 42% ± 2% in both softwoods and hardwoods. Crystalline cellulose is impermeable to water and it is only in the amorphous regions of the cell wall that water molecules become strongly bonded to the hydroxyl groups of cellulose. Thus, cellulose contributes to the water absorption of wood through its numerous hydroxyl groups.

Hemicelluloses like celluloses are polysaccharides. They are associated with cellulose and lignin in the cell wall and are gelatinous by nature. The major hemicellulose in hardwoods is an acidic xylan and accounts for 25% ± 5% of the extractive free wood (Siau 1984).

Lignins are three dimensional polymers composed primarily of phenylpropane units and have a relatively high molecular weight compared with cellulose and hemicellulose. Siau (1984) reports that the cell wall material (not including water) of temperate hardwoods is comprised of 25% ± 3% lignin. Lignin offers protection to the wood against microbial degradation and it also serves to reduce its hygroscopicity. Cellulose and especially hemicellulose are far more hygroscopic than lignin.

1.1.4 Cell Wall Structure

Wood cell walls consist of the three major components mentioned above where cellulose is the skeleton, hemicellulose is the matrix and lignin is the adhesive substance binding the cells together and giving rigidity to the cell wall.

Cellulose polysaccharides in woody plant cells are chained together to form extremely long crystalline microfibrils of great tensile strength. These microfibrils are embedded in and coated by the lignin and hemicellulose to form a matrix. Thus the wall structure forms a natural fiber-composite. This differs from most artificial

composite materials in that the matrix is water reactive and changes both its volume and elastic properties with moisture content.

Wood cell walls consist of a primary wall and secondary wall. The primary wall is the first to develop and is stretched and elongated during initial growth of the cell. It consists of a thin network of randomly arranged microfibrils and is only 0.1 to 0.2μm thick (Siau 1984). The primary wall is the only wall present in parenchyma cells (see section 1.1.2.3). The secondary wall is then laid down on the inside of the primary wall, usually after elongation of the cell has ceased.

The secondary wall is further subdivided into three layers designated S_1, S_2 and S_3, each having different helical arrangement of its microfibrils. The following values of layer thickness and microfibril angle are from Siau (1984). The layer nearest the primary wall is called the S_1 layer. The S_1 layer is 0.2 to 0.5 μm thick in earlywood and can reach a thickness of 0.1 μm in latewood. The microfibrils of the S_1 layer are orientated at an average angle of 60° to 80° to the fibre axis.

The middle or S_2 layer is the thickest of the three secondary wall layers with thickness from 1.0 to 2.0 μm in earlywood and from 3 to 8 μm in latewood. The microfibril angle of this layer also varies between the earlywood and latewood from 10° to 30° to the fibre axis respectively.

The S_3 layer, lying nearest to the cell cavity or *lumen*, is only 0.1 to 0.2 μm thick in both earlywood and latewood. Its microfibrils are almost transverse to the fibre axis.

Individual cells are joined together by intercellular material between their primary walls. This *middle lamella* is an amorphous mass, rich in lignin and low in cellulose. When the formation of the cell is complete, impregnation of the middle lamella with lignin begins, and gradually extends throughout the cell wall. The many capillaries present between the microfibrils become filled with polyphenols and other extractives when the sapwood changes into heartwood.

The following diagram illustrates the general structure of the wood cell wall and the helical orientation of the cellulose microfibrils within each wall layer.

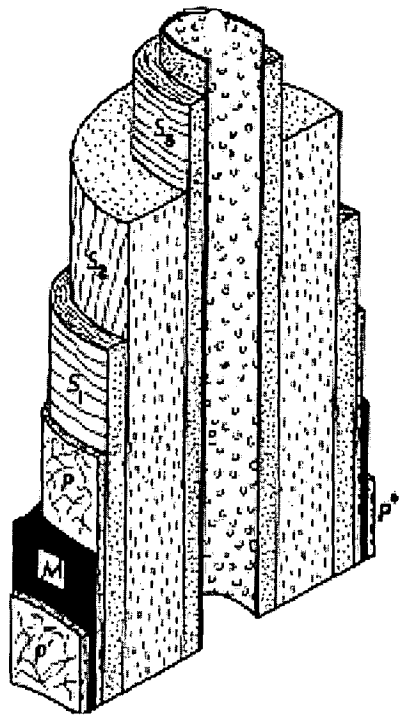

Figure 1.2 - A diagram illustrating the general structure of the cell wall of axially elongated wood elements and the helical orientation of the cellulose microfibrils within each wall layer. M, middle lamella; P, primary wall; S_1, outer layer of the secondary wall; S_2, middle layer of the secondary wall; S_3, innermost layer of the secondary wall; P', primary walls of adjoining cells. Diagram extracted from Siau (1984).

During the cell formation process there are regions in the secondary cell wall, which develop and are known as *pits*. Pits form a canal between the cell lumen and the primary wall which permits the flow of liquid from one cell to another. The pits of two adjoining cells usually oppose one another to form a *pit-pair*. The primary walls of the two such opposing cells, and the intervening middle lamella, form what is termed the *pit membrane*. Cronshaw (1960) discovered that the pit openings in *E. regnans* were less than 64nm in diameter. Therefore the pits in Tasmanian eucalypt species are sufficiently small that movement of water out of the cell lumens is dominated by molecular diffusion. This is why water movement during drying of Tasmanian Oak can be adequately described using Fick's Law (equation 2.2.4) as described by Schaffner and Doe (1981).

1.2 Collapse Shrinkage

During the seasoning process from green to dry timber can experience two types of shrinkage; normal shrinkage and collapse shrinkage.

To appreciate the fundamental differences between normal shrinkage and collapse shrinkage it is necessary to understand the relationship of each to the removal of water from timber. Green timber contains free water in the cell lumens and bound water in the cell wall. Free water is generally removed before the bound water. When the cell's lumens are empty of free water but all bound water remains, the wood is said to be at the fibre saturation point, (FSP). The FSP is expressed as a percentage of moisture content (MC). Normal shrinkage occurs at MCs below FSP in all timbers due to the removal of bound water from cell walls.

In certain timber species (especially in ash-type eucalypts) there may be an abnormal shrinkage during drying. This commences in the green wood as it starts to dry and continues until all the free water of the cell lumens has been removed. It can usually be recognised as in most cases it causes an irregular corrugation or distortion of the timber surface. This form of shrinkage is caused by the caving in of the walls of the wood cells during drying. It is therefore, appropriately known as 'collapse' shrinkage.

1.2.1 Collapse History

The American timber expert H. D. Tiemann (1915) was the first to examine in detail excessive shrinkage in eucalypts and to point out its distinction from normal shrinkage. When drying Californian blue gum (*Eucalyptus globulus*, Labill.) at Berkeley in 1913, Tiemann's attention was drawn to the extremely high shrinkage of the blue gum racking sticks. Following the discovery, Tiemann gave the name 'collapse' to the phenomenon and published his liquid tension theory in 1915 (see 1.2.2.1).

Kauman (1965) states that the next big advance regarding collapse history was in 1917 with independent observations by two Australian timber men, James Grant, and his son, George Grant. James Grant noticed the effect of accidental soaking in boiling water in eliminating collapse from blue gum wheel rims. George, at the time, was performing kiln seasoning of ash-type eucalypts, and was getting unsatisfactory results by following the recommended American procedure of heating green timber in a saturated atmosphere before commencing the drying schedule. He decided to reverse the order and steam after drying. He was successful in showing that the excessive loss of dimension could be largely recovered by such a steaming treatment which has since become known as 'reconditioning' (Anon. 1942).

Research on collapse has proceeded rapidly. Following these major breakthroughs much detailed research was accomplished in the twenties and thirties by Tiemann and others in the United States and by Elliot, Greenhill and others in Australia.

Research was interrupted until the late forties due to the Second World War and was taken up again in Australia by Bisset and Elwood (1951) who investigated eucalypt veneers.

1.2.2 Collapse Theories

1.2.2.1 Hydrostatic (Liquid) Tension Theory

The most widely accepted theories attribute collapse to hydrostatic tension forces in the fibre lumens. This theory was first provided by Tiemann (1915). This theory is based on the concept that collapse is due to the hydrostatic tensions acting in the water filled lumens of the wood fibres. During the drying of wood above FSP, the free capillary water in the cell lumens is withdrawn through the cell pits. A meniscus is formed at the air-water interface in one of the pits. This can induce hydrostatic tension in the water. If this tension exceeds the compressive strength of the cell walls, the cell collapses.

Tiemann proposed that a liquid held in a capillary behind the convex face of a curved meniscus, is in a state of negative pressure such that:

$$P = \sigma\left(\frac{1}{r_1} + \frac{1}{r_2}\right) \qquad (1.2.2.1)$$

where : P = total liquid tension,

σ = surface tension, and

r_1, r_2 = principal radii of the curved surface.

Prerequisites for the theory to be justifiable are; firstly that the cell lumens of the wood must be completely filled with water initially; secondly there must be no pits in the cell walls larger than a very small limiting size; and thirdly the strength of the cell walls must be insufficient to withstand the applied stress.

Liquid in tension is in a metastable state. Thus, it is prone to fracture, creating a bubble of water vapour. This process is known as 'cavitation'.

1.2.2.2 Shrinkage Stress Theory

Clark (1927) was the first to suggest that collapse might be induced by the compressive stresses arising during drying. He states that stresses are caused by shrinkage due to the presence of a moisture gradient, and may compress the inner core of a board sufficiently to cause collapse. Stamm and Loughborough (1942) considered compression stresses to be the main cause of collapse, but this does not agree with evidence presented by Kaumann (1958) that collapse can occur in wood dried under tension. Also, Innes (1996) produced evidence that wood dried at high temperatures will collapse very early in the drying process. This tends to discount the shrinkage stress theory in the early stages of drying, as there is insufficient opportunity for compressive stresses to occur, due to the lack of a large moisture gradient.

1.2.2.3 Comprehensive Theory

Kaumann (1960) showed that both hydrostatic liquid tension acting in individual cell lumens, and drying stresses involving large numbers of cells, contribute to the production of collapse, and that the collapse can be predicted from the surface tension data and from the structural and rheological properties of the wood.

According to his theory, collapse is produced when hydrostatic tension P (from equation 1.2.2.2), exceeds the stress, Q, acting in the wood at the limit of plastic flow. Thus the liquid tension collapse C_L, is given by:

$$C_L = k_L(P-Q)(1-e^{(-t/\tau)}) \qquad (1.2.2.2)$$

where k_L = deformation coefficient,

t = time, and

τ = relaxation time of collapse process.

For compression stress collapse, Kaumann replaced the (P - Q) factor in equation 1.2.2.2 by the compressive stress. This is taken as a linear function of the potential difference in shrinkage between case and core.

Kaumann found that in sawn mountain ash (*E. regnans*), τ was of the order of 2 hours at 20°C and ½ hour at 53°C, and the factor $(1 - e^{(-t/\tau)})$ may be taken as constant. The remaining factors are approximately linear functions of the wood temperature, and the total collapse, C^i, may therefore be written:

$$C^i = a_0 + b_0 n + \left[a_1 + b_1(1-n)\right]T_w + b_2(1-n)S_0^j \qquad (1.2.2.3)$$

where T_w = the wood temperature,

S_0 = collapse free shrinkage,

a_k and b_k depend only on surface tension and the properties of the wood,

n = 0 for negligible end grain drying, 1 if drying is mainly through the end grain,

i, j = represent the structural directions of the wood.

From the sorption isotherm and by mercury penetration, Kaumann determined the capillary radii r (see equation 1.2.2.1). He showed that the liquid tension collapse could be approximated by careful drying of 2.5cm cubes from exposed end grain. Kaumann's values, calculated using this theory, agreed strongly with data from an experiment on *E. regnans*.

1.2.2.4 Boiling Theory

It is well established in the theory of boiling that there is a minimum diameter of vapour bubble that can grow against surface tension forces. Smaller bubbles form intermittently but rapidly collapse having only a short life. When water is trapped within fibres whose internal diameter is less than this minimum or critical value, vapour bubbles cannot grow and the water goes into tension. Under such conditions, very large tension stresses exist in the water so the fibre walls collapse as cylinders under internal tension.

The critical radius, r_{crit}, is given by Volmer (1939), as cited by Gerum et al (1977), as:

$$r_{crit} = \frac{4\sigma}{3P} \qquad (1.2.2.4)$$

where σ = surface tension,

P = total liquid tension,

A bubble with a smaller radius than r_{crit} decreases and a bubble with a larger radius than r_{crit} increases. The activation energy A_k required to create a bubble is given by:

$$A_k = \frac{16\pi\sigma^3}{3(P_K - P_l)} \qquad (1.2.2.5)$$

where P_K = pressure inside bubble,

P_l = pressure of the metastable liquid phase.

The probability of the creation of a critical bubble in the considered metastable state is defined by T and (P_K - P_l) and is given by,

$$J \approx Z_1 \exp\left(-\frac{\lambda}{kT}\right)\sqrt{\frac{6\sigma}{(3-b)m}}\exp\left(-\frac{16\pi\sigma^3}{3kT\left(P_K - P_l\right)^2}\right) \qquad (1.2.2.6)$$

where Z_l = number of molecules per cm^3,

k = Boltzmann's constant,

m = mass of molecule,

λ = molecular latent heat of evaporation,

b = (P_K - P_l) / P_K,

T = temperature.

Innes (1996) suggests that the applicability of this theory is questionable as it was originally designed for pure liquids, and does not take into account surface effects.

1.2.3 Process Variables Affecting Collapse

1.2.3.1 Temperature

Most research workers have found that collapse susceptible timber is more likely to collapse if subjected to high temperatures during the early stages of drying of green material (Tiemann 1915, Greenhill 1938, C.S.I.R.O 1942, Gottstein and McCombe 1956, Kaumann 1959, Innes 1996a). Oliver (1986) suggests that collapse is strongly dependent on temperature because lower temperatures stiffen fibre walls.

Innes (1996a) investigated collapse shrinkage in slices of latewood and earlywood bands of *Eucalyptus regnans*. He found that collapse shrinkage in earlywood was evident only when slices were dried at temperatures above a minimum temperature termed the 'collapse threshold temperature' (CTT). This was further tested on end-coated cross section boards approximately 200mm long which were rapidly dried at dry-bulb temperatures below the CTT for earlywood and latewood. Incipient checks were found in the latewood of these boards. Board sections dried at higher temperatures showed internal checks in both earlywood and latewood bands.

The lowest dry-bulb temperature tested for board sections was 20°C. Innes (1996a) states that 'the board samples did not demonstrate visible collapse or internal checking in the earlywood below 26°C. Further tests at temperatures below 20°C would be required to establish a collapse threshold temperature for the latewood'.

Other investigations of temperature effects on collapse are those regarding heating treatments on timber before the drying process. Greenhill (1938) was the first to investigate the influence of preheating on collapse. He found that in the *E. regnans* investigated, collapse increased four-fold after heating at 100°C for 2 days or at 82°C for 32 days. Preheating also severely reduced the recovery obtained from reconditioning. For treatments longer than 4 days at 100°C, the collapse became irrecoverable.

Similarly Kauman (1961) pretreated samples of *E. regnans* at temperatures ranging from 20°C to 138°C for periods ranging from ¼ to 14 days. The humidity was kept constant. The thermal degradation of the samples was measured by measuring the acidity (pH) of the samples.

Kaumann (1961) concluded that thermal degradation of green wood causes large increases in total shrinkage due to increased collapse during subsequent drying, and severely reduces the recovery obtainable by reconditioning. The acidity of the material measured after the heat treatment increased with temperature and duration of treatment up to a maximum and then decreased. The increase in shrinkage was found to be roughly proportional to the increase in acidity up to the maximum. When the acidity decreased there was no more change in shrinkage or loss of recovery.

The effect of thermal degradation on shrinkage and recovery was highly significant for treatments exceeding 1 to 2 days at 82°C, 6 hours at110°C, and 2 hours at 137°C (Kaumann 1961).

1.2.3.2 Moisture Content and Basic Density

Chafe (1985) investigated the relationship between collapse, volumetric shrinkage, moisture content and basic density for trees of *E. regnans*. The data was measured from core samples taken at four heights (from ground level) from eight trees. The cores were further cut into 50mm segments. All shrinkage values were calculated and expressed in per cent of green volume. Collapse was measured as the difference between the total volumetric shrinkage and the volumetric shrinkage following reconditioning. Results showed that the severity of collapse increases with higher moisture contents. When collapse was plotted against basic density, there was an inverse relationship. Notwithstanding this association, moisture content was generally a superior indicator of collapse.

1.2.4 Anatomical Variables Affecting Collapse

1.2.4.1 Species, Age and Climate

Since the discovery of collapse many investigations have shown that many Australian timber species, especially those of the commercially valuable 'ash' type eucalypt group are particularly prone to collapse. Within timbers of the same species, collapse often varies with geographical distribution. For example, 'ash' eucalypts grown in Tasmania usually exhibit worse collapse than their Victorian counterparts of the same species (Kaumann 1965). Timber from certain localities is often reported to collapse badly. For instance, timber grown in particularly high winds (Guernsey, 1951) and timber grown in areas of swamp (C.S.I.R.O., 1942).

Findings have also indicated that timber from immature trees of collapse prone timbers tends to collapse more readily than that from mature trees (C.S.I.R.O., 1942). Kaumann (1965) suggests that this may be due to the generally faster growth of young trees leading to wider spacing of the late wood bands. Correlation of collapse intensity with tree age may also be due to chemical changes in the wood through hydrolysis of acetyl groups (Stewart et al., 1961).

1.2.4.2 Position within Tree

Collapse severity not only varies between and within tree species it can also vary within single trees. Pankevicus (1961) states that the total shrinkage and recoverable collapse both tend to be higher in logs from the base of the tree than from logs cut from further up the tree.

Collapse intensity also varies in the radial direction from sapwood to pith. Cuevas (1969) studied the variation of shrinkage with distance from the pith of 24 trees of *E. viminalis* (Labill). The investigation showed tangential collapse shrinkage was highest in a zone approximately midway between the bark and the pith, whereas radial shrinkage and radial collapse shrinkage were independent of radial position in the tree.

Similarly, Chafe (1996) examined segmented increment cores from three trees of *E. regnans*. These demonstrated that collapse increased with distance from the periphery to about 85% of the radius where it continued a precipitous decline towards the pith. It was argued that compression failures in the fibre walls of the brittle heart core were responsible for the steep decline in collapse.

Other studies have shown that sapwood does not generally show appreciable collapse and wood containing brittle heart tends to collapse more readily (C.S.I.R.O., 1942).

1.2.4.3 Growth Rings

Investigations have shown that collapse shrinkage occurs at different levels between early and late wood bands of timber from the same tree or sawn board.

Bisset and Ellwood (1951) used photomicrography and dimensional changes in shrinkage on small specimens to demonstrate the differences in collapse and normal shrinkage of early and late wood bands of *E. regnans* and *E. delegatensis*. From this study it was shown that the collapse in early wood was approximately 170% (2.7 times) greater than collapse in late wood. The greatest normal shrinkage however occurred in the late wood. It was hypothesised that the differential collapse shrinkage between early and late wood bands was sufficient to cause large checks in the early wood.

Bisset and Ellwood (1951) attributed these results to the fact that the specific gravity of the early wood was considerably less than that of the late wood. The lower specific gravity of the early wood was attributed to its lower ratio of cell wall thickness to lumen size than that of the late wood. The difference between cell wall thickness in the growth bands was negligible compared to the approximately 3:1 ratio of lumen diameter between the early wood and late wood bands respectively. The slightly higher wall thickness found in the late wood bands accounted for them exhibiting greater normal shrinkage because they hold more bound water compared to the same volume of early wood (Bisset and Ellwood, 1951).

Innes (1996a) measured the tangential shrinkage on longitudinal-tangential slices of separate earlywood and latewood from one board of *Eucalyptus regnans* at various temperatures. Innes (1996a) discovered collapse shrinkage in latewood slices occurred at lower temperatures than in earlywood slices.

1.2.4.4 Chemical and Cell Structure

Kaumann (1965) states that collapse depends on at least two properties of the cell wall: pore sizes and strength; and that small variations in either can cause large variations in collapse intensity. He declares that correlation of collapse with any anatomical feature will be at least partly obscured by random statistical variations of these properties.

Guernsey (1951) indicated that collapse in western red cedar increased with resin content. Similarly Chafe (1987) studied the influence of extractive component on the shrinkage behavior in eucalypts. Statistical analysis of available data suggested that collapse was positively related to the amount of encrusting and extraneous materials and negatively related to the amount of polysaccharide cell wall component.

Chafe (1987) hypothesised that extractives are responsible for increasing collapse of some species and causing collapse resistance in others. In accordance with the liquid tension theory of Tiemann (1915), extractives deposited upon pit membranes are sufficient to reduce permeability to such an extent that, given sufficiently weak cell walls, collapse will occur. Alternatively, the concentration of extractives in cell walls of some species may be so high that the extensive bulking action severely limits the shrinkage and prevents or minimises collapse on a material that might otherwise be collapse prone. Extractives occluding the cell lumen or pits could also play a collapse limiting role (Chafe 1987).

1.2.4.5 Grain Direction and Board Dimensions

Various studies have indicated that collapse intensity is also dependent on grain direction and dimensions of the sawn board.

Kaumann (1958) prepared specimens with dimensions 100 × 25 × 25mm (cross section × length) with the growth rings parallel (backsawn), perpendicular (quartersawn), and at 45° to the 100mm faces. The material was dried at 49, 65 and 82°C, at two levels of RH (15 and 80%) and was selected from five mature trees of *E. regnans* grown in southern Tasmania and three trees of same species grown in Victoria.

Collapse was measured as the difference between the total volumetric shrinkage and the volumetric shrinkage following reconditioning. Results show total shrinkage (measured as a per cent reduction in area) and collapse were greatest with the backsawn grain direction and least when it was quartersawn. Kaumann (1958) states that evidence obtained in the study indicated that the intensity of collapse depended to some extent on the specimen shape and on the grain direction within the specimen (due to sawing pattern). This behavior was believed to indicate that drying stresses were not without influence on the magnitude of collapse.

Scanning electron microscopy was used by Wilkins (1986) to investigate collapse near the radial and tangential edges of dried wood blocks. The study found collapse occurring commonly at the periphery of a wood block when fibres were undamaged. Damaged fibres at the edge did not collapse but the adjacent fibres frequently did, indicating the presence of true collapse rather than the flattening of cells due to forces generated by normal shrinkage. These results were said to support the hydrostatic tension theory of collapse (Wilkins, 1986).

1.2.5 Collapse Related to Checking

Certain types of timbers are prone to both surface checking and internal checking or 'honeycombing'. Surface checking is generally believed to be caused by stresses caused by moisture gradients due to drying (Waterson, 1997). If the surface moisture content drops too quickly then a steep gradient can occur. Therefore the outer layer of a board shrinks before the inner core and causes the core to go into compression. Thus the outer layer is under tension and if the tensile force is large enough the surface of the board will split or check.

Honeycomb checks are those which initially occur inside a board's core. Honeycomb checks may not be found until the timber is sold and machined to uncover the hidden checks. Both types of checking are undesirable forms of degrade.

Many researchers have found that there exists a relationship between collapse and honeycombing and surface checking. Oliver (1986) states that in almost all cases honeycomb checking occurs as a result of timber collapse. He also observed that collapse checking starts in the earlywood. It appears that the higher initial moisture content of the earlywood contributes to greater collapse shrinkage in the earlywood than in the latewood.

Booker (1994) states that it is not collapse that causes internal checking but that water stress causes either collapse or internal checking, or both together. In other words, internal checking and collapse are in fact competing phenomena both caused by water tension. If the maximum water stress is small or the wood very strong, neither collapse nor internal checking will occur. Booker (1994) presented a theory of internal checking and collapse that predicts that collapse can occur in a board without internal checking, provided it extends to the side surface of the board. Internal checking must precede collapse that is confined to the interior of the board. Internal checking, like collapse, is caused by water stress. Once internal checking occurs in a board this may be followed by collapse, but this is not inevitable. These theories presented by Booker (1994) were obtained by experimenting with radiata pine which is a softwood and may not be relevant to hardwood.

Chafe (1998) demonstrated that because internal checking was negatively related to density and positively related to moisture content, it was closely associated with collapse.

1.2.6 Collapse Prevention through Pretreatments

Collapse prevention through pretreatments of green sawn timber is the basis for the study established in this thesis. Work to minimise collapse through pretreatments concerns all factors which influence liquid surface tension, affect the strength of the wood, or alter its elastic properties, anatomical or chemical composition. Collapse pretreatments can be divided into two categories; physical and chemical pretreatments.

1.2.6.1 Physical Pretreatments

Gottstein and McCombe (1956) believed that heating green timber before drying would decrease collapse intensity. The study was performed on a green log of *E. delegatensis* and one of *E. obliqua*. Short cross sections were cut from the logs and cut into segments. The segments were subjected to several different preliminary heat treatments ranging from soaking in water at 21°C to steaming at 100°C for 48 hours. They were then air dried to EMC in the laboratory. It was observed that the preliminary heat treatments in both water and steam increased the severity of gross shrinkage (normal plus collapse shrinkage). The gross shrinkage was more than doubled by the heat treatment at 100°C.

From this work Gottstein and McCombe (1956) concluded that green sawn 'ash' eucalypt timbers must not be subjected to a heat treatment before drying and the heat incurred in the timber from the forest to the saw must be held at a minimum. Also reconditioning of these timbers should not be attempted until the MC is reduced to a

value sufficiently low to ensure avoidance of collapse caused by excessive temperature.

Choong et al. (1996) soaked six hardwood species in hot water for 10 hours at 70°C. The pretreatment was reported to have improved the movement of moisture above and below fibre saturation point. Choong et al. (1996) believes that the improvement in moisture movement during drying was due to the redistribution of water-soluble extractives in wood, which increases the accessibility of water in the cell walls.

Vermaas (2000) suggested hot water pre-soaking as a possible area of research at the FWPRDC hardwood sector-drying workshop.

Another physical pretreatment is pre-freezing of the timber. Wright (1967) pre-froze *E. regnans* at 0, -20, -78, and -194°C. When drying was completed, the results obtained showed that pre-freezing modified the drying behavior of the wood. The data suggested that by pre-freezing at -20°C the subsequent collapse was reduced by some 40%, and that by pre-freezing at -78°C collapse was reduced by about 50%.

Wright (1967) showed that prefreezing alone was not as effective as first anticipated in achieving a sawn product free of collapse; it is also clear, however, that pre-freezing considerably reduces the intensity of collapse development during the early stages of drying, and that this could well avert the risk of related checking at that stage. It was concluded that the cost of this sort of treatment and the size of equipment required meant that it was not economically viable.

Illic (1995) also investigated the effects of pre-freezing various species of hardwoods and softwoods at different temperatures for different time periods. Through his investigations Illic (1995) found that pre-freezing wood at -20°C seemed to be the most beneficial. He found that pretreatments need not exceed 12-24 hours. Illic (1995) stated that although pre-freezing produces marked reductions in shrinkage, collapse and drying degrade in heartwood of numerous softwood and hardwood species, a number of species do not respond in either drying rate or by a shrinkage reduction. Eucalypts respond with a moderate collapse reduction, but show little

improvement in internal checking, and as such, pre-freezing would seem to be of limited value.

Yang (1997) investigated the possibility of reducing collapse through the inducement of cell wall deformations in the wood of regrowth *E. regnans* prior to drying. Cell-wall deformations were induced by longitudinal compression which resulted in the physical dislocation of the cell wall. The compression treatment, however, had only a marginal effect on recoverable collapse, the total number of internal checks, and the total area of checking before reconditioning.

Schaffner (1981) developed a one-dimensional stress and drying model of timber. He used this model to assess the effectiveness of semi-permeable coatings on wood surface in reducing drying stresses. His work was performed on 80 25mm 2.1m long backsawn 'Tasmanian Oak' boards. Forty of the boards were coated and forty were uncoated. The coating consisted of animal glue (collagen), talcum powder and water in the proportions (by weight); 3.5 water : 1 dry animal glue crystals : 1.9 talcum powder. Schaffner (1981) found that application of this coating to board surfaces prior to drying at a thickness of 0.7mm (± 10%) was effective in reducing surface checking to an acceptable level for approximately 80% of coated material. He also discovered that the maximum tensile stress in the surface fibres of coated boards were only one third of the maximum surface stress in matched uncoated boards dried under the same atmospheric conditions.

Unfortunately, Schaffner's (1981) findings were not deemed economically viable due to the cost of the coating, and the additional costs of application and removal of the coating.

1.2.6.2 Chemical Pretreatments

When drying wood it is necessary to reduce the surface moisture concentrations thus setting up a mass concentration differential. If the moisture gradient becomes too severe, pronounced drying stresses develop which are likely to result in surface checking. Alternatively, the mass concentration differential may be lowered by a chemical treatment of the timber (Desch, 1953), thus making it possible to keep the gradient within safe limits during drying to help reduce the risk of surface checking. Chemical control of checking is obtained by introducing a water-soluble chemical into the surface layers of the wood.

Campbell (1959) suggests that to get the maximum benefit from chemical pretreatments, the timber must be in as green a condition as possible before treatment. Hence treatment should be carried out immediately after sawing. The chemical will not diffuse as freely into partly dried wood, neither can the treatment reverse the development of seasoning degrade which may already have occurred. Campbell (1959) also suggests different application methods for the chemical involved. He describes the spreading method, where the chemical is sandwiched between layers of timber forming a block pile and sufficient time given for the chemical to leach into the surface layers. Dipping, spray or brush treatments can also be used but Campbell (1959) states that the best results can be obtained by using a soaking process. This consists of soaking the material in a solution of the chemical. He suggests that 1-2 days, per 25mm of thickness, is sufficient to give the desired penetration in the surface layers.

Of the chemicals researched by Campbell (1959) the cheapest and most promising is sodium chloride (common table salt). It is reported to have small anti-shrink properties and suitable vapour pressure modification. Weeden (1980) states that sodium chloride has the disadvantages of being corrosive when the treated timber comes in contact with either steel cutters used in machining or with ferrous metal fastenings. It is understood that the Morton Salt Company of Chicago, U.S.A., has overcome this problem with their product known as Morton Lumber Cure, which is a salt mixture containing a corrosion inhibitor (Campbell, 1959). The timber also tends

to 'sweat' when in conditions above 75% relative humidity. The problem of sweating can be avoided by planing off the impregnated layer after seasoning (Weeden, 1980).

Mackay (1972) used Glycol methacrylate (GMA) monomer as a chemical pretreatment with the aim to obtain greater bulking of wood cell walls to improve long term dimensional stability of the material while gaining an improvement in strength. GMA was chosen for Mackey's study because of its miscibility with water. The hardness of the polymer is related to the amount of water present and can be reduced by the addition of polyethylene glycol (PEG) which causes the polymer to become more elastic and makes application easier. Test boards were brush coated with the polymer and then placed in a cabinet, flushed with nitrogen, and held in this atmosphere at around 20°C for 2 hours to allow full polymerisation. Subsequent examination showed the depth of penetration and polymerisation to be up to 2mm.

Surface treatment with GMA reduced the amount of checking in rough sawn boards by about 18% (Mackay, 1972). Mackay (1972) attributes its effect as being twofold, first a bulking action in reducing shrinkage to some extent, and secondly a strengthening action increasing resistance to tension stresses which occur during drying.

Bariska (1975) found that pretreating 80 year old beechwood with anhydrous ammonia (NH_3) severely increased the level of collapse in the dried product. This was attributed to the ammonia causing pores in the cell wall to completely close. The rate of total shrinkage was also dramatically increased due to large reductions in the size of cell lumina.

1.2.7 Collapse Prediction.

Prediction of the onset of collapse has been studied by various parties. The purpose of collapse prediction is primarily to avoid collapse during the seasoning process and to discard overly collapse prone material.

Illic and Chafe (1986) investigated the relationships between collapse and both depth of pin penetration, and electrical pulse resistance (EPR), using a Shigometer. This instrument employs a sliding hammer electrode holder fitted with two insulated pins spaced 25mm apart. The assessment was performed on boards from 118 trees of *E. delegatensis*. Results showed that collapse was highly significantly related to depth of penetration and significantly negatively related to EPR. The analysis demonstrated that depth of penetration measurements could provide an indication of collapse susceptibility. The analysis of collapse against penetration of the EPR did not provide a clear indication of collapse susceptibility.

Illic and Ellwood (1986) dried small predictor samples at 100°C and measured the resultant changes in their shape and area using an image processor. The measurements were expressed as a collapse factor (CF) and as volumetric shrinkage (VS), where:

$$CF = \frac{(\text{the perimeter of the cross section of board})^2}{\text{cross - sectional area of board}} \qquad (1.2.7.1)$$

and

$$VS = 1 - \frac{D}{G} \qquad (1.2.7.2)$$

where D = area of cross section (less the area occupied by internal checks)

G = area of green cross section.

The results of this study gave linear correlations, significant to 0.1%, between collapse in kiln dried boards and the CF and VS measurements made. The temperatures at which samples were kiln dried were not specified in the report.

Innes (1995) implemented a mathematical model to analyse the stress and strain in the walls of hardwood fibre (particularly Tasmanian eucalypts) with the aim of predicting the onset of collapse.

The fibre cells were modeled as thick walled cylinders, because eucalypt fibres are typically round with a ratio of outside diameter to wall thickness of 5:1. The length to diameter ratio of the fibre cells is typically of the order of 50:1 (Innes, 1995) so longitudinal effects were considered negligible. The model simulates the S1, S2, and S3 layers of the secondary fibre wall, each of which consists primarily of helically wound cellulose microfibrils (Siau 1984). The primary wall was neglected due to its random microfibril direction and small thickness. The model solves for the stress distribution through the cylinder wall from the inside to the outside.

The model demonstrated that the stresses and strains in the fibre cell wall are sensitive to changes of the order of 5°C. It also showed that the shrinkage of a fibre due to the removal of free water from the lumen is very small while the fibre retains its axial symmetry. Innes (1995) states that the model can be used together with measurement of collapse prone timbers to determine conditions which will avoid collapse during seasoning.

After further investigations in 1996, Innes discovered that the best way of avoiding collapse and collapse checking is to dry at temperatures below the 'collapse threshold temperature' (CTT) of both the earlywood and latewood until all parts of the wood are below FSP. This may not be feasible when using conventional drying for timbers which have a CTT of less than around 10-15°C due to the difficulty in maintaining kiln temperatures below ambient.

1.3 Reconditioning

Reconditioning is the term used to describe the treatment which permanently restores the regular size and profile of collapsed timber. It can reduce or remove collapse but has no effect on any normal shrinkage that has taken place. Although reconditioning can remove collapse it does not remove collapse induced checking.

1.3.1 Theory of Reconditioning

Reconditioning was first used by James and George Grant in 1917 as mentioned in section 1.2.1. The generally accepted theory of reconditioning by Greenhill (1938) postulates that there are two main structural layers in the cell wall. One of these remains elastic under normal conditions, whereas the other one is inelastic and may hold the first in a distorted condition. Under the influence of heat, the second layer is rendered plastic and allows the elastic energy stored in the first to expand the cell back to its original shape unless there have been local physical failures.

Although the elastic and inelastic layers have not yet been clearly identified, Kaumann (1965) suggests that the elastic layer may be located in the innermost layer of the secondary wall (S3 layer) and the inelastic layer is located in the amorphous lignin and hemicellulose incrustations of the primary wall. Conversely, Wardrop and Dadswell (1955) state that lignin increases the elasticity of the cell wall.

Greenhill's (1938) data suggests that the rate of recovery depends largely on the rate of penetration of heat into the wood. However, at each temperature, recovery proceeds to a definite point beyond which it will not increase, even if the treatment is prolonged.

1.3.2 Reconditioning process

The reconditioning process favoured by the Tasmanian hardwood timber industry consists of exposure of the timber to saturated steam at 100°C for 4 to 6 hours in the case of 25mm stock and, 6 to 12 hours for 50mm stock (Anon 1942). The treatment is undertaken in a 'reconditioning chamber' which is essentially a brick or concrete shell of suitable size, source of saturated steam running along the bottom.

For best results, the core M.C. of the timber should be just below F.S.P. before reconditioning. If the timber is not dry enough the reconditioning treatment is likely to intensify collapse in the core zone. If dried below approximately 12% MC, prior to

reconditioning, collapse recovery may not be complete. C.S.I.R.O. (revised 1982) suggests that in practice, between 18 and 20% average MC is considered the best stage to recondition. Normal reconditioning increases the average MC by about 2 to 3% after the stack has cooled down, but the redrying time after reconditioning is not excessive.

C.S.I.R.O. (revised 1982) states research has shown that the amount of recovery gradually increases with increase in steaming temperature (at saturated conditions) from about 70°C up to 100°C. Recovery will still increase from 100°C to 130°C but not enough to be economically beneficial in terms of having to steam in a pressure vessel. Any further increases in temperature have shown collapse recovery to be reduced.

1.4 Critical Summary

As a result of the findings of chapter two, chapter three of this thesis is concerned with the prevention of collapse of regrowth *E. obliqua* through the use of pretreatments. Three pretreatments were used based on; positive results recorded by other researchers given in the literature review presented in this chapter, and availability and cost of each process.

They are:

1. Hot water soaking as suggested by Vermaas (2000) and Choong et al. (1996).

2. Saturated salt (NaCl) solution soaking of boards described by Campbell (1959).

3. Block stacking green boards with a sandwich of salt (NaCl) between the layers again suggested by Campbell (1959).

Chapter 2. Monitoring the KilnSched Program for Drying Regrowth *Eucalyptus obliqua*

2.1 Introduction

The initial aim of this research was to optimise pre-drying schedules for 25mm thick regrowth *Eucalyptus obliqua* using the KilnSched scheduling program (see 2.2.3.2). The rationale for focussing on pre-drying is that the time taken to dry to fibre saturation is typically several weeks (kiln drying) or months (air drying), whereas final drying can easily and safely be achieved within 48 hours. The majority of drying degrade occurs at moisture contents above fibre saturation.

The first part of this experiment involved daily measurement of moisture profiles during trials in the $1m^3$ research kiln located at the University of Tasmania in order to accurately determine the deviation of KilnSched from measured behaviour. From trials performed with the research kiln at the Killafaddy site it is clearly evident that the average moisture content of the timber decreases more rapidly in the first two to three weeks of drying than KilnSched predicts. After this period the drying closely follows the model. The problem appears to be in the modelling of the drying occurring at the surface of the boards, rather than the moisture movement within the boards.

In the past KilnSched has successfully been used to produce drying schedules for old growth material. However the model has been far from successful when used to generate drying schedules for regrowth material. It has been noted in the last few years, from trials performed by Michael Lee and the University of Tasmania, that a great deal of the regrowth eucalypt material seasoned commercially is harder to dry without degrade than its old growth equivalent. Therefore age and growth rate may cause differences in the level of seasoning difficulty through altered timber drying variables such as collapse susceptibility, shrinkage, diffusion coefficient and strength.

Also, the eucalypt material logged today comes from a wider range of areas, altitudes and climates than ever before.

The second part of the experiment was to investigate the variation of collapse threshold temperature during pre-drying. The results were expected to create an improved scheduling system that would increase the dry bulb temperature with decreasing moisture content through drying, thus decreasing drying time.

Collapse threshold temperatures measured in the second part of the experiment were below the achievable range of testing. Therefore another trial was conducted to find the exact collapse threshold temperature of the material.

2.2 Apparatus

The following equipment was utilised for the investigations undertaken in this trial.

2.2.1 Experimental Timber Kiln

C. Purdon and the Tasmanian Timber Promotion Board in conjunction with the Department of Mechanical Engineering, University of Tasmania originally designed the timber kiln used in this trial in 1980. Minor modifications have been made since 1980 including lengthening of the kiln, conversion from steam to water spray humidification, and improved control through the use of the Clever Kiln Control (CKC) program (see 2.2.2). The kiln (see figure 2.1) was built because it was necessary to study timber seasoning on a larger scale.

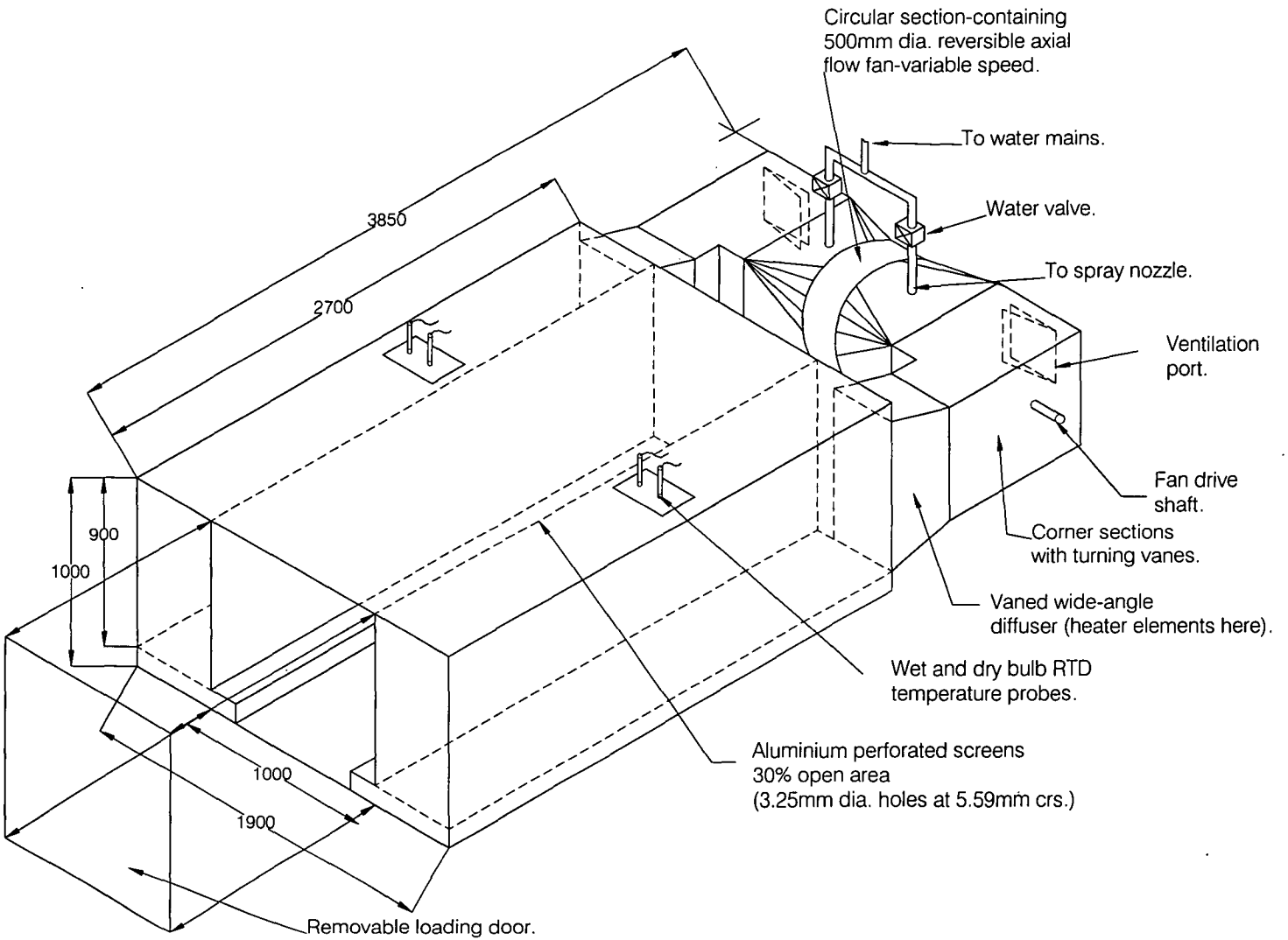

Figure 2.1 - Experimental Timber Kiln

The kiln chamber which houses the racked timber for drying has dimensions 1m × 1m × 2.7m which gives a working section drying capacity of approximately $1m^3$ of timber. A reversible, 500mm-diameter axial flow fan driven by a 750-watt variable speed motor circulates airflow. The kiln is constructed of aluminium sheet over a steel frame and is covered with 50mm of rock wool insulation backed with reflective foil.

Kiln temperature and humidity is measured by two sets of wet and dry bulb PT100 resistance-temperature devices (RTD's). These are located on either side of the kiln stack (see figure 2.1) so temperature and humidity can be controlled from measurements obtained on either the air inlet, air outlet or an average of both sides of the stack. An external RTD was used to measure the ambient temperature surrounding the kiln (not shown in figure 2.1).

Heating is provided by two 1500-watt finned-tube electric heating elements. These are housed in the vaned wide-angled diffuser sections on one side of the kiln.

Humidity is increased by two Acme PJ12 water spray nozzles connected to the mains water supply. The nozzles provide 50% of spray droplets with diameters of less than 50μm.

Whereas the heaters and sprays are dedicated to heat and humidity control alone, the vents are used in a supervisory manner to 'fine tune' dry bulb temperature and humidity (see equation 2.2.2).

Racked timber is loaded into the kiln using a hydraulic pallet lifter.

2.2.2 Kiln Hardware and Control

The heaters, vents and sprays are controlled with 0-10V DC signals, initially supplied from the analogue output channels of a Boston Technology PC30B A/D board in a personal computer. An amplification stage is used to buffer the A/D board from the kiln hardware. The computer used was an IBM compatible 486/Dx66 running the CKC program under WINDOWS 3.1.

Heating of the kiln air is controlled by a SCR (Silicon- Control-Rectifier) unit. Humidification is controlled with a pulse-width modulated signal proportional to the required spray setting.

Standard Proportional Integral Derivative (PID) control algorithms are employed to control the kiln conditions. The control task is complicated by two facts. Firstly, two input variables are measured (dry bulb temperature (DBT) and wet bulb temperature (WBT)) and three output variables are required to control the kiln (Heaters, Sprays and Vents). Secondly, the DBT and WBT are coupled, so poor DBT control will be manifested directly as poor WBT control, no matter how sound the WBT control algorithm is. Thus DBT and relative humidity were selected as control variables and controlled independently with separate PID algorithms. The critical output state in DBT control is the heaters whilst the relative humidity is controlled by the sprays. The vents are controlled separately with a proportional control algorithm described below. The vent is used as a relative humidity 'fine tuner' and to lower the DBT in the event of a sudden DBT increase. Each PID algorithm uses the current error in process variable, the previous error and the error prior to the previous error. The PID algorithm is based on central difference differentiation and trapezoidal integration. The DBT algorithm is as follows:

$$u_k = u_{k-1} + (K_p + \frac{K_i T}{2} + \frac{K_d}{T})e_k - (K_p + \frac{2K_d}{T} - \frac{K_i T}{2})e_{k-1} + \frac{K_d}{T}e_{k-2} \qquad (2.2.1)$$

where:

e_k = the k^{th} error equal to (DBT set point$_k$ - DBT$_k$).

u_k = the k^{th} output state (heater setting).

K_p = proportional gain

K_i = integral gain

K_d = differential gain

The relative humidity algorithm incorporates the same algorithm but DBT errors are replaced with relative humidity errors and the output state corresponds to the spray setting.

The values of K_p, K_i, K_d are adjusted by the kiln operator to optimise the kiln transient response and steady state control. The relative gain values are totally dependent on the particular kiln in operation.

The vent error function is based on differences in the relative humidity between readings. That is,

$$error = currentRH - setpointRH \tag{2.2.2}$$

and

$$u_k = u_{k-1} + (error)K_v \tag{2.2.3}$$

where

u_k = the k^{th} output state (vent setting)

K_v = proportional vent gain.

2.2.3 Clever Kiln Controller® (CKC)

The University of Tasmania has been active in timber seasoning research since the early 1980's when Richard Schaffner was sponsored by the Tasmanian Timber Promotion Board to do a Masters degree under the supervision of Associate Professor Peter Doe. Work focused on developing a computer model that would predict the stresses in hardwood timber during seasoning. Emeritus Professor Arch Oliver built on Schaffner's work to write a program called DRYWOOD from which KilnSched (Kiln Scheduling Program) was subsequently developed.

As a result of a three year collaborative grant a kiln controller (the Clever Kiln Controller® or CKC) was developed. The CKC is an online modelling and acoustic emission (AE) monitoring program.

2.2.3.1 Modes of Operation

The CKC operates in one of three distinct modes, each mode incorporating additional optimisation functionality. The basic 'Schedule Setpoint mode' is a simple PID feedback control system that maintains kiln temperatures at preset setpoint temperatures in a time based schedule defined by the user. In 'AE (acoustic emission) mode', the DBT is held constant while the WBT is varied in response to AE readings. In 'SmartKiln mode', CKC develops an optimum schedule with SMARTKILN (discussed in 2.2.3.2). When the AE rate exceeds the control value, the AE controller immediately determines new setpoint temperatures to prevent surface checking. The basic 'Schedule Setpoint mode' was used by the author for this section of research.

2.2.3.2 Online Drying Simulation Programs

The kiln dry and wet bulb temperatures are datalogged every 15 seconds for the duration of drying. This data is averaged every 4 minutes and the processed temperatures are referred to as the Historical Kiln Conditions (HKC).

Three online drying programs are employed in CKC : KilnSched, MCPROFILES and SMARTKILN.

KilnSched is the drying simulation program used in this study. It is based on a non linear stress and drying model developed by Oliver (1991). KilnSched models one-dimensional flow of heat and mass from the board centre to the air stream over a board's wide surfaces. Strictly KilnSched should be restricted to wholly backsawn or quartersawn material cut far from the centre of the tree. KilnSched models the development of the boundary layer across a board at the centre of a kiln stack to

calculate the heat and mass transfer at the board surface. Wu (1989) determined that drying of Tasmanian eucalypts was adequately described by Fick's Law:

$$\frac{\partial q}{\partial t} = D\frac{\partial^2 q}{\partial y^2} \qquad (2.2.4)$$

where q is moisture concentration (kg/m^3), and D is diffusion co-efficient (m^2/hour). KilnSched employs a single reference diffusion coefficient dependent on temperature but independent of moisture content and stress. KilnSched also utilises a non linear stress-strain curve based on numerous laboratory compression and bending tests (Oliver 1991). In the model, the directly measurable net strain is given as the sum of the unconfined shrinkage strain, instantaneous strain, creep strain and the mechano-sorptive strain.

The unconfined shrinkage strain is that shrinkage measured on a specimen sufficiently thin to be considered at uniform moisture content and restrained from distortion out of the specimen plane. The instantaneous strain is the immediate change of strain resulting from a change of applied stress and thus is equivalent to the strain measured in a short-term loading test. The failure criterion at which surface checking is taken to occur used in KilnSched is an instantaneous strain of 0.02. This value was determined on laboratory tests on old growth *E. regnans* by Schaffner (1981). Creep strain is the progressive strain which occurs under applied stress at constant moisture content. It is a function of time, stress and temperature but independent of moisture content as long as the moisture content remains constant. The mechano-sorptive strain is the extra strain occurring during moisture content changes under applied stress.

KilnSched allows the operator to develop a 'safe' schedule during the early stages of drying, when limited material properties have been obtained. These material properties are as follows: basic density, unconfined shrinkage at FSP, unconfined shrinkage at EMC, FSP, EMC, diffusion coefficient, rack stick spacing, board width, board thickness, control strain and collapse threshold temperature. The schedule is applied to the green timber.

MCPROFILES is employed to determine the material diffusion coefficient. MCPROFILES simulates the development of moisture profiles during drying. Moisture profiles are measured at regular intervals during the drying process using the slicing technique (see appendix A2). MCPROFILES uses the HKC to calculate moisture distribution development with an arbitrary 'trial' diffusion coefficient. The user visually compares the calculated and measured moisture profiles and adjusts the diffusion coefficient by trial and error until a satisfactory fit between calculated and measured drying behaviour is obtained. This process takes 3-4 slicings at 24 hour intervals including an initial 'green' slicing. The operator refines the diffusion coefficient value each time a new profile is measured.

SMARTKILN (Booker, 1994) is a program based on KilnSched which generates a continuously varying schedule that maximises drying rate whilst holding the surface instantaneous strain at a 'safe' level.

2.2.4 Timber Slicer

A purpose-built timber slicer (Figure 2.2) was used for measurements of both unconfined shrinkage and moisture profile (see appendices A2 and A4 for these procedures). It was used to cut thin wafers from cross section blocks. It consists of a sharp blade from a hand plane operated by a lever. The sample was sliced by clamping and feeding it forward under the plane blade.

2.2.5 Travelling Microscope

A travelling microscope was used to measure unconfined shrinkage in both the tangential and radial directions of sliced samples (see Appendix A4 for a detailed description of this procedure). Figure 2.3 depicts a shrinkage specimen in a wire bridle and the travelling microscope.

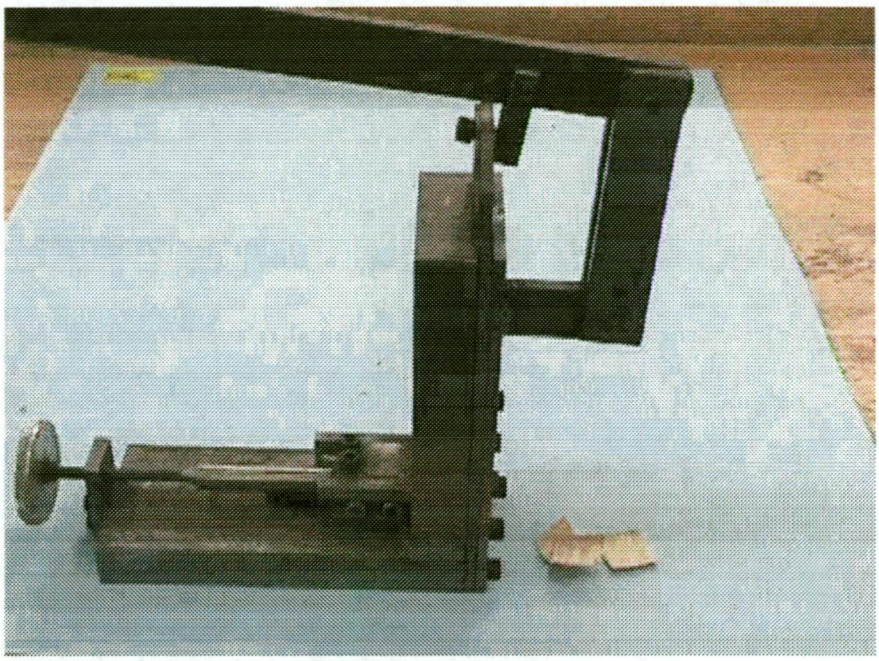

Figure 2.2 - Timber Slicer,

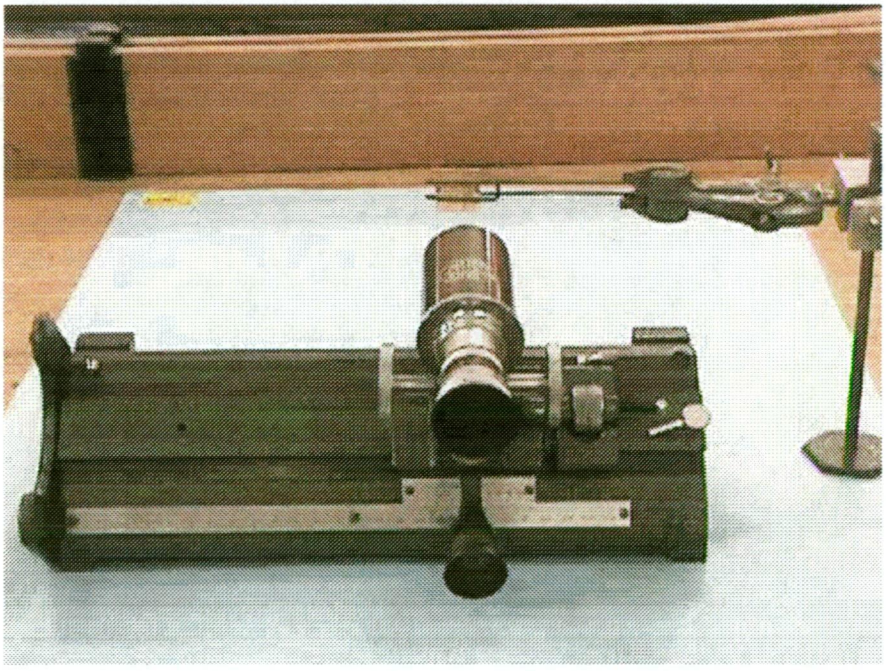

Figure 2.3 - Travelling Microscope.

2.2.6 Collapse Chambers and Data Acquisition

Collapse threshold temperature measurements require a controlled temperature vented environment. Three collapse chambers were built by this author and the appropriate data acquisition and control equipment was utilised to achieve these requirements.

Figure 2.4 shows a schematic drawing of one of the collapse chambers and the associated data acquisition and control equipment. The body of the chamber was made from 10mm plywood. The lid was hinged at one end of the chamber and fixed down with two latches on the opposite side. A strip of foam window sealant was used around the lid's edge to prevent air flow and venting through the lid. The inside of the chamber was lined with roofing foil for insulation purposes. Samples sat on the sample shelf (also made from 10mm plywood) on their edge with the length of the samples running parallel to the chamber's length. The shelf was able to hold thirty 28 × 100 × 125 mm samples.

Heating was provided using two 85W carbon filament heater bulbs connected to the mains power supply. A small 12V DC computer fan was used to maintain steady air flow circulation throughout the chamber. The air flow was measured at 0.3m/s. Two 10mm diameter holes provided ventilation. Dry bulb temperature was measured using a standard PT100 RTD probe.

The temperature inside the chamber was controlled using a DT500 datataker and a laptop PC running the appropriate software. The temperature was controlled by a simple on/off relay system with 0°C deadband. Measurements were made every 5 seconds.

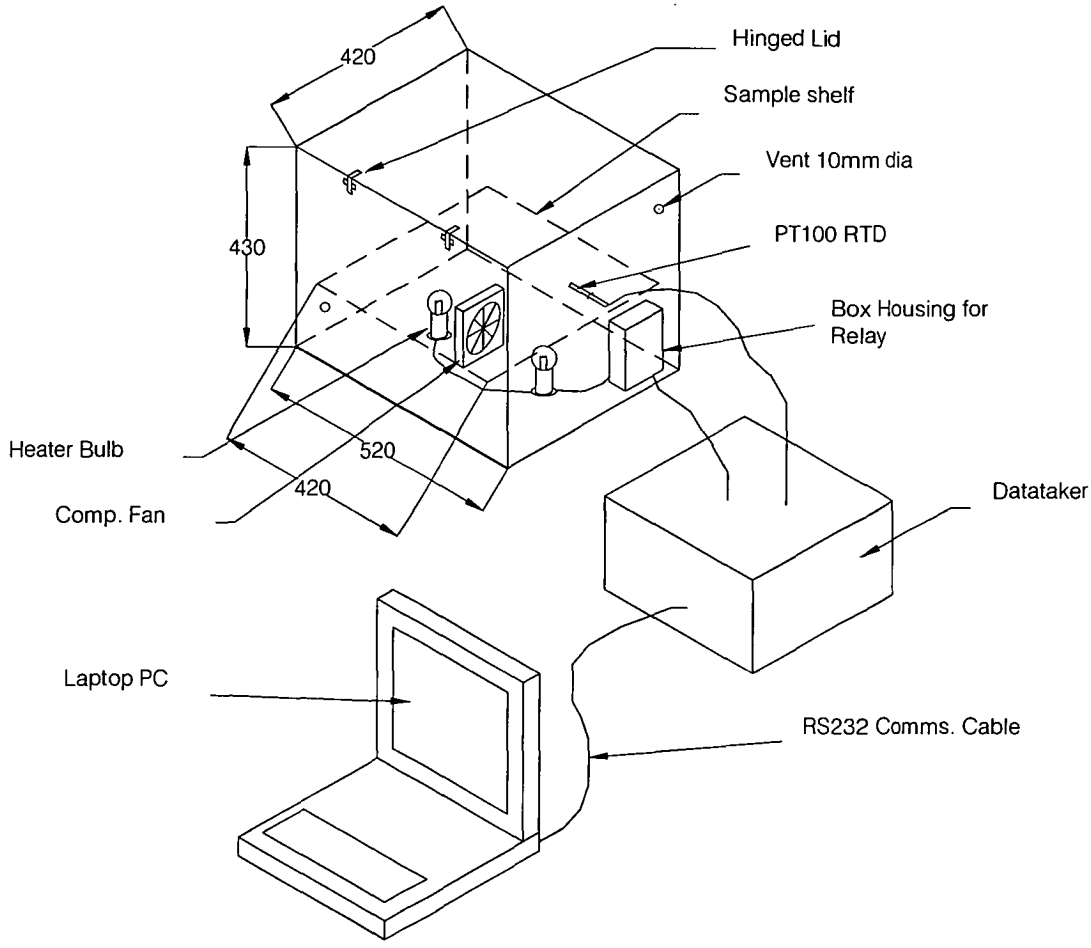

Figure 2.4 - Collapse chamber and associated control devices.

2.3 Equipment Calibration (Experimental Timber Kiln)

Each of the temperature probes were calibrated to ± 0.1 °C using a temperature standard.

The CKC program incorporates a fan speed controller output. It is common practice in the Tasmanian hardwood industry to kiln dry stock with a constant air flow through the racked timber of 0.5m/s because it provides a good compromise between drying

speed and degrade with reasonable DBT control. Therefore 0.5m/s of air flow was the desired airflow through the rack of timber in the experimental kiln.

Air flow measurements were taken in the central vertical plane of the plenum starting 20mm from the top and every 100mm thereafter to 720mm (20mm from the bottom). Measurements were repeated for CKC fan speeds of 60, 40, 30, and 20%. The resulting air velocities are shown in table 2.1.

	Distance from top of plenum (mm).							
	X1	X2	X3	X4	X5	X6	X7	X8
CKC Air Speed (%)	20	120	220	320	420	520	620	720
60	3	2.1	2.1	1.9	2	1.7	1.5	1.6
40	1.7	1.3	1.2	1.3	1.2	0.9	0.9	1.2
30	1.4	0.9	0.9	0.9	0.9	0.8	0.6	1.1
20	0.8	0.6	0.5	0.5	0.5	0.6	0.6	0.6

Table 2.1 - Plenum air velocity m/s.

The average volumetric air flow through the plenum was calculated using equation 2.3.1.

$$V_{plenum} = \left(V_1 \times \left[\frac{x_2 - x_1}{2} + x_1\right] \times y\right) + \left(\sum_{i=1}^{6} V_i \times (x_{i+1} - x_i) \times y\right) + \left(V_8 \times \left[\frac{x_8 - x_7}{2} + x_1\right] \times y\right)$$

(2.3.1)

where V_{plenum} = average volumetric air flow through the plenum (m^3/s),

$V_1 \rightarrow V_8$ = Velocity measured at $x_1 \rightarrow x_8$ respectively (m/s^2),

$x_1 \rightarrow x_8$ = Distance from top of plenum (m),

y = plenum width (in this case y = 0.47m).

The average estimated air velocity through the timber rack was calculated by dividing the plenum volumetric air flows by the area of air flow through the rack face.

The area of the rack face open to air flow is: Area = 0.64125 m^2.

$$A_{flow} = V_{plenum} / \text{Area} \qquad (2.3.2)$$

The estimated air flow through the rack values for each of the CKC air speed settings is shown in table 2.2.

CKC Air Speed (%)	Plenum Vol. Air Flow (m^3/s)	Estimated Stack Air Vel. (m/s)
60	0.68	1.06
40	0.42	0.65
30	0.32	0.49
20	0.20	0.31

Table 2.2 - Estimated air velocity through rack.

These results show that for a CKC setting of 30% the average air flow through the racked timber is 0.49m/s. This value is close enough to the 0.5 m/s value required. The fan speed was set at 30% for the duration of this trial.

2.4 Methodology

2.4.1 Sample Preparation (Racking)

Sixty 135 × 28mm back sawn and one hundred and eighteen 100 × 28mm quarter sawn 5.1m length boards of *E. obliqua* were milled by Boral Board Mills - Western Junction. The timber was sawn from naturally regenerated regrowth logs courtesy of Forestry Tasmania - Huon Division. All boards met the select criteria as defined by AS2796.2: 1985. The boards were block packed and fully wrapped in plastic to prevent the boards from drying. The pack was wrapped in impermeable plastic wrap and then transported to Boral Board Mills - Killafaddy.

Each board was graded for end split and surface checking and then cut in half to an approximate length of 2.5m. A 0.1m length section was removed from the centre of the boards and immediately tested for initial average moisture content and basic

density (see appendices A1 and A3). Upon completion of docking, the boards were all end coated with Log Keote 732. The boards were re-packed and wrapped before being transported to the trial kiln site at the University of Tasmania - Launceston.

The timber was racked as shown in figure 2.5. The bottom four rows of the rack each consisted of seven 100 × 28mm quarter sawn boards equally spaced to give a rack width of 750mm. The following seven rows each contained four 135 × 28mm back sawn and two 100 × 28mm quarter sawn boards placed together to maintain a rack width of 750 mm.

The top four rows were again made up of seven 100 × 28mm quarter sawn boards. The 100 × 28mm quarter sawn boards were chosen as they were used for moisture meter correction data generation for *E. obliqua*. (See Chapter 4). Each row of boards were separated by five equally spaced rack sticks (approximately 625mm apart) as shown in figure 2.5. The rack sticks were dressed to 19 × 50 × 750mm. The overall dimensions of the entire stack were approximately 690 × 750 × 2500mm.

During the racking process six 135 × 28mm samples were chosen to be used as test samples. The samples chosen were as free of imperfections (such as knots, spiral grain, rot etc.) as possible. Each board was clearly labelled from A to F.

The six samples were then cut to a length of 1700mm. The remaining 800mm lengths were discarded.

A length of 500mm was docked from the freshly sawn end of each 1700mm board and given the same label as the board from which it was sawn. The freshly sawn ends were marked for both the 500mm and 1200mm samples. Both ends of the 1200mm samples were coated in Log Keote 732. One face of the 1200mm and 500mm samples was marked 'top'. The 500mm samples were wrapped in plastic to prevent them from drying.

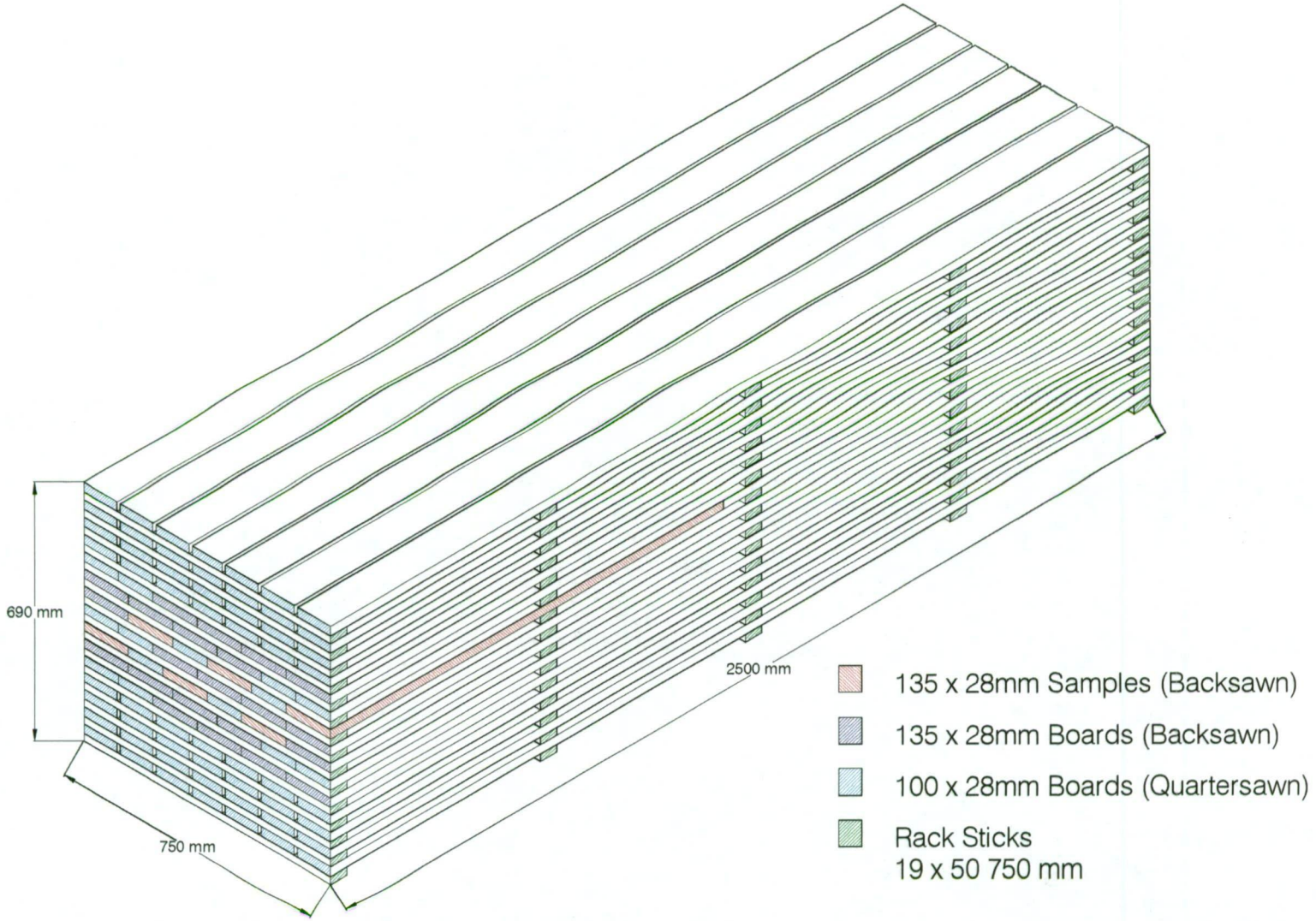

Figure 2.5-Kiln rack formation used to monitor the first two weeks of drying

The 1200mm sample boards were placed in the rack at the positions as indicated by figure 2.5. Six 135 × 28mm boards were cut to a length of 1300mm and were used to butt up against the 1200mm sample boards to make up a whole (2500mm) board length. The sample boards were orientated so that the end which had the 500mm section removed was inside the stack and the face marked 'top' faced upwards.

Notches were cut into the rack sticks above the six samples so that the samples could be easily removed from the end of the stack for testing.

2.4.2 Initial Measurement of Sample Properties.

Procedures A1 to A5 (appendix A) were employed to determine initial properties of timber samples. The methodologies included procedures to determine average MC, moisture profile, basic density, tangential and radial shrinkage, and collapse threshold temperature. Average MC and basic density values were measured on the 0.1m length cross sections taken from all of the boards while the other properties were measured on the six 500mm long sample boards cut from the larger 1200mm samples during racking.

Immediately following racking the 500mm samples were removed from the plastic wrap and cut to different lengths for the measurement of the initial timber properties. Figure 2.6 shows the length of sections cut and which property was to be measured for each section.

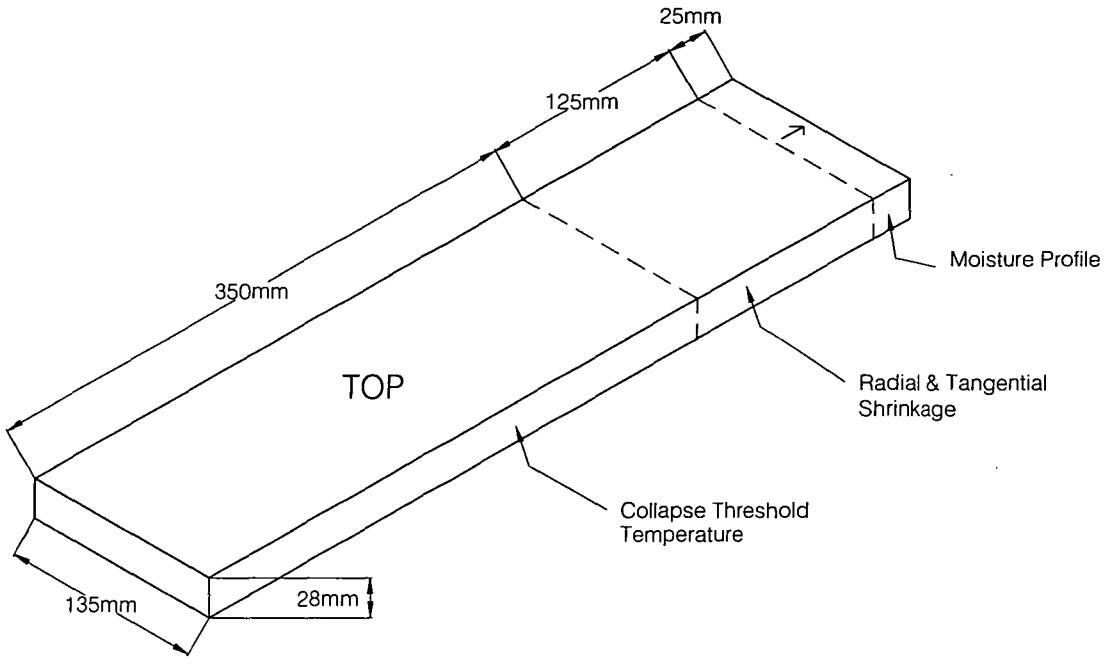

Figure 2.6 - 500mm long sample showing initial property sections.

Note from the diagram that the section to be used to measure the initial moisture profile of the sample comes from the marked end (arrow) sawn from the end of the 1200mm sample. Following the commencement of drying further profiles were measured daily from the marked end of the 1200mm sample in order to minimise the effect of MC variation along the board length.

The sections sawn from the 500mm sample were sealed in plastic bags and the procedures in appendices A2, A4 and A5 were employed to measure moisture profile, tangential and radial shrinkage, and collapse threshold temperature.

For the collapse threshold temperature measurements the 350mm sections were cut further into seven 50mm sections each of which was end coated and labelled according to the label on the 350mm section (i.e. A, B, C, D, E, or F). This differs from the method given in A5 that suggests using 150mm long sections. Smaller test lengths were used due to limitations in kiln size. Initially three of the 50mm sections were chosen for each sample and placed in one of the three constant temperature boxes set at 22°C, 24°C and 26°C respectively.

2.4.3 Monitoring the First 2-3 Weeks of Drying.

Initially the kiln was set to control the dry and wet bulb temperatures at 20°C and 19°C respectively giving a relative humidity of 91.5%. Drying below 20°C was not practicable because of higher ambient temperatures. A 1°C wet bulb depression is the smallest depression that the kiln can accurately control.

Moisture profiles of samples A - F were taken daily for the first nine days. Approximately 40mm were cut from the inside end of each board for testing and the board was then replaced in the same orientation in the stack following end-coating. Using the first 5 daily moisture profiles the diffusion coefficient was calculated using MCPROFILES (see 2.2.3.2). Once the diffusion coefficients were estimated, along with previous variables measured, KilnSched was employed to produce a drying schedule based on boards of the backsawn grain orientation.

Further moisture profiles were taken from samples A-F after days eleven, thirteen, fifteen, seventeen and twenty. The kiln was turned off after 21 days and each face of each board was scored for signs of collapse and surface checking.

2.4.4 Repeated Collapse Threshold Temperature Measurements

Collapse threshold temperature measurements were repeated on a further six boards after the three week drying trial was complete. This is because the collapse threshold temperatures measured in 2.4.2 were below the ambient temperature of the laboratory, therefore exact collapse threshold temperatures could not be obtained. To overcome this problem the three constant temperature controlled chambers were placed in a chemical storage cool room. The cool room was controlled at a constant temperature of 3°C. The material used was from the same source as for the three week drying trial. The timber was previously wrapped in impermeable plastic to prevent surface drying.

2.5 Results and Analysis

2.5.1 Grading Results

After sawing, each board was graded for end split, surface checking and quality. Appendix B1 shows this measured data of which the following results were obtained:

	# Quarter Sawn Boards	Percentage of Total (%)	# Back Sawn Boards	Percentage of Total (%)
Total	114	100	60	100
Select	71	62.3	21	52.9
Standard	34	29.8	21	31.6
Utility	9	7.9	18	15.5
End Split	11	9.6	53	91.7

Table 2.3 - Grade quality results.

	Quarter Sawn	Back Sawn
% End Split of Total Length	0.6	16
Average End Split (m)	0.3	0.8
End Split Range (m)	0.5 to 0.1	0.1 to 2.5

Table 2.4 - End split results.

The grade quality results (table 2.3) for both the quartersawn and backsawn boards are similar which is not surprising considering the boards were sawn from the same logs.

Initial end split after sawing was more prevalent in the backsawn boards. The average end split length for quartersawn boards was less than that for backsawn boards. The backsawn boards displayed a greater value for the end split of the total length than the quartersawn boards.

There was no evidence of initial surface checking on any of the boards.

2.5.2 MC and Basic Density Results

Upon grading, each board was immediately tested for average moisture content and basic density. The measured data is shown in appendix B2. Results determined from these are given in table 2.5.

	M.C.Results	Basic Density Results
Average	83.6 %	602.8 kg/m3
Minimum	54.8 %	474.9 kg/m3
Maximum	114.8 %	715.9 kg/m3
% Witihin ± 10% of Ave.	51.7 %	79.8 %
% Witihin ± 5% of Ave.	27.5 %	50.6 %

Table 2.5 - MC and Basic Density Results

These results indicate that less deviation from the average exists for the basic density values than for MC.

2.5.3 Tangential and Radial Shrinkage Results

Normal tangential and radial shrinkages were measured at FSP and EMC for the six samples labelled A to F. Radial and tangential shrinkage curves are given in Appendix B3.1 and B3.2 respectively. Tables 2.6 and 2.7 display the shrinkage results obtained from the shrinkage curves. Negative shrinkage values are a result of experimental error.

Sample	FSP (%)	% Shrinkage	EMC (%)	% Shrinkage
A	30	0.2	10	5.5
B	30	0	9	5.6
C	30	0	10	7.8
D	25	0	8	7.1
E	30	0	9	5.7
F	35	0.2	9	5.8
AVERAGE	30	0.1	9	6.3

Table 2.6 - Radial Shrinkage results.

Sample	FSP (%)	% Shrinkage	EMC (%)	% Shrinkage
A	35	0.5	11	8.6
B	35	1	10	9.3
C	35	1	10	9.2
D	35	1	10.5	8.5
E	35	0.8	10.5	8.8
F	35	0.4	11	9.7
AVERAGE	35	0.8	10.5	9.0

Table 2.7 - Tangential Shrinkage results.

2.5.4 Collapse Threshold Temperature Results

The collapse threshold temperatures of samples A to F were each measured initially at 26°C, 24°C, 22°C, 20°C and 18°C.

Each of the samples showed signs of collapse at each of the temperatures tested. At the time the tests took place, testing for collapse threshold temperature below 18°C was not possible due to the laboratory ambient temperatures at the time of the year. Therefore it was not possible to find the collapse threshold temperatures for these samples. Usually the starting temperature of the kiln drying schedule is governed by the collapse threshold temperature. (i.e. set 1 or 2 degrees lower than the collapse threshold temperature). In this case the starting temperature of the kiln was made as low as practicable (20°C).

After the three week drying trial further collapse threshold temperatures were measured from six boards derived from the original source. Three of the boards had collapse threshold temperatures of 10°C, two of 7°C whilst the remaining sample collapsed at 4°C.

2.5.5 Moisture Profile Results

Moisture profiles were taken daily from samples A - F for the first 9 days of drying and then on days eleven, thirteen, fifteen, seventeen and twenty. Moisture profile graphs for each sample showing each profile recorded are given in appendix B5.

2.5.6 Diffusion Coefficient and Scheduling Results

Moisture profiles from the first five days drying were used in conjunction with MCPROFILES (see 2.2.3.2.) to calculate diffusion coefficients for each sample. For each sample (A to F) the diffusion coefficient was estimated at 1×10^{-7} m^2/hour.

Once the diffusion coefficient values were obtained KilnSched was employed to produce a 'safe' drying schedule. The schedule predicted only one change in kiln conditions over the three weeks of kiln drying. This was to lower the wet bulb temperature from 19°C to 18.5°C after nine days. The dry bulb temperature did not change from 20°C throughout the drying process. Thus after nine days the relative humidity inside the kiln was reduced from 91.5% to 87.4%.

2.5.7 Drying Rate Comparison

Using the KilnSched simulation data, the simulated drying rate in terms of core moisture content versus time was compared with the actual drying rate derived from

the average core moisture contents of the moisture profile samples. The results are shown graphically in figure 2.7.

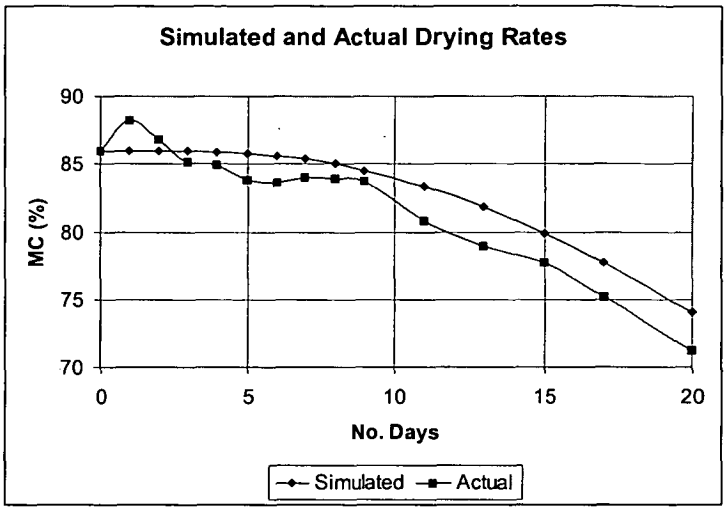

Figure 2.7 – Drying rate comparison.

2.5.8 Final Surface Checking and Collapse Results

After the three week drying period each board was removed and scored for evidence of collapse and surface checking. Appendix B5 contains the measured data. Of the 68 quartersawn boards scored, 62% showed signs of surface checking and 56% were checked on both faces. 90% of the quartersawn boards were collapsed. Of the 22 backsawn boards scored, 91% showed signs of surface checking and 83% were checked on both faces. 100% of these boards were collapsed.

2.6 Conclusions

Previous regrowth backsawn drying trials conducted for the Forest and Forest Industries Council (FFIC) produced poorer grade recovery figures for green sawn boards than measured for this trial. The increased amount of select grade measured in this trial can be attributed to log selection. Logs selected were of above average

quality and as free from end split, knots, gum vein and other imperfections as possible.

The end split recovery results were consistent with previous trials conducted. The results show that the length and occurrence of end splitting in backsawn boards was significantly greater then that for the quartersawn boards. The mechanism which controls the difference in levels of end split between backsawn and quartersawn boards is unknown, however the greater level of tangential shrinkage measured compared with radial shrinkage may explain this mechanism.

Average moisture content, basic density and shrinkage values were consistent with data measured from previous trials on Tasmanian regrowth eucalypt material. The most alarming results however were the collapse threshold temperature measurements. Although the exact collapse threshold temperature values were unknown, they were known to be below 18°C. Due to ambient conditions the kiln could not accurately control below a dry bulb temperature of 20°C. This was obviously above the collapse threshold temperature.

After the three week drying period the result of drying above the collapse threshold temperature was evident. The levels of degrade through surface checking were unsatisfactorily high for both the quartersawn and backsawn board orientations. It was noted that the severity of surface checking was related to the severity of collapse. The small number of quartersawn boards that did not collapse showed no sign of surface checking.

After the three week drying trial subsequent collapse threshold temperatures were measured on six boards. The results showed that half of the boards collapsed at a maximum threshold temperature of 10°C. These low collapse threshold temperatures correlated with the severity of collapse measured in the three week drying trial.

From previous trials, it is evident that the drying rate of the timber decreases more rapidly in the first two to three weeks of drying than KilnSched predicts. This held true for this trial (see figure 2.7).

Overall the levels of collapse and surface checking, after three weeks of drying under the mildest possible conditions available, were extremely high. Therefore the following chapter is concerned with reducing the levels of degrade from collapse-induced checking through pretreatment regimes on green sawn boards.

Chapter 3. Drying after Pretreatment Regimes

3.1 Introduction

Due to the low collapse threshold temperatures measured for regrowth *E. obliqua* in the previous chapter, this section of work was aimed at reducing the severity of collapse, surface and internal checking of this timber after drying. To achieve this objective, three pretreatments were performed on green regrowth *E. obliqua* before the commencement of drying.

The regimes include two chemical pretreatments of green sawn boards involving sodium chloride (table salt), and a physical pretreatment involving presoaking green logs in hot water. The pretreatments are based on those given by Cambell (1959), Weeden (1980) and Gottstein and McCombe (1956). The major consideration for choosing these pretreatments over others was the low cost involved. Sodium chloride is inexpensive compared with other chemical alternatives and presoaking is also a low cost pretreatment compared with other physical pretreatments such as prefreezing (Wright, 1967 and Illic 1995)

3.2 Apparatus

The investigations undertaken in this chapter employed the following equipment.

3.2.1 Drying Kiln

A larger experimental drying kiln was used for this section of research than the one used in chapter 2. The larger kiln was required to dry all of the timber for this research simultaneously.

The kiln was originally built for the Tasmanian timber industry in 1997 specifically to carry out research into the seasoning of backsawn regrowth eucalypts. The kiln is a conventional overhead fan, steam heated unit typical of those used in the Tasmanian industry.

The kiln shell and base are constructed of pre-cast concrete panels with silica magnesium slag in the aggregate. The structure is approximately 7.5m long x 4.8m wide and 4m high on a concrete slab base 0.65m thick. The unit has one 3.2m high x 3m wide aluminum door that is fully sealed and insulated with rock-wool, with three hinge points and one slide bar locking mechanism (container style locking mechanism - see figure 3.1). Inlet and outlet humidity and over temperature control vents are located on the side walls.

The unit has a complete high pressure steam heating system including a main steam shut off valve, associated steam line, dual pressure reducing valve set, a safety valve set, air bleeds on each line, two 12mm control valves, and two 50mm isolating valves. Four steam heat exchangers and two full sets of condensate returns are used consisting of two indicators, two strainers, two water traps, two sight glasses, and four isolating valves.

The air circulation system consists of six aluminum 1.2m diameter fans with associated shrouds and baffle plates. Six sets of 5kw motors (externally fitted), shafts and stands are controlled by one variable speed drive.

Wet and dry bulb temperatures are measured at eight points in the kiln using sixteen PT100 RTD's with eight water baths and external filling tanks for the wet bulb wicks.

The kiln is controlled by a PC running Honeywell Scan3000 software on a UNIX platform.

Figure 3.1 is a photograph of the kiln showing the front end with the door open. The kiln is loaded using an electrically driven traverse which runs along the rails shown at the bottom of figure 3.1.

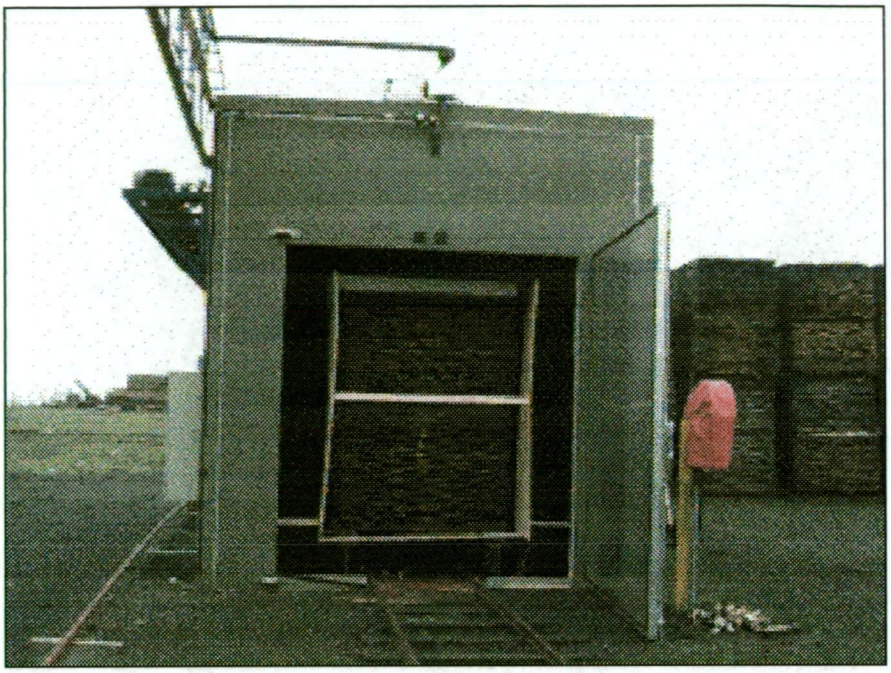

Figure 3.1 - Experimental kiln.

3.2.2 Pretreatment Regimes

The salt solution regime involved soaking green boards in a saturated NaCl solution. The boards were placed in a 660 × 660 × 2640mm open topped container. The container was made from 4mm steel. Approximately 300 litres of water was placed inside the container. 140kg of coarse salt was mixed with the water to produce a saturated solution.

Coarse salt was also used for the salt hessian regime. Hessian fabric was used to wrap the pretreated pack.

Timber from the presoaked regime was sawn from logs that were presoaked in water at 45°C. The presoaking took place in a 3.5m long water bath located at Gunns Veneers - Somerset.

3.3 Methodology

3.3.1 Green Sawing

Two hundred 100 × 28mm backsawn boards of *E. obliqua* were milled by Boral Board Mills - Western Junction. The timber was sawn from naturally regenerated regrowth logs courtesy of Forestry Tasmania - Huon Division. The logs each had an average mid diameter of 450mm. Two of the logs had been presoaked (see 3.3.2) prior to sawing. All boards met the select criteria as defined by AS2796.2: 1985. The boards were block packed and fully wrapped in plastic to prevent the boards from drying. The pack was then transported to Tasmanian Board Mills - Killafaddy.

3.3.2 Pre Treatment Regimes, Controls & Preparation

3.3.2.1 Salt Solution Regime

This pretreatment regime utilised fifty 5.1m length boards. All boards were back sawn having dimensions of 100 × 28mm. Each board was graded for end split and quality as defined by AS2796.2: 1985. This regime consisted of one pretreatment block stack and one control block stack containing fifty 2.5m length boards each. This was obtained by cutting the 5.1m lengths in half. The 5.1m length boards were all individually numbered at each end. Prefixes A and B were given to the numbers at each end of each board. Once the boards were halved they were sorted into two groups numbered with the A and B prefix respectively. Boards numbered with an A prefix were used for the salt solution regime and those numbered with the B prefix were used as control boards. The regime pack and its corresponding control pack

were racked in the same orientation according to the board numbers. Thus direct end result comparisons could be made. The control and pre-treatment packs were stacked 5 boards wide × 10 boards high.

The control pack was stacked, end coated and plastic wrapped. The pretreatment pack was not wrapped but was fully immersed in a bath, consisting of water and dissolved sodium chloride (table salt), for nine weeks. Enough salt was used to create a saturated salt solution.

3.3.2.2 Hessian Regime

Fifty 5.1m length backsawn boards were used for this regime. A 2.5m length pretreatment pack and corresponding control pack were graded, cut and labeled as for the previous regime (3.3.2.1). The pretreatment pack was stacked 5 boards wide × 10 boards high with a layer of coarse sea salt applied between each row of boards. The boards were end coated then fully wrapped in hessian fabric. A salt layer was also present between the hessian layer and the timber on the top and bottom rows. Finally the pack was hosed down so that the hessian was fully saturated. The control pack was stacked in the same labeled order as the pretreatment pack. Both packs were stored undercover for nine weeks as for regime 3.3.2.1.

3.3.2.3 Pre-Soaked Logs

Boards used for this regime were sawn from three 3m long logs pre-soaked in hot water for 72 hours at 45 °C. Approximately equal numbers of boards were selected from each to obtain fifty 3m length boards. The boards were block stacked, end coated in Log Keote and fully wrapped in an impermeable plastic wrap. A control stack was not present for this regime as the log was pretreated before it was sawn. The packs were stored undercover for nine weeks until kiln drying.

3.3.3 Sampling and Testing

The boards were stacked according to the regimes 3.3.2.1 - 3.3.2.3. Five 500mm length test sections were sawn from five sample boards for each regime and control pack. The test sections were removed from each of the six packs from the second, third and fourth top rows at the positions shown in figure 3.2.

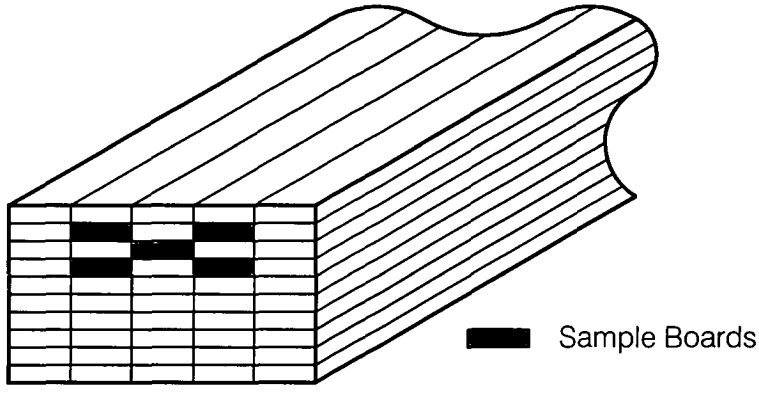

Figure 3.2 - Sample board positions.

The test sections were given the same labels as the boards from which they were cut. Note that due to the racking process the sample boards for the regime packs and corresponding control packs were from the same original 5.1m length board. The sample boards removed for docking were all re-end coated at the freshly sawn ends and replaced in the appropriate pack in the same orientation. In order to fill the gaps left by removal of the samples, 500mm green end coated sections (obtained from left over green sawn 5.1m length boards) were used as a buffer upon re packing. For the hessian regime pack, fresh salt was reapplied to the surfaces of the sample boards upon repacking. The control packs and regime packs were all repacked according to the three regimes except the hessian covering was not re-wet.

The 25 500mm test sections were all end coated at the sawn ends and wrapped in impermeable plastic until testing.

Test sections were measured for moisture profile, average MC, and collapse threshold temperature in that order as soon as practically possible (see appendix A for methodologies). Approximately 25mm was removed from the coated ends of each board and discarded. Two 25mm length strips were used to determine both the moisture profile and average MC of the boards. The remaining 400mm section was cut into five 80mm lengths, each of which was end coated and plastic wrapped in preparation to determine the collapse threshold temperature (see appendix A5).

After a three week period the sampling procedure was repeated for each of the four packs from regimes 3.3.2.1 and 3.3.2.2. The only exception was that the buffer boards were replaced by 1m end coated sections to fill the gaps caused by further sampling. Sampling was not repeated for the pre-soaked regime as the boards were already pretreated upon stacking.

The sampling procedure was again repeated after a further three weeks, and buffer boards of 1.5 m were used upon repacking.

A further three weeks was allowed and the sampling procedure repeated for a final time. At this stage the pretreatments for the salt solution and hessian regimes continued for nine weeks.

3.3.4 Kiln Drying

The boards from each of the regime and control packs were racked randomly and kiln dried in the Killafaddy kiln at initial dry and wet bulb temperatures of 22°C and 20.5°C respectively. The air flow velocity through the stack was approximately 0.5m/s and the air flow direction was reversed every four hours. Five 500mm samples were taken at the centre of one board from each of the three regime packs and the two control packs. These boards were randomly placed at the side of the rack for easy removal. These sample boards were used to monitor the progress of drying by

measuring their average moisture contents. The predrying process took 58 days to dry the boards to FSP. The boards were reconditioned before final drying. The reconditioning schedule consisted of a two hour ramp up to 98°C, then four hours at 98°C under saturated conditions. The boards were final dried to EMC after 6 days at a dry bulb temperature of 70°C and a wet bulb temperature of 55°C. The drying schedule used is shown in table 3.1.

No. of Days	DBT (deg C)	WBT (deg C)	Air Velocity (m/s)
0	22	20.5	0.5
7	22	20	0.5
14	23	20.5	0.5
21	23	20	0.5
28	23	20	0.5
35	24	19.5	0.5
42	24	19	0.5
49	24	19	0.5
58	24	19	0.5
58 D, 4 hours	98	98	0.5
64D, 4 hours	70	55	0.5

Table 3.1 - drying Schedule

3.3.5 Grading

Visual grading for surface checking and collapse was performed on every board for the three regimes and their corresponding control boards once the stack was dried to FSP. As the boards were still rough sawn accurate quantitative measurements of the severity of surface checking and collapse was deemed impractical. Instead, surface checking and collapse were recorded on a 'yes/no' basis regardless of the severity. This process was performed on each face of each board.

The boards were then reconditioned and final dried following the schedule given in table 3.1.

At this stage each board had been final dried, reconditioned and had a nominal rough sawn thickness of 28mm. Each board was then reduced to 25mm thickness by removing an equal thickness off each face using an electric feed planer. As the boards

exhibited a smooth surface finish, the length of surface checking was measured for each face of each board rather than on a 'yes/no' basis. The face exhibiting the greatest percentage of surface checking was also noted according to the growth ring orientation. That is, the worst case checking occurs either on the inner (closest to pith) or the outer board face (closest to bark) for backsawn boards.

The boards were then planed down further to a thickness of 22mm by removing 1.5mm from each face. Surface check measurements were repeated as for the 25mm planed boards. The process was again repeated for a board thickness of 19mm. This process allows the measurement of surface checking penetration depth.

3.3.6 Final Measurements

After each board was graded for surface checking they were cut into 5 equal lengths. Each section from each board was numbered according to the original board number and each sawn end was labeled 'a' to 'd' from one end of each board to the other. Each sawn end was inspected for internal checking to see if any of the pre-treatments used affected the levels of internal checking. Internal check measurements for each saw cut (a to d) from every board, included; the number of internal checks occurring over the cross sectional area, the width of the widest growth ring where checking occurred and the number of growth rings where checking was present.

Finally a 25mm length section was sawn from the centre section from each board (cut b-c). This was used to determine the final dry density and EMC of each board. These procedures are given in appendices A3 and A1 respectively where the green volume in A3 is replaced by the EMC volume to give dry density.

3.4 Results and Analysis

3.4.1 Grading Results

After green sawing, each board was graded for end split, surface checking and quality (as defined by AS2796.2: 1985). Appendix C1 shows this measured data of which the following summarised results were obtained:

	# of Boards	Percentage of Total
Total	100	-
Select	23	23
Standard	42	42
Utility	35	35

Table 3.2 - Grade quality results.

% End Split of Total # of Boards	90
% End Split of Total Length	8.6
Average End Split (m)	0.43
End Split Range (m)	0.05 to 0.8

Table 3.3 - End split results.

Comparing the grade quality results given in table 3.2 with those from the previous trial (see table 2.3) indicates that the logs sawn for this trial were of a lower quality. This is evident from the lower percentage of select boards graded (23% cf. 52.9%) and hence the higher percentages of standard and utility grades. The percentage of utility boards graded was approximately twice that for timber graded for the previous trial (35% cf. 15.5%).

The percentage end split of the total length and the average end split values measured for the boards in this trial were approximately half that of the figures given in table 2.4 previously (8.6% cf. 16%, 0.43m cf. 0.8m respectively).

3.4.2 Progressive Moisture Content Profile Results

Appendix C2 contains moisture content profile graphs for each of the 5 sample boards taken from the salt/hessian and salt solution regime and control packs. Each graph contains four profiles for each sample taken initially and after three, six and nine weeks.

The surface moisture content of samples belonging to both the salt solution and salt/hessian regimes showed a marked decrease over the nine week period compared with their corresponding control samples. Profiles from the salt solution regime showed a larger decrease in MC after the first 0-3 week period than the salt/hessian regime and the control packs.

3.4.3 Progressive Average Moisture Content and Basic Density Results

Progressive average moisture contents and basic density values were measured over the 9 week pretreatment period from test samples belonging to the salt/hessian and salt solution regime and control packs, as explained in section 3.3.3. These results are given in appendix C3.3. A graphical representation of these results is given in figures 3.3 - 3.10.

Average moisture content and basic density measurements were taken from five samples for the presoaked regime prior to kiln drying. These measurements are given in appendix C3.4.

Figures 3.3 - 3.6 indicate a greater decrease of MC from week 0-3 for the salt/hessian and salt solution regime samples compared with subsequent weeks and their corresponding control samples, which were relatively unchanged. The average decrease in MC as a percentage of the initial MC from weeks 0-3 for the salt/hessian

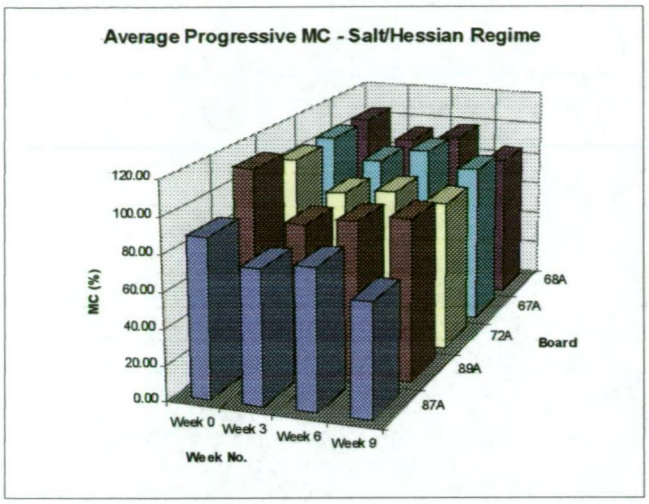

Figure 3.3 - Average progressive M.C. - Salt/Hessian Regime

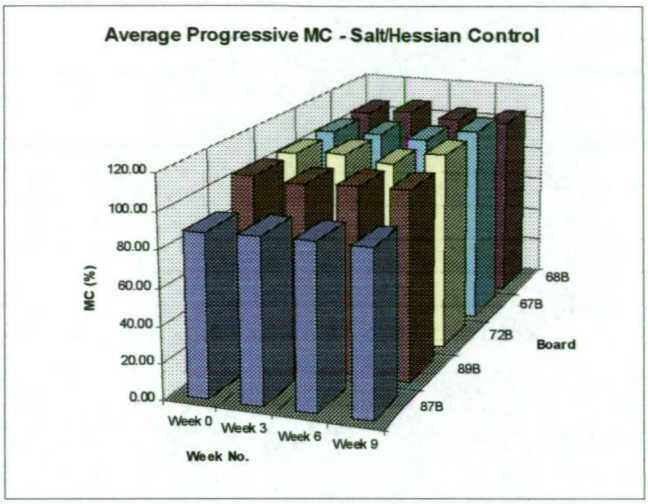

Figure 3.4 - Average progressive M.C. - Salt/Hessian Control

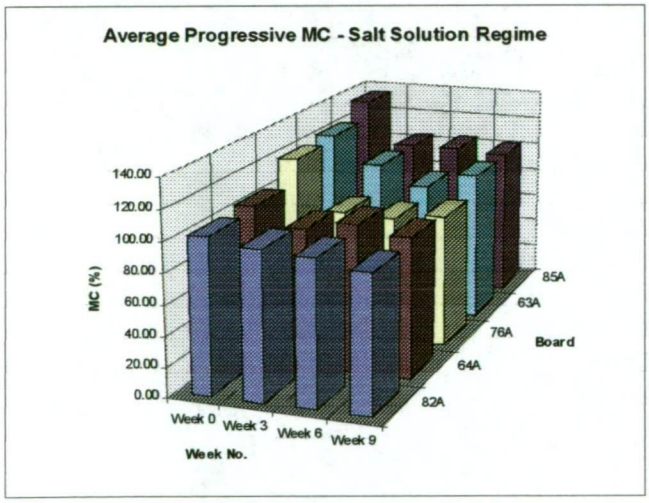

Figure 3.5 - Average progressive M.C. - Salt Solution Regime

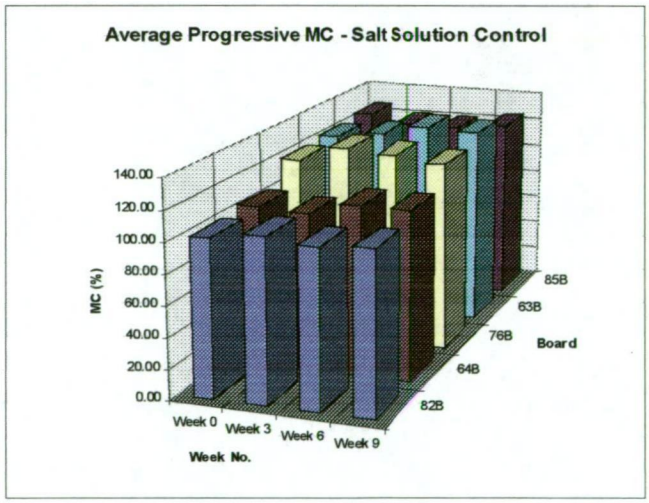

Figure 3.6 - Average progressive M.C. – Salt Solution Control

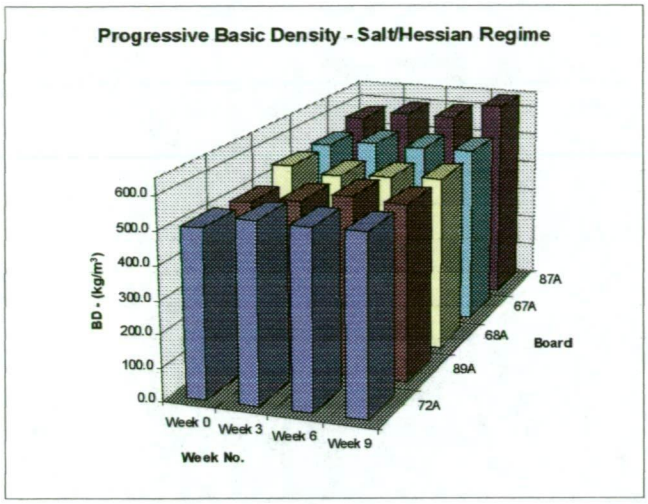

Figure 3.7 - Progressive Basic Density - Salt/Hessian Regime

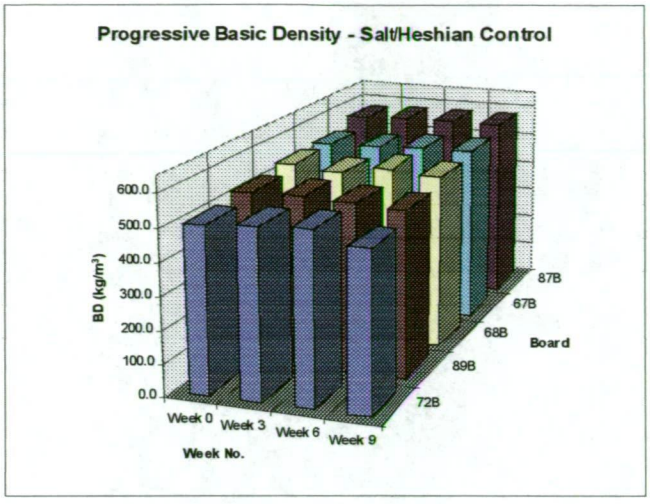

Figure 3.8 - Progressive Basic Density - Salt/Hessian Control

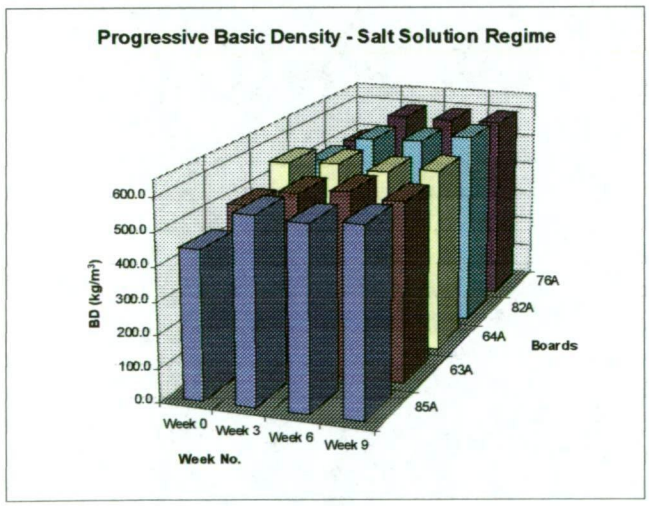

Figure 3.9 - Progressive Basic Density - Salt Solution Regime

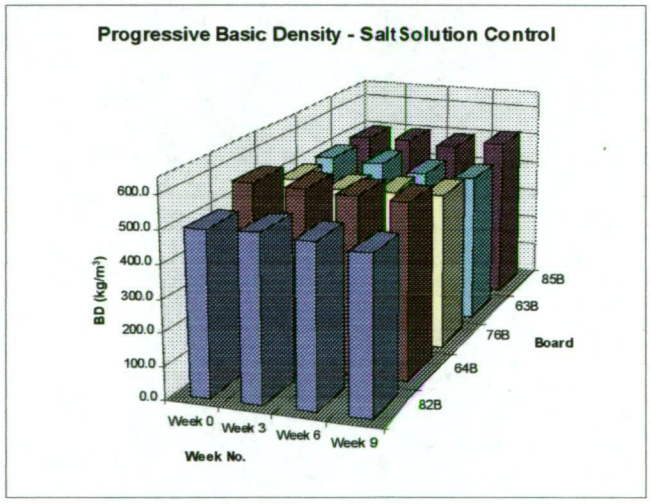

Figure 3.10 - Progressive Basic Density - Salt Solution Control

and salt solution regime samples were 16.1% and 16.6% respectively. The corresponding control sample values were 0.4% and 2.1% respectively.

Conversely the basic densities increased for the regime samples compared with their corresponding controls in the 0-3 week period.

This suggests that most of the affect of the salt pretreatments occur in the 0-3 week period, and the water in the surfaces of the boards is being replaced by the salt.

3.4.4 Progressive Collapse Threshold Temperature Results

Progressive collapse threshold temperature values were measured over 9 weeks from test samples belonging to the salt/hessian and salt solution regime and control packs as explained in section 3.3.3. As the presoaked regime occurred over 3 days in week 0 the collapse threshold temperature measurements for this regime were measured at the end of week nine prior to kiln drying. The resulting collapse threshold temperatures measured at 0, 3, 6, and 9 weeks are given in table 3.4.

The average collapse threshold temperature results given in table 3.3 display a significant increase (7°C to 15.8°C) for the salt solution regime, through weeks 0 - 6, compared with the other regimes and control packs (ranging from 6.8°C to 8°C). At this stage the salt solution regime is the most effective at increasing the collapse threshold temperature.

		Collapse Threshold Temp. (degrees C)			
Regime/Control Pack	Sample #	Week 0	Week 3	Week 6	Week9
Salt/Hessian Regime	63B	7	8	8	8
	64B	7	8	8	8
	76B	7	8	6	6
	82B	7	8	6	6
	85B	7	7	6	6
	Average	7	7.8	6.8	6.8
Salt/Hessian Control	63	7	7	8	8
	64	7	8	8	8
	76	7	8	6	6
	82	7	8	6	6
	85	7	7	6	6
	Average	7	7.6	6.8	6.8
Salt Solution Regime	67B	7	10	17	17
	68B	7	8	14	14
	72B	7	8	17	17
	87B	7	10	17	17
	89B	7	8	14	14
	Average	7	8.8	15.8	15.8
Salt Solution Control	67	7	8	9	9
	68	7	8	9	9
	72	7	8	8	8
	87	7	10	8	8
	89	7	8	6	6
	Average	7	8.4	8	8
Presoaked Regime	101	-	-	-	6
	102	-	-	-	8
	103	-	-	-	6
	104	-	-	-	7
	105	-	-	-	7
	Average	-	-	-	6.8

Table 3.4 - Progressive Collapse Threshold Temperature Results

3.4.5 Pre-Reconditioning Visual Grading

Visual grading for surface checking and collapse was performed on every board (yes/no basis) for the three regimes and their corresponding control boards once the stack was dried to FSP as explained in section 3.3.5. The complete set of these results is given in appendix C4. These results were further analysed to find the percentage of

collapse free, check free and clear boards free of both surface checking and collapse (table 3.5).

	% Collapse Free			% Check Free			% Clear
Regime/Control Pack	Side 1	Side 2	Both Sides	Side 1	Side 2	Both Sides	Both Sides
Salt/Hessian Regime	37.8	37.8	22.2	46.7	37.8	31.1	11.1
Salt/Hessian Control	25.6	18.6	7.0	30.2	23.3	20.9	0.0
Salt Solution Regime	4.7	2.3	2.3	2.3	0.0	0.0	0.0
Salt Solution Control	31.1	28.9	8.9	22.2	17.8	13.3	2.2
Presoaked Regime	22.7	26.7	11.4	43.2	31.8	25.0	4.5

Table 3.5 - Progressive collapse and surface checking results.

As the boards at this stage were rough sawn, for practical reasons the results were measured visually on a yes/no basis. Therefore the results in table 3.5 are a measure of the number of boards exhibiting any collapse and surface checking and not a measure of collapse and surface checking severity.

On the basis of the percentage of boards free of collapse and surface checking and the overall percentage of clear boards, the salt/hessian regime produced the most favorable results. 22.2% of the salt/hessian regime boards were collapse free on both sides. This is approximately double that of the next highest; the presoaked regime. In all cases the salt solution regime displayed the least favorable results compared with the other regimes and controls. The salt solution regime did not contain any boards free from both collapse and surface checking.

3.4.6 Final Dried Checking Penetration Results

The checking length and collapse for each board was measured for each regime and control after the boards had been dressed to 25mm, 22mm, and 19mm as explained in section 3.3.5. These results are given in appendix C5. The percentage of overall board length exhibiting surface checking for each regime and control at each dressed board thickness was obtained from the results and is given in table 3.6. Table 3.7 shows the percentage of unchecked board faces on the upside, downside and both sides for each

regime and control pack. A rank sum test was performed on the raw data to compare the regimes and control packs to find if the results were statistically significantly different. The results of this analysis are given in table 3.8.

	Percentage of Overall Board Length Checked (%)								
Pack	Up side 25mm	Down Side 25mm	Both Sides 25mm	Up side 22mm	Down Side 22mm	Both Sides 22mm	Up side 19mm	Down Side 19mm	Both Sides 19mm
Salt Solution Regime	30	40	35	18	24	21	13	16	15
Salt Solution Control	57	66	61	33	37	35	19	22	21
Slt/Hessian Regime	54	56	55	27	22	24	17	7	12
Salt/Hessian Control	36	35	36	24	20	22	14	11	12
Presoaked Regime	43	64	53	26	17	21	15	7	11

Figure Table 3.6 - Percentage of overall board length checked.

	Percentage of Unchecked Board Faces (%)								
Pack	Up side 25mm	Down Side 25mm	Both Sides 25mm	Up side 22mm	Down Side 22mm	Both Sides 22mm	Up side 19mm	Down Side 19mm	Both Sides 19mm
Salt Solution Regime	31.1	26.7	17.8	40.0	31.1	28.9	55.6	42.2	37.8
Salt Solution Control	11.6	2.3	2.3	25.6	27.9	16.3	30.2	39.5	23.3
Slt/Hessian Regime	16.3	7.0	7.0	39.5	39.5	34.9	48.8	58.1	44.2
Salt/Hessian Control	18.2	13.6	2.3	36.4	50.0	31.8	40.9	56.8	38.6
Presoaked Regime	9.5	4.8	0.0	40.5	45.2	31.0	69.0	78.6	61.9

Table 3.7 - Percentage of unchecked board faces.

Pack Comparison	Salt Solution vs Salt Solution Control		Salt/Hessian vs Salt/Hessian Control		Salt Solution vs Salt/Hessian	
Checking Length	Significantly Different ?	P Value	Significantly Different ?	P Value	Significantly Different ?	P Value
Up Side 25mm	Yes	< 0.001	No	0.240	Yes	0.005
Down Side 25mm	Yes	< 0.001	No	0.083	Yes	0.024
Up Side 22mm	Yes	0.042	No	0.929	No	0.372
Down Side 22mm	No	0.141	No	0.680	No	0.231
Up Side 19mm	No	0.103	No	0.812	No	0.507
Down Side 19mm	No	0.467	No	0.763	No	0.093

Pack Comparison	Salt Solution vs Presoaked		Salt/Hessian vs Presoaked	
Checking Length	Significantly Different ?	P Value	Significantly Different ?	P Value
Up Side 25mm	Yes	0.015	No	0.933
Down Side 25mm	Yes	< 0.001	Yes	0.007
Up Side 22mm	No	0.483	No	0.909
Down Side 22mm	No	0.174	No	0.722
Up Side 19mm	No	0.313	No	0.127
Down Side 19mm	Yes	0.012	No	0.182

Table 3.8 - Rank Sum significance test results.

Every board was measured for signs of collapse from each regime and control pack. Not one board displayed evidence of collapse shrinkage after the boards had been reconditioned and dressed to a thickness of 25mm.

Of the three pretreatment regimes, boards derived from the salt solution regime possessed the smallest percentage of overall board length surface checked on both sides at a dressed thickness of 25mm (35% compared with 55% and 53%, see table 3.6). These figures (both sides at 25mm) also show that the salt solution regime contains almost half the percentage of overall board surface checking compared to the salt solution control boards. Conversely the salt/hessian regime's percentage of overall board length exhibiting surface checking at 25mm both sides was 19% greater than the salt/hessian control boards.

The percentage of overall board length surface checking results at a dressed thickness of 19mm both sides for each regime and control pack are more even than at a dressed thickness of 25mm. The salt solution regime value was still less than it's control pack (15% compared with 21%) at 19mm. The salt/hessian regime value was the same as the corresponding control pack (12%) and the presoaked regime value was still the lowest (11%).

The primary objective of this chapter was to increase the amount of dried boards free of surface checking and collapse shrinkage through pretreating green boards. As no collapse shrinkage was evident after the boards were dressed to a thickness of 25mm the percentage of unchecked faces data (table 3.7) is a direct measure of totally clear boards for each regime and control pack at each dressed thickness. The figures pertaining to the percentage of unchecked faces on both sides are very important as these relate to the amount of boards totally free of surface checking and collapse.

At a dressed thickness of 25mm the salt solution regime produced the most desirable level of unchecked board faces on both sides at 17.8%. The corresponding control pack for this regime produced only 2.3% of boards free from surface checking on both faces. Similarly the salt/hessian control pack produced the same figure (2.3%). The

salt/hessian regime was the next best regime at this stage in terms of surface check free recovery (7%). 0% of presoaked boards ware check free on both faces at a dressed thickness of 25mm.

However, at a dressed thickness of 19mm 61.9% of presoaked boards were surface check free on both sides. This figure is significantly greater than the salt solution and salt/hessian regimes values which were 37.8% and 44.2% respectively. Both of these salt regime values were higher than their corresponding control values which were 23.3 and 38.6 respectively.

At this stage the salt solution regime produced the most boards free of surface checks for a dressed thickness of 25mm while the presoaked regime did the same for a dressed thickness of 19mm.

3.4.7 Internal Checking Results

After each board was graded for surface checking they were cut into 5 equal lengths of which each cut section was inspected for internal checking as explained in section 3.3.6. The purpose of this exercise was to inspect each sawn end for internal checking to see if any of the pre-treatments used affected the levels of internal checking. Internal check measurements for each saw cut from every board, included; the number of internal checks occurring over the cross sectional area, the width of the widest growth ring where checking occurred and the number of growth rings where checking was present. These results are given in appendix C6.

Pack	Percentage of Boards Containing Internal Checks (%)	Number of Internal Checks Measured
Salt Solution Regime	48.9	501
Salt Solution Control	23.3	169
Slt/Hessian Regime	7.0	11
Salt/Hessian Control	13.6	30
Presoaked Regime	2.4	21

Table 3.9 - Internal checking analysis.

This data was analysed to find the percentage of boards containing internal checks and the total number of internal checks detected from each regime and control pack. These figures are shown in table 3.9. The results show that almost half (48.9%) of the salt solution regime boards contain internal checking. This is over twice the value obtained for the salt solution control pack (23.3%). The percentage of salt/hessian regime boards containing surface checking was considerably lower (7%) than both the salt solution regime and the salt/hessian control pack (13.6). The presoaked regime figure was by far the most favorable at only 2.4%.

3.4.8 Final Average MC and Dry Density Results

Final measurements were taken to determine the final dry density and EMC of each board. They can be seen in appendix C7 in the form of MC dry density histograms. The data was analysed to find the average, minimum and maximum MC and dry density values for each regime and control pack. These are given in table 3.10.

	Salt/Hessian Regime		Salt/Hessian Control		Salt Solution Regime		Salt Solution Control		Presoaked Regime	
	MC (%)	DD (kg/m^3)	MC (%)	DD (kg/m^3)	MC (%)	DD (kg/m^3)	MC (%)	DD (kg/m^3)	MC (%)	DD (kg/m^3)
Ave.	13.8	879.16	10.9	901.81	14.1	876.83	11.9	893.49	11.9	894
Min.	11.9	860.15	9.6	894.4	13.0	867.23	10.6	882.8	10.7	883
Max.	16.3	893.78	11.8	912.1	15.3	885.32	13.3	904.52	13.3	903

Table 3.10 - MC and dry density results.

The average MC values for both of the salt pretreatment regimes are 2-3% higher than the control packs and the presoaked regime. This is likely to be caused by the hygroscopic nature of salt assuming that salt permeation has penetrated to the 19mm thick core of the boards.

3.5 Conclusions

Logs sawn for this trial were of a poorer grade quality (see AS 2796.2:1985) than those logs sawn for the three week drying trial (chapter 2). This is evident from the lower percentage of select boards graded. Conversely, the average end split values measured for this trial were approximately half that from boards measured in chapter 2. These results display the large degree of variability that exists between eucalypt timbers sawn from the same species taken from the same area.

Progressive average MC results indicated a significant decrease in average MC for the salt/hessian and salt solution regime boards compared with their corresponding control packs, over the 0 -3 week period. This result was also found on the progressive moisture content profile graphs. This implies that the salt was responsible for the average MC decrease and its effect is greatest between weeks 0 and 3. The loss of MC over this period can be attributed to the salt diffusing into the surface of the boards (see 1.2.6.2 - Chemical pretreatments).

From the progressive collapse threshold temperature results, the salt solution regime was found to be the most effective at increasing the collapse threshold temperature. The other regimes did not significantly alter the collapse threshold temperature over the pretreatment period. The average collapse threshold temperature of the salt solution samples after the pretreatment period (15.8°C) was still below the ambient conditions for kiln drying.

Even though the collapse threshold temperature was increased by the salt solution regime, this regime possessed the least favorable pre-reconditioning surface check and collapse grading results. None of these boards were free of both surface checking and collapse at the pre-reconditioning stage. The salt solution/hessian regime displayed the best results having 11.1% of boards free of surface checking and collapse on both sides.

After the timber was reconditioned, final dried and dressed to a thickness of 25mm there was no sign of collapse shrinkage on any board. Surface checking penetration data showed the salt solution regime produced the most desirable percentage of unchecked board faces on both sides of 17.8%. The presoaked regime produced the least favorable results at a dressed thickness of 25mm with no boards free of surface checking on both faces. At a dressed thickness of 19mm however, 61.9% of the presoaked regime boards were check free on both sides. This figure was significantly greater than the other regimes. The salt regime values were higher than their corresponding control values, indicating an improvement in check free recovery due to the pretreatments. The increase in check free recovery for the presoaked regime from a dressed thickness of 25mm to 19mm indicates that the checks do not penetrate as deeply as for the other regimes even though boards from the presoaked regime at 25mm were all surface checked. This may be due to the presoaking reducing the level of internal stresses in the timber due to the heat treatment.

The severity of internal checking was greatly increased by the salt solution regime compared with its control (48.9% cf. 23.3%). Internal checking was slightly reduced by the salt/hessian regime. The level of internal checking for the presoaked regime was significantly less than the other regimes (2.4%). Again this may be attributed to reducing internal stress levels from the presoaking pretreatment.

Average EMC values for both the salt regimes were 2-3% higher than for the control packs and the presoaked regime. This may be attributed to the diffusion of the salt into the board surfaces of these regimes and the hygroscopic nature of salt.

Overall the presoaked regime was by far the best regime for increasing the levels of timber recovery through reducing degrade caused by internal checking and surface checking. The presoaked regime greatly reduced internal check and surface check levels at a dressed thickness of 19mm. Also, the EMC of the boards from this regime is comparable to the untreated control packs. As the salt regime's EMC values were considerably higher, possibly caused by introduction of salt into the surface layers, strength properties and corrosion of metallic foreign bodies introduced into the timber

may be affected. The presoaked regime is both practical industrially and inexpensive as it requires only water and heat. Also, corrosive chemicals are not involved.

3.6 Further Work

The following section describes further research which could be undertaken as an extension of the work discussed in this thesis.

- Repeating the presoaked pretreatment regime and using half of the logs for pretreating and the other half for control boards.

- Repeating the presoaked pretreatment regime and soaking logs for greater and shorter time lengths, and at different temperatures, to see if recovery values are improved.

- Investigations into the ultimate strain value given in KILNSCHED to see if it differs between old growth and regrowth.

Chapter 4. Moisture Meter Species Correction Determination for *E. obliqua*

4.1 Introduction

This chapter is a continuation of the moisture meter species correction work performed on *E. delegatensis* by Redman (1997).

As this work is a continuation from Redman (1997) the following review explaining certain aspects regarding this work has been extracted and summarised from Redman (1997).

4.2 Moisture Meters

A moisture meter is an electronic device used to measure the MC of wood by measuring one of the electrical properties of resistance, dielectric loss or capacitance (dielectric constant). Below about 25 to 30 % MC the electrical resistance of wood rapidly increases with decreasing MC whilst the capacitance and dielectric loss both decrease with a fall of MC.

Two types of moisture meters were used for this work, they are the resistance and capacitance type moisture meters.

4.2.1 Resistance Type Meters

Hand held electrical resistance type moisture meters are the most commonly used commercially. They operate by measuring the electrical resistance between two electrodes which are driven into the wood. The electrical resistance is then converted to a percentage MC and displayed either on an analogue dial or digital display. Three

electrode types exist for resistance type moisture meters. They are the blade, uninsulated pin and insulated pin types.

Blade type electrodes are strong and durable and are still used in areas of production, however they are not used commonly with hand held moisture meters. They measure only the lowest resistance or highest MC between the electrodes.

Insulated type electrodes on the other hand, can be used to measure moisture gradients throughout the thickness of a piece of timber. As they are normally driven at greater depths into the timber, the MC is measured between the uninsulated tips only. Insulated type electrodes are normally driven into the wood using a slide/hammer assembly. This type of resistance type meter was used for this work.

Uninsulated electrodes are used to measure approximate average MCs as the MC is read at the point of least resistance or greatest moisture content between them. These electrodes can also be driven in using a slide/hammer assembly. Alternatively two nails can be hammered into a piece of timber at a specified distance and orientation and the MC is read using either a nail contactor or a two wire/alligator clip type assembly. Nail electrodes are a convenient way of monitoring MC of timber as it dries in racks as the nails can be left in the timber during drying, thus repeated measurements can be made easily.

For all of the above electrode types the electrodes should be inserted so that the current flows in the direction specified in the instructions supplied with the meter. This is most commonly in the direction parallel to the timber grain.

4.2.2 Dielectric Type - Meters

These type of meters depend upon the change of dielectric properties of a piece of timber with changing MC. A dielectric is defined as a substance or medium that can sustain an electric field. Two different meter measuring techniques are available for measuring the dielectric properties of wood.

Capacitance meters are the most common type of dielectric meter. The electrodes of these type of meters are usually of the form of four or more metal buttons or a metal surface which is pressed against the surface of the timber to be tested. In order to take readings, capacitance meters use either a radio frequency or microwave oscillator to generate a three-dimensional electromagnetic field. This field penetrates through the surface of the timber and measures its dielectric constant. This type of capacitance moisture meter was used for this work.

Microwave capacitance-type moisture meters use a microwave oscillator to generate microwaves which penetrate the wood to determine its dielectric properties. Microwaves are basically a much higher frequency radio wave exhibiting the same electromagnetic properties. These meters are potentially less likely to be affected by resistance and preservative salts than conventional radio frequency capacitance meters. These type of meters are predominantly made as a stationary device.

Stationary meter systems use non contact electrode sensors and are predominantly used in large scale sawmills on timber conveyers. Hand held capacitance meters generally use surface contact electrodes which are non penetrating, giving them the appeal of being a non destructive method of measuring moisture. These meters are able to read MCs below 6% and may be used over painted or polished surfaces (CSIRO, 1974).

The other type of dielectric-type moisture meter is the power loss type. These meters measure the amount of power the timber absorbs from the electromagnetic field, however they are not widely used due to field penetration limitations.

4.3 Factors Affecting Moisture Meter Readings

The following factors can greatly affect the measurements taken by hand held moisture meters.

Resistance type meter readings can be affected by the following: bad pin contact, moisture gradient, moisture meter range, species variation, temperature and chemicals introduced into the timber. Most of these factors can be eliminated however species variation can only be eliminated through the generation of species correction data. Temperature effects can be negated by using the temperature correction table obtained from AS/NZS 1080.1 (1997). This table is given in figure 4.1.

TEMPERATURE CORRECTION

Meter reading, %	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Wood temperature, °C	Moisture content corrected for temperature, %																						
5	7	8	9	11	12	13	14	15	16	17	19	20	21	22	—	—	—	—	—	—	—	—	—
10	7	8	9	10	11	12	13	14	16	17	18	19	20	21	22	—	—	—	—	—	—	—	—
15	6	7	8	9	11	12	13	14	15	16	17	18	19	20	22	—	—	—	—	—	—	—	—
20	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	—	—	—	—	—	—
25	—	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	—	—	—	—	—
30	—	6	7	8	9	10	11	12	12	13	14	15	16	17	18	19	20	21	22	—	—	—	—
35	—	—	6	7	8	9	10	11	12	13	14	15	15	16	17	18	19	20	21	22	—	—	—
40	—	—	—	6	7	8	9	10	11	12	13	14	15	16	16	17	18	19	20	21	22	—	—
50	—	—	—	—	6	7	8	9	10	11	11	12	13	14	15	16	17	18	19	19	20	21	22
60	—	—	—	—	—	6	7	8	8	9	10	11	12	13	14	14	15	16	17	18	19	20	20
70	—	—	—	—	—	—	—	3	7	8	9	10	11	11	12	13	14	15	16	16	17	18	19
80	—	—	—	—	—	—	—	—	6	7	8	9	9	10	11	12	13	13	14	15	16	17	18
90	—	—	—	—	—	—	—	—	—	6	7	8	8	9	10	11	11	12	13	14	15	15	16

NOTE: Temperature correction should be applied before species correction.

Figure 4.1 - Temperature correction table.

Note that at a wood temperature of 20°C no correction is required.

Dielectric type meter measurements can be affected by the following factors: timber density, timber thickness, moisture gradient, temperature, species, contact and chemicals. Redman (1997) found that timber density greatly affects the accuracy of dielectric type meters. Temperature correction data is currently not available for

capacitance-type moisture meters. The manufacturer's instructions for the Wagner range of meters claim that none are needed between temperatures of 10 and 43°C.

4.4 Basis for generating species correction data for moisture meters

The basis for generating species correction data for moisture meters is the comparison of measured MCs using a moisture meter with the oven dry method (see appendix A1). The oven dry method is considered to be the most accurate method of measuring MC (AS/NZS 1080.1, 1997). It is for this reason that the oven dry method is used as the standard for comparison. In order to obtain the most accurate results possible, factors affecting moisture meter readings need to be eliminated. Therefore precautions concerning temperature, moisture meter contact, moisture meter range, chemicals, moisture gradient and timber thickness affecting moisture meter readings must be made.

Provided the limitations of each MC determination method are appreciated accurate measurements can be made. For both the oven dry and moisture meter methods repeated measurements and careful interpretation of values measured are required to obtain an accurate estimate of MC. Considering the advantages of each method is a useful way of choosing which one to use

The following describes the advantages of the oven dry method for measuring MC. The complete range of moisture contents can be measured via this method whereas moisture meters only have a limited range. A direct, definitive moisture content can be achieved free from the effects of variable resistance and electrolytic contaminants. Accurate measurements of moisture gradients throughout the thickness of a piece of timber can be achieved (AS/NZS 1080.1, 1997).

Moisture meter advantages are as follows. Instant moisture meter readings can be taken frequently with a moisture meter, as opposed to the oven dry method where at

least twenty four hours are required. Many readings can be made at any one time with minimal effort. The oven dry method is restricted by the capacity of the oven used. Moisture meters (especially capacitance-type) are a non destructive means of measuring moisture content. A loss due to the cutting of samples results when using the oven-dry method.

Resistance type moisture meters are generally calibrated to Douglas fir. When using moisture meters on timber other than Douglas fir it is necessary that species correction data is used. Species correction data for resistance type moisture meters already exists for a vast number of species (AS/NZS1080.1, 1997).

A number of resistance-type meter species correction data is available for Tasmanian eucalypt species (AS/NZS1080.1, 1997). This data has been taken from Hartley (1995) where each species was 'tested at 20 to 21°C with the current flow perpendicular to the grain'. The resistance of timber is greater across the grain than with the grain. The effect is very small on readings 10% or lower, and can be disregarded. Above 10% the effect becomes more apparent. The resistance-type meters used predominantly in the Tasmanian timber industry specify that measurements should be made parallel to the grain. Thus, it is evident that the species correction data currently available in the standard (AS/NZS1080.1, 1997) may be incorrect when using those meters which specify 'parallel to the grain measurements'. Therefore the basis of this authors work is to create species correction data for Tasmanian commercial eucalypt species using moisture meters which are widely used in the industry today.

4.5 Equipment Overview

Using the literature review cited in Redman (1997) as a guide, decisions regarding the methodology and equipment for generation of moisture meter correction data for *E. obliqua* were made by the author. They are as follows:

Correction data was generated for two resistance-type and two capacitance-type meters.

The capacitance-type meters chosen for this study both take measurements to a depth of 19mm. It was decided that sample boards should be dressed to a thickness of 24mm to allow for possible overshoot of the electromagnetic waves at a depth of 19mm. The manufacturer of the resistance-type meters used in this study suggest that readings should be taken at a depth of one fifth of the thickness of a board to obtain a legitimate reading of its average MC. This theory was tested and confirmed by Redman (1997). Therefore all resistance-type moisture meter readings were taken with pins driven to a depth of 5mm.

Conditioning of samples was achieved using a sealed, temperature controlled cabinet, with a capacity to store 42 samples. Humidity was controlled using saturated salt solutions in a bath in the bottom of the chamber. This method of conditioning was used as Edwards (date unknown) suggests that this is the most accurate method of conditioning samples. The samples were conditioned at 20°C and all moisture meter measurements were made at this temperature to avoid using temperature correction data for the resistance-type moisture meters.

Three EMC values were chosen to take correction data readings. They are 18, 13, and 8%. Thus, three different salt solutions were needed to obtain these conditions. The salts were chosen using Greenspan (1977) and CRC (1980-1981) on the basis of their relative humidities at 20°C to give the EMCs above. The relative humidities corresponding to EMC values of 18, 13 and 8% at 20°C are 85, 75, and 45% respectively. Where there existed more than 1 type of salt to achieve the appropriate

condition, the salt chosen was the least expensive with respect to the amount needed to produce 5 litres of saturated solution. A salt was not chosen if it was deemed hazardous to a person's health.

The conditioning cabinet was able to hold 42 samples. Enough material was provided to produce 40 samples of the required dimensions. 36 samples were used to take correction data measurements, while the other four samples were used as test samples for measuring moisture gradients during the study.

4.6 Experimental Apparatus

The following equipment was used in this experiment for the preparing, conditioning and measurement processes.

4.6.1 Conditioning

The most important piece of equipment used in the conditioning process was the conditioning chamber. The purpose of the chamber was to maintain a constant relative humidity at a constant temperature. The chamber itself was basically a hollow rectangular box on wooden legs. Its internal dimensions were 795mm high × 795 wide × 345mm deep. The walls were made from timber paneling followed by a 20mm foam layer and finally a layer of fibre glass. The fibre glass, on the interior side of the chamber, is used because of its impermeability to moisture and resistance to corrosion. The foam layer is used for thermal insulation.

The chamber had hinged doors at the front and top for easy access. Both doors are sealed when shut in order to keep the humidity of the air inside the chamber as constant as possible.

The humidity of the conditioning chamber was controlled using 5 litres of a saturated salt solution placed in a bath situated towards the bottom of the chamber. The salt solution bath is elevated approximately 200mm from the bottom of the chamber by an aluminium stand. It rests on a 2mm sheet of perforated aluminium allowing for air and heat flow.

The timber samples are racked on two shelves made from perforated aluminium sheeting. The samples stand on their edges and are supported by rivets. Each shelf is able to hold a maximum of 21 samples of the dimensions given in section 4.5. The samples are separated from each other to allow sufficient air flow between them.

Heat was supplied to the conditioning chamber via two 65W heating bulbs (similar in appearance to household light bulbs) situated at the bottom of the chamber below the salt bath. Two heating elements are sufficient to hold the temperature of the chamber at 20°C.

A fan is positioned at the top of the chamber. This maintains a constant air flow, humidity and temperature distribution throughout the inside of the chamber.

Two RTDs were used to measure the wet bulb and dry bulb temperature of the air inside the conditioning chamber. The wet bulb temperature probe was covered with a wet sheath or wick. The wick was wetted via a hose connected to the wick which leads to a water reservoir, housed on the exterior of the chamber. The probes were situated below the fan blade as air flow is required over the wet bulb probe to measure the wet bulb temperature accurately.

The temperature values measured by the RTDs were read by the Datataker 500 as for the trial in chapter 2 (see 2.2.6). The datataker 500 was programmed to control a relay to maintain the temperature inside of the chamber at 20 ± 0.1 °C. The following diagram shows a flow diagram of the conditioning equipment.

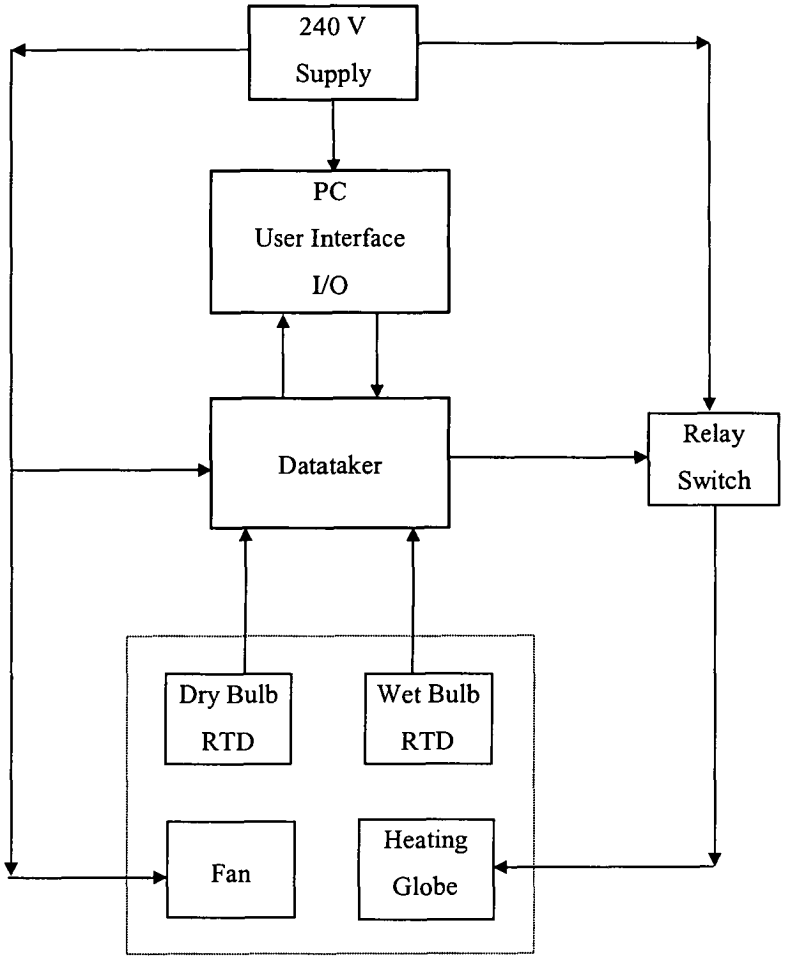

Figure 4.2 - Flow diagram of conditioning apparatus setup.

4.6.2 Measurements

Two capacitance-type and two resistance-type moisture meters were used for calibration measurements. Two Wagner L606 capacitance-type meters, a Delmhorst G-30 and Delmhorst RC-IC resistance-type meters were used.

A calibration block was used to calibrate the resistance-type moisture meters at 22 and 12% MC.

As previously mentioned a timber slicer was used to determine the moisture distribution of the test samples.

4.7 Methodology

4.7.1 Sample Preparation

Eight randomly selected boards of *E. obliqua* of length 1.8m were acquired from Neville Smith Timber - Tasmania. All boards met the select criteria as defined by AS 2796.2: 1985. The boards were partially air seasoned at Neville Smith Timber - Tasmania..

Using planing and sawing equipment at the University of Tasmania - Launceston the boards were planed on both sides to a thickness of 24mm. A 400mm length was cut from the ends of each board and discarded as specified by AS/NZS 1080.1: 1997. Then 40 230mm lengths were cut from the remaining timber. A 30mm section was cut from the end of each sample length and its MC was calculated using the oven dry method. The mass of the samples were measured immediately after the 30mm section was cut so that its progressive MC and oven dry weight could be obtained. Thus the dimensions of each sample were 24mm × 100mm × 200mm.

4.7.2 Conditioning and Measurements

Thirty seven samples were used for determining moisture meter correction data, while four samples were used as test pieces for measuring moisture distribution.

The air dried samples were initially racked in the conditioning chamber at 20°C and 85% relative humidity to an EMC of approximately 18%. The humidity was controlled using 5 litres of a potassium chloride saturated salt solution. The samples

were held at these conditions until they reached equilibrium. The samples were defined as having reached equilibrium once their weights remained constant to within 0.1% over a period of 48 hours and the moisture distribution measurements of the test pieces were 'flat' to within ± 1% MC. Once equilibrium was achieved at this condition, MC measurements using the moisture meters could be taken.

The samples were individually removed from the conditioning cabinet and the MC was measured on both of the planed faces of the sample, using each of the four meters. This is a total of eight measurements for each sample. The locations of the capacitance-type moisture meters on the surfaces of each sample were marked so that the meters could be repositioned in the same places when the measurements were repeated for other MCs. The weight of each sample was recorded after the moisture meter measurements were made for each sample. When the samples were not being handled or conditioned they were wrapped in an impermeable plastic wrap.

Once the moisture meter MC measurements were made, the samples were dried in a vented oven at approximately 50°C until the average MC of the samples was 13-14 %. The next equilibrium MC to be tested was 13%. 13-14% MC was chosen as the value to dry the samples in order to speed up the equalising process from 18% MC to 13% MC. The value was obtained by weighing the samples periodically during the final drying process. The conditioning and MC measuring process was repeated for relative humidities of 75% and 45%, using saturated salt solutions of sodium bromide and magnesium chloride respectively. The relative humidities correspond to EMCs of approximately 13% and 8% respectively. Drying between EMCs was repeated between each set of measurements to average MCs corresponding to the next EMC value for conditioning.

Once the measurements were made for the final EMC value (8%), the samples were all oven dried according to AS/NZS 1080.1, 1997 and then weighed.

4.8 Results and Analysis

The eight sample boards used to obtain the samples were labeled from A to H. Once the samples were obtained they were numbered and labeled according to the board from which they were cut i.e. A1, A2 .. A5, B1 .. B5 etc. Samples D2, F3 and H4 were chosen to be used for moisture profile measurements.

The initial MC was found for each sample by following the technique given in appendix A1, the results of which can be found in Appendix D1. The initial MC of the samples ranged between 14.0 and 14.8% giving an average initial MC of 14.3%. The predicted oven dry weight was also obtained (see appendix A1) in order to monitor the approximate MC of each sample throughout the calibration process.

The samples were initially placed in the conditioning chamber at the appropriate conditions to give equilibrium to approximately 18% MC. The samples were weighed periodically over the equalisation. After a period of 38 days the samples had an average MC of 17.6% and were exhibiting changes in weight of less than 0.1% over a period of 48 hours. The samples had MCs ranging from 16.7 to 19.2%. A moisture profile of samples D2 and F3 and H2 were measured. The profiles were 'flat' to within ± 1 % MC.

Once the samples were deemed to have reached equilibrium, the MC of each sample was measured using the four moisture meters. A table showing the moisture meter calibration results for sample equalisation at approximately 18% MC are in Appendix A2. The table contains the predicted MC of each sample, the resistance and capacitance type meter measurements on both sides of the samples and the average MC obtained from both types of meters.

After drying the samples for approximately 24 hours in a vented oven at 50°C they were replaced into the conditioning chamber to equilibrate to an EMC of approximately 13%. The samples took 44 days to equilibrate. The average MC of the

samples after this period was 13.2% with an MC range from 12 to 13.6% (see appendix A3).

The samples were dried once more in the oven at 50°C until each sample exhibited an average MC of approximately 8%. Equalisation of the samples in the conditioning chamber was repeated for an equilibrium MC of approximately 8%. After 29 days the samples had sufficiently equalised with samples ranging in MC from 7.3 to 9% giving an average MC of 8%. Moisture meter data was repeated after equalisation and the results are given in Appendix A4.

Once the moisture meter readings were completed the samples were oven dried according to the standard (AS/NZS 1080.1, 1997).

Plots of meter reading versus oven dry MC including regression lines are shown in Figures 4.3 and 4.4 for the resistance- and capacitance-type meters respectively. On each graph the data is in three groups which correspond to the three equilibrium MCs. The r^2 value or correlation factor and regression line equations are shown on figures 4.3 and 4.4. The correlation factors are 0.95 and 0.96 for the resistance- and capacitance-type meter plots respectively.

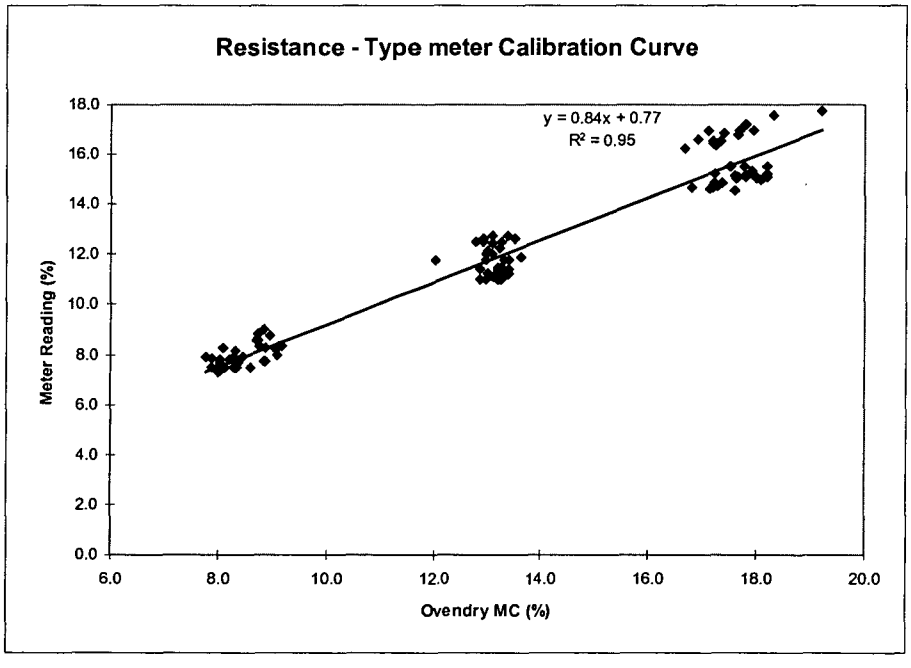

Figure 4.3 - Resistance-type meter regression plot.

It should be noted that the resistance-type meter regression plot (figure 4.3) looks like two sets of data exist above and below the regression line. This could be confused to be caused by using two different meters, however this is not the case as both of the meters were calibrated and each plot is an average of both of the meter values measured.

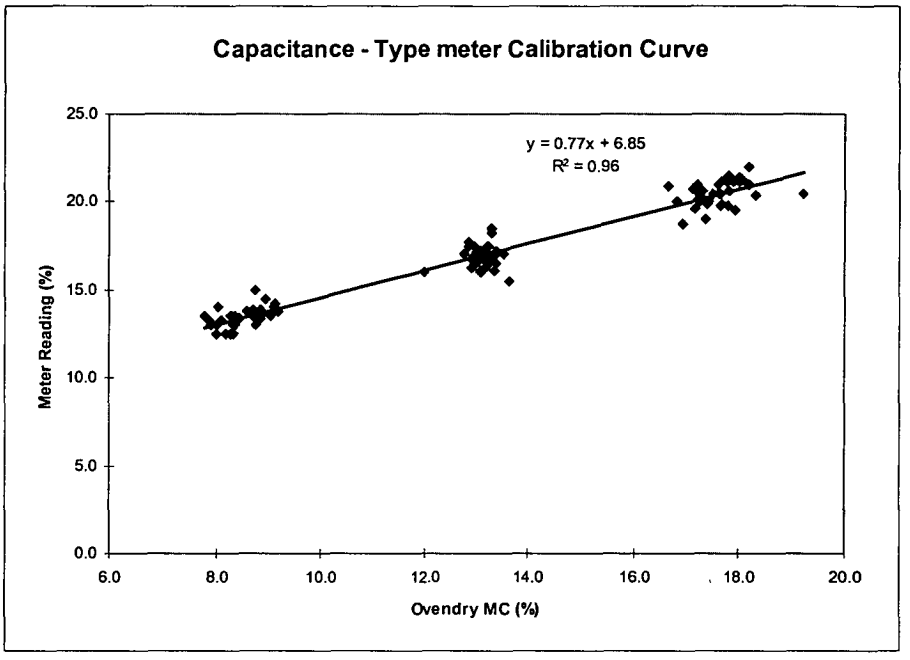

Figure 4.4 Capacitance-type meter regression plot.

The corrected (corrected = oven dry) values for the resistance type and capacitance type meters are shown in Table 4.1 for *E. obliqua*. The corrected values for *E. obliqua* given in the Australian standard (AS/NZ 1080.1, 1997) are also shown in table 4.1. As the corrected values were derived from only three EMC points (8%, 13%, and 18%) the points in between were interpolated to the nearest percent from the regression lines. Correction values could have been extrapolated above and below the EMC points trialled however the validity of these values would be doubtful. The omission of the extrapolated values is evident in table 4.1. The resistance-type meter correction data shows that for meter readings from 8 to 13% MC and 14 to 16% MC positive corrections of 2% and 3% are required respectively according to data

obtained by this author. The correction factors used in AS/NZS 1080.1 (1997) shows a positive correction of 1% is required for meter readings from 6 to 24%.

Moisture Meter Reading (%MC)	Authors corrected values for resistance-type meter (%MC)	Aus. Standard corrected values for resistance-type meter (%MC)	Authors corrected values for capacitance-type meter (%MC)
6	-	7	-
7	-	8	-
8	9	9	-
9	10	10	-
10	11	11	-
11	12	12	-
12	13	13	-
13	14	14	8
14	16	15	9
15	17	16	11
16	18	17	12
17	-	18	13
18	-	19	14
19	-	20	16
20	-	21	17
21	-	22	18
22	-	23	-
23	-	24	-
24	-	25	-

Table 4.1 - Correction table for *E. obliqua.*

4.9 Conclusions

It is evident that the corrected values for resistance-type moisture meters used on *E.obliqua* deviate from those given in the Australian Standard. The cause of this deviation is most likely due to the difference in meter electrode placement with respect to the timber grain direction, as described in section 4.4. This deviation was also present for species correction figures for *E. delegatensis* also (Redman, 1997).

The regression trendline for the resistance and capacitance type meters indicate a strong fit. The regression trendline for capacitance - type meter readings performed on *E. delegatensis* previously (Redman, 1997) was not a strong fit due to density effects.

The readings on the capacitance-type meter are between 5 and 3 % higher than the actual MC of the wood. As there are no current corrected values for capacitance-type meters and *E. obliqua* the type of instrument used would be considered very poor by the timber industry.

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Appendix A. Timber Sampling Procedures

The following procedures were employed to determine certain properties of timber samples at different stages throughout this work. The methodologies included in this Appendix are procedures to determine average MC, moisture content profile, basic density, tangential and radial shrinkage, and collapse threshold temperature.

A1 Average Moisture Content (Oven Dry Method)

Average moisture content is determined by following Australian/New Zealand Standard 1080, Part1 - 1997, 'Timber -Methods of Test. Method 1 : Moisture Content.' The following is a summary of AS/NZS 1080.1.

A1.1 Procedure

Timber samples to be tested should be selected randomly and should not contain a high resin or oil content or other volatile extractives. Timber containing a high resin/oil content can effect the accuracy of results.

Test pieces for the determination of MC should be cut at a distance of no less than 0.4 metres from the end of the piece of timber. The test piece should incorporate the whole cross-sectional area for which the MC is required. After cutting, the test piece needs to be brushed or scraped so as to remove any loose splinters and sawdust that may drop off during drying. The test piece should then be weighed immediately after scraping in order to prevent further drying of the piece. If the test piece can not be weighed immediately it must be securely wrapped in a non permeable material such as plastic timber wrapping or aluminum foil and then stored in a dry, shaded, cool place.

The test pieces must be weighed on a balance with a sensitivity of not less than 1 in 500.

After the initial weight has been obtained, the test pieces need to be dried in a well ventilated oven at a temperature of 103 ± 2° C. The drying takes place until a constant dry mass is obtained. To ensure that a constant mass has been obtained the test pieces are left for approximately 24 hours in the oven. They are then weighed and reweighed after 2 to 5 hours. If the weight recorded is within 0.2 % of the previous weight then the samples are said to be oven dried to a constant mass. If the difference between the first and second weight is greater than or equal to 0.2 %, then a further period of drying is necessary until the last two weighings agree to within 0.2 %.

A1.2 Calculation

Once the initial mass and oven dry mass of a test piece have been determined the percentage moisture content of the sample can be calculated using the following formula:

$$MC = \left(\frac{Wi - Wo}{Wo}\right) \times 100 \qquad (a1.1)$$

Where MC = percentage moisture content of test piece.

Wi = initial mass of test piece.

Wo = final oven dry mass of test piece.

The oven dry method can be used to monitor the average MC of timber samples during the drying process. This can be done quickly and accurately, at any particular time.

The initial MC of a sample which is to be monitored during drying must first be known. This is achieved by cutting off a test piece from the sample to be monitored and oven drying the test piece to determine its MC as previously described. It is important to weigh both the test piece and the sample to be monitored immediately

after cutting. The MC of the test piece is used as the initial MC of the monitored sample.

Having calculated the initial MC of the sample board, and knowing its original weight, it is then possible to determine its oven dry weight by a simple manipulation of the MC determination equation (a1.1), giving:

$$Wo = \left(\frac{Wi}{MC + 100}\right) \times 100 \qquad \text{(a1.2)}$$

Once the oven dry weight of the test piece is known the MC of the sample board can be determined any time thereafter, by simply weighing the sample board and applying the MC equation (a1.2) where Wi is the current weight of the sample.

A2 Moisture Profile

The purpose of this test is to determine the variation of moisture content through the thickness of a board sample.

A2.1 Procedure

The portion of the sample chosen should be free from any imperfections such as gum veins and knots. The test piece should incorporate the whole cross-sectional area for which the MC profile is required.

Initially the top of the sample needs to be defined by marking the section to be cut with a T. Then a 25mm sample is cut at a distance of no less than 0.5m from the end of the piece of timber (see Figure A2.1). It should be noted that 25mm is convenient for the microtome slicer used by this author.

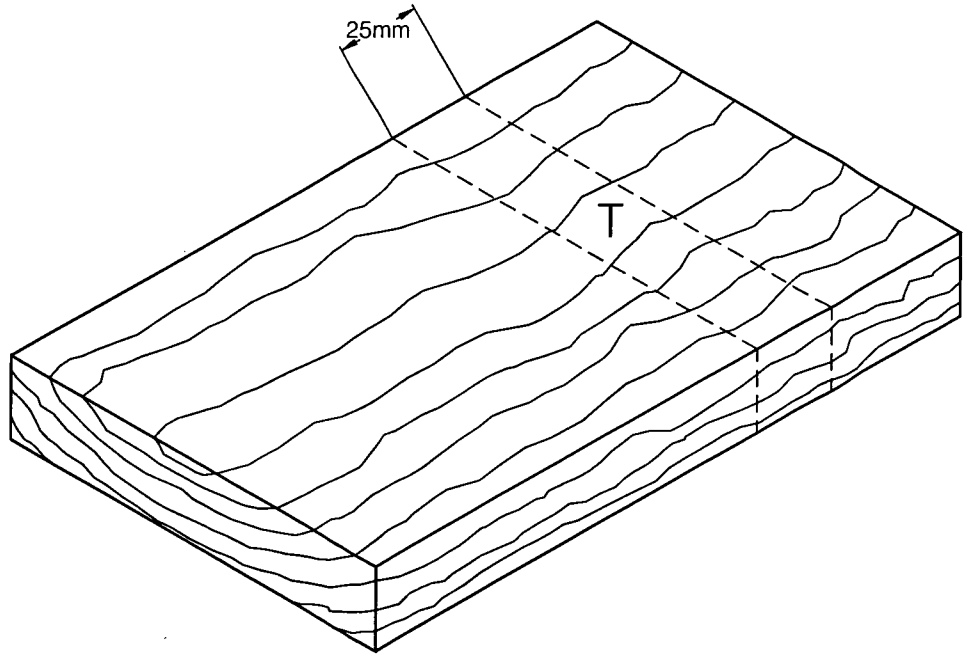


Figure A2.1 - Cut 1

From roughly the centre of the sample obtained from Figure A2.1 two cuts were made 25mm apart parallel to the original length of the board (see Figure A2.2).

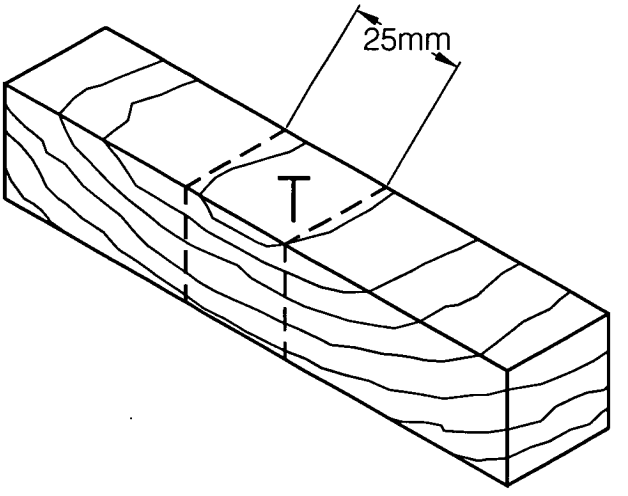


Figure A2.2 - Cut 2

A MC profile sample should now be left with the following dimensions: 25mm × 25mm × the thickness of the original sample. This is clearly illustrated by figure A2.3. Note that the top side of the sample should still be marked with a T.

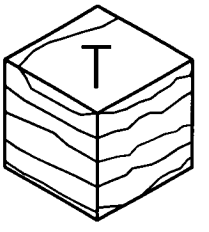


Figure A2.3 - Profile Sample (25mm × 25mm × thickness)

It is now extremely important to wrap the sample in plastic to prevent any further drying and advance to the slicing stage as quickly as practically possible to prevent moisture redistribution.

A timber slicer (see figure 2.2) is used to thinly slice the board sample and consists of a sharp blade and lever apparatus. The sample is sliced by clamping and feeding it forward under a plane blade. The plane blade is pulled down to slice the sample.

Initially the sample is placed in the timber slicer such that the side marked with a T is sliced off first. The sample is orientated so that the blade cuts with the grain to aid in the slicing process. The sample is secured in the timber slicer and fed forward so that a slice of approximately 1mm is removed.

The slice is numbered and then weighed on a balance accurate to 0.001g. The sample's number and weight are recorded. The thickness of the slice is then measured using a set of callipers accurate to 0.01mm and recorded.

This process is repeated approximately five times. The sample is then rotated through 180 degrees so that slices taken from the face opposite to the originally marked T. The slicing process is repeated on this side of the sample for a further six slices. The remaining piece of sample is removed from the timber slicer, weighed, numbered and measured for thickness.

The slices and the centre piece are then oven dried following the same rules as for the average MC procedure explained in Appendix A1.1.

A2.2 Calculation

Once the slices have been oven dried their individual average MCs can be calculated using formula a1.1. Thus a graph of the variation of MC with thickness through the sample board can be produced.

A3 Basic Density (Water Displacement Method)

Basic density is defined as:

$$\text{Basic Density} = \frac{\text{dry mass}}{\text{green volume}} \qquad \text{(a3.1)}$$

Basic density samples should be cut from green boards at a length of approximately 25mm. The sample should be free from all imperfections so that the sample size is board width × board thickness × 25mm.

The green volume is determined by the water displacement method. A zeroed balance with a beaker of water resting on it is required. The freshly cut green samples are fully immersed in the beaker so that they are just under the surface of the water but not touching the sides of the beaker. The sample is held in this position using a pin or small nail. The balance reading when the sample is submerged is the mass of the water displaced by the sample. The density of water is taken to be 1000kg/m^3, therefore the displaced volume of water can be calculated. This volume is equal to the green volume of the test sample.

The sample is then dried in a lab oven at 103°±2°C as for A/NZS 1080.1 - 1997 (see Appendix A1), cooled in a desiccator and weighed to give the dry mass. The basic density of the sample is calculated using equation a3.1.

A4 Normal Tangential and Radial Shrinkage

The purpose of this test is to determine the normal tangential and normal radial unconfined shrinkage of a sample board by using slicing. Unconfined normal shrinkage is defined as the shrinkage measured at different MCs on thin unrestrained samples presumed to be at a uniform MC. It differs from total shrinkage on thin samples which is a measurement of the sum of both collapse and normal shrinkage. Net shrinkage is a measurement of the linear sum of the four components of strain, namely; instantaneous strain, unconfined shrinkage strain, machano sorptive strain and creep.

A4.1 Procedure

Two block samples should be cut for measurements for both tangential and radial shrinkage. The samples are cut as for the MC profile test, (Appendix A2) see Figures A2.1, A2.2, A2.3. The cross sections from which the blocks are obtained should be cut at least 500mm from the end of the board, adjacent to each other along the length of the board, and free of imperfections.

A typical block should have approximate dimensions of 35mm × 35mm × board thickness. For a back sawn block the radial, tangential, and longitudinal directions are shown in Figure A4.1 where the directions are denoted by R, T, and L respectively.

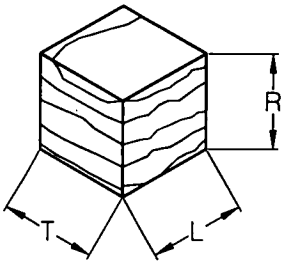


Figure A4.1 - Back sawn cube showing R, T, L directions.

Normal longitudinal and normal radial shrinkage is measured on R-T slices (see the dashed line in Figure A4.2) taken from the block sample. Several slices are cut to a thickness of 0.8 ± 0.3mm using the microtome. This thickness tolerance ensures that all of the fibres are cut so that shrinkage due to collapse does not occur. A cut fibre will not collapse as tension of the cell wall will not be set up if the ends of the fibres are not whole. Two of the slices are selected and placed in wire bridles for ease of handling, support and to prevent out of plane deformation of the slices. One slice is used for radial shrinkage measurements while the other slice is for tangential shrinkage measurements.

The slices are numbered and a couple of reference marks are made approximately 25 to 30mm apart. The reference marks on the slice to be used for normal radial shrinkage measurements are made parallel to the radial plane R as shown in Figure A4.2. The same is true for the tangential shrinkage slice and the tangential direction T.

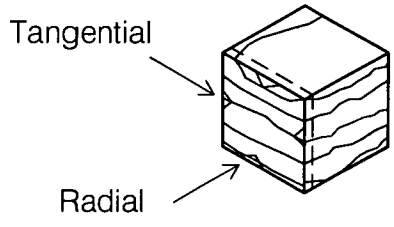


Figure A4.2 - RT slice showing tangential and radial shrinkage reference marks.

Immediately after the slices have been numbered and marked the distance between the two marks is measured to within 0.01mm using a travelling microscope (see diagram) and the mass of the slice and the bridle are recorded to the nearest mg. This process is repeated until the slice reaches EMC i.e. until the mass recorded stops decreasing.

The slices are finally oven dried at 103±2°C according to A/NZS 1080.1-1997. The final dry mass of the slice and bridle is measured and recorded. Finally the slice is discarded and the mass of the bridle is recorded.

A4.2 Calculation

The percentage moisture content at each 15 minute reading is calculated using the following equation:

$$\text{Moisture Content} = \left(\frac{\text{wet mass - dry mass}}{\text{dry mass - bridle mass}}\right) \times 100 \qquad \text{(a4.1)}$$

The percentage of shrinkage at each reading can be calculated using:

$$\text{Shrinkage} = \left(1 - \frac{\text{current distance between two marks}}{\text{initial distance between two marks}}\right) \times 100 \qquad \text{(a4.2)}$$

The data is then plotted with the moisture content on the vertical axis and shrinkage on the horizontal axis.

A5 Collapse Threshold Temperature (Board Section Method)

The board section method of measuring the collapse threshold temperature was first developed by Innes (1995b). The purpose of this test is to measure the collapse threshold temperature of timber samples. The collapse threshold temperature is defined as the temperature at which negligible collapse occurs (Innes, 1995b).

A5.1 Procedure

The sample should be at least 150mm long in the longitudinal direction and free from all imperfections. The sample boards should be cut no closer than 50mm from the end of the board (to negate the effects of end drying) and immediately end coated to prevent moisture loss. The samples not being used immediately should be fully wrapped in plastic.

Samples are then placed in an oven at various temperatures for approximately 48 hours. After this time, the boards are cross cut into approximately 50mm length strips, and the cut surfaces examined for any signs of collapse. After such a short period of drying, collapse is often only seen as a slightly rippled board surface, although collapse checks can sometimes be found near the surfaces. These are not to be confused with surface checks; and checks which intersect a surface cannot be assumed to be collapse checks.

Appendix B. Monitoring first three weeks of drying data and results

B1 Grading Data

Board #	Select	Std.	Ute.	Defect	End Split (m)	Board #	Select	Std.	Ute.	Defect	End Split (m)
1	*				0	46	*				0
2	*				0	47		*		gum vein	0
3			*	sapwood	0	48		*		gum vein	0
4			*	sapwood	0	49		*		sapwood	0
5	*				0	50		*		knot	0
6	*				0	51		*		sapwood	0
7		*		gum vein	0	52		*		sapwood	0
8			*	sapwood	0	53			*	gum vein	0
9	*				0	54		*		gum vein	0.4
10	*				0	55	*				0
11		*		brown stain	0	56	*				0
12	*				0	57	*				0
13	*				0	58		*		sapwood	0
14			*	sapwood	0	59			*	rot	0
15		*		brown stain	0	60		*		end split	0.5
16	*				0	61	*				0.1
17	*				0	62		*		rot	0.2
18	*				0	63			*	rot	0.3
19	*				0	64	*				0.4
20	*				0	65		*		knot	0
21	*				0	66	*				0
22			*	gum vein	0	67	*				0
23		*		sapwood	0	68	*				0
24		*		sapwood	0	69		*		sapwood	0.3
25		*		gum vein	0	70		*		knot	0.2
26	*				0	71				short	0
27	*				0	72	*			short	0
28	*				0	73	*				0
29	*				0	74	*				0
30		*		sapwood	0	75	*				0
31		*		gum vain	0	76	*				0
32		*		gum vain	0	77	*				0
33	*				0	78	*				0
34	*				0	79	*				0
35	*				0	80	*				0
36	*				0	81	*				0
37		*		gum vein	0	82	*				0
38		*		gum vein	0	83	*				0
39		*		sapwood	0.4	84		*		gum vein	0
40		*		end split	0.4	85	*				0
41	*				0	86	*				0
42	*				0	87	*				0
43	*				0	88	*				0
44		*		sapwood	0	89	*				0
45	*				0.3	90	*				0

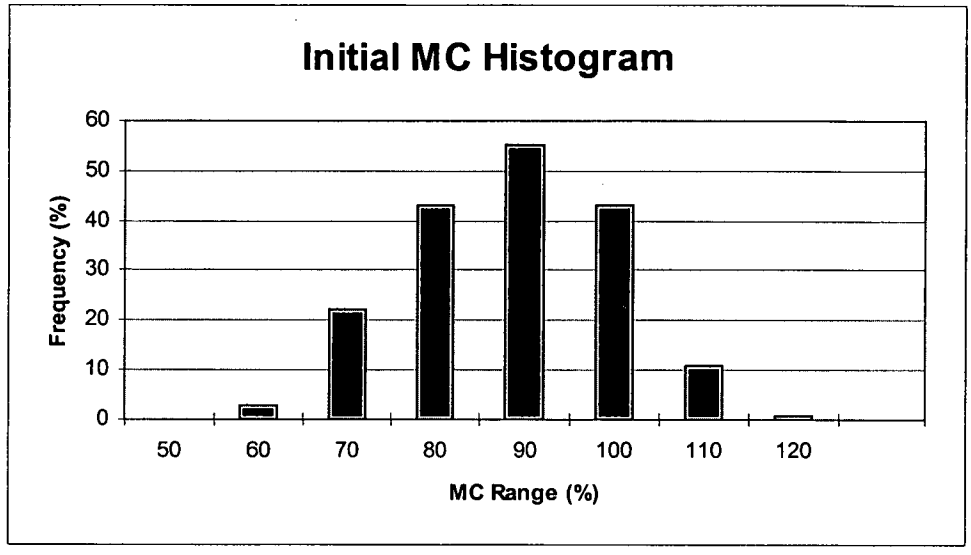
Board #	Select	Std.	Ute.	Defect	End Split (m)	Board #	Select	Std.	Ute.	Defect	End Split (m)
91				short	0	132B	*				0.1
92		*		sapwood	0	133A	*				0.9
93		*		sapwood	0	133B		*		knot	0.3
94				short	0	134A		*		gum vein	0.3
95	*				0	134B		*		gum vein	0.4
96	*				0	135A	*				0.3
97				short	0	135B			*	knot	0.5
98	*				0	136A		*		knot	1.3
99	*				0	136B		*		knot	0.5
100	*				0	137A		*		knot	0.3
101	*				0	137B		*		gum vein	0.5
102	*				0	138A	*				0.3
103	*				0	138B		*		sap	0.5
104	*				0	139A			*	knot	0.3
105	*				0	139B			*	split total	2.5
106			*	sapwood	0	140A	*				0
107		*		sapwood	0	140B	*				1.3
108	*			-	0	141A	*				0.3
109		*		gum vein	0	141B			*	split total	2.5
110	*			-	0	142A	*				0.9
111		*		sapwood	0	142B			*	sapwood	0.4
112	*				0	143A		*		sapwood	0.2
113	*				0	143B	*				0.3
114	*				0	144A		*		knot	0.3
115		*		sapwood	0	144B			*	rot	0.4
116	*				0	145A	*				0.2
117	*				0	145B	*				0.3
118	*				0	146A	*				0.2
119A	*				1	146B		*		sapwood	0.4
119B		*		knot	0.5	147A		*		sapwood	0.2
120A	*			-	0.2	147B	*				0.3
120B		*		gum vein	0	148A		*		sapwood	0
121A	*				0.2	148B			*	sapwood	0
121B	*				0.3	149A		*		sapwood	0
122A	*				0.4	149B	*				0.3
122B			*	knot	0.3	150A	*				0.2
123A	*				0.2	150B	*				0.2
123B	*				0.2	151A	*				0
124A	*				0.2	151B	*				0.3
124B	*				0	152A	*				0.3
125A	*				1.2	152B	*				0.3
125B		*		knot	0.4	153A	*				0.5
126A	*				0	153B	*				0.2
126B	*			sapwood	0	154A	*				0.4
127A	*				0.2	154B	*				0
127B	-		*	knot/heart	0.2	155A		*		sapwood	0
128A	*				0.1	155B	*				0
128B	*				0.1	156A	*				0.1
129A	*				0.2	156B	*				0.2
129B	*				0.1	157A		*		gum vein	0.2
130A	*				0.3	157B		*		gum vein	0
130B	*				0.4	158A	*				1.2
131A	-			runoff	0	158B		*		rot	0.3
131B	*				0.3	159A			*	sapwood	1.2
132A	*				0.2	159B		*		rot	0

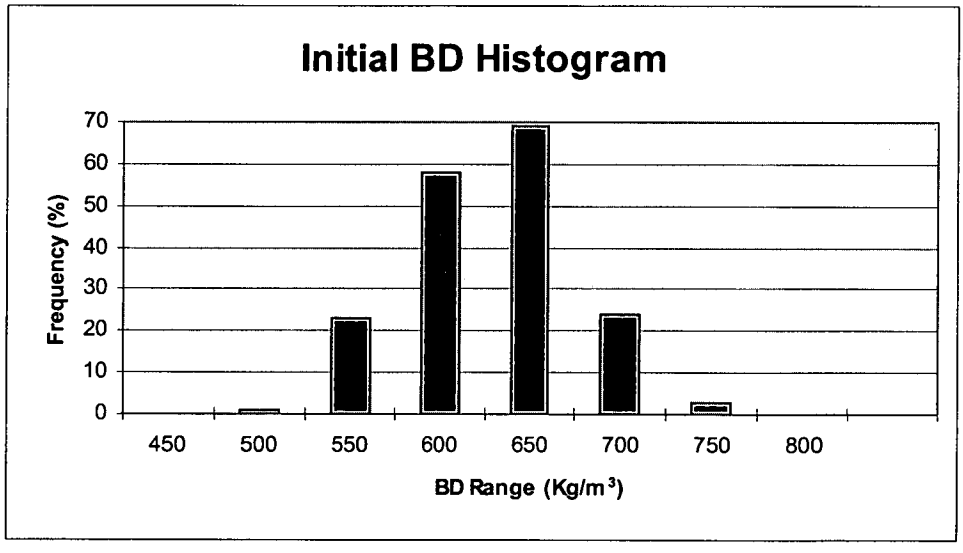
Board #	Select	Std.	Ute.	Defect	End Split (m)
160A	*				2
160B	*				0
161A	*				0
161B			*	heart	0.8
162A	*				0
162B	*				0.5
163A	*				0.4
163B	*				0.3
164A	*				0.3
164B	*				0.5
165A			*	knot	0
165B			*	knot	1
166A	*				0.4
166B			*	knot	1.2
167A	*				0.3
167B		*		gum vein	1.5
168A		*		sapwood	1.2
168B	*				0
169A		*		gum vein	0.4
169B		*		gum vein	1
170A			*	knot	0.4
170B		*		rot	0.4
171A	*				0.4
171B		*		gum vein	0.3
172A			*	sapwood	0
172B		*		sapwood	1.2
173A			*	gum vein	1.2
173B	*				0.3
174A			*	rot	0.4
174B		*		knot	0.3
175A		*		gum vein	0
175B			*	sapwood	0
176A		*		sapwood	0
176B		*		rot	0
177A			*	rot	1.2
177B		*		rot	0.4
178A		*		sapwood	0.2
178B		*		knot	0.8

Note: Each board was graded for signs of surface checking. This is not shown in this data because no evidence of surface checking was present.

B2 Initial Moisture Content and Basic Density Data

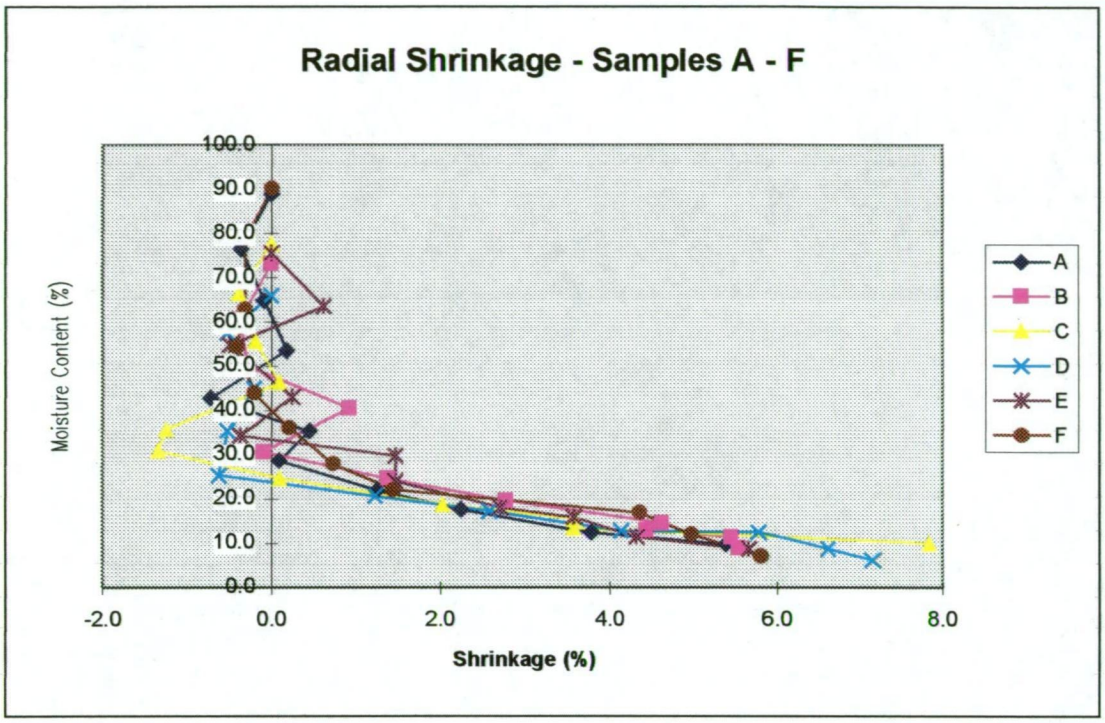
Note: The following data is represented as histograms and is derived from a total of 178 samples.





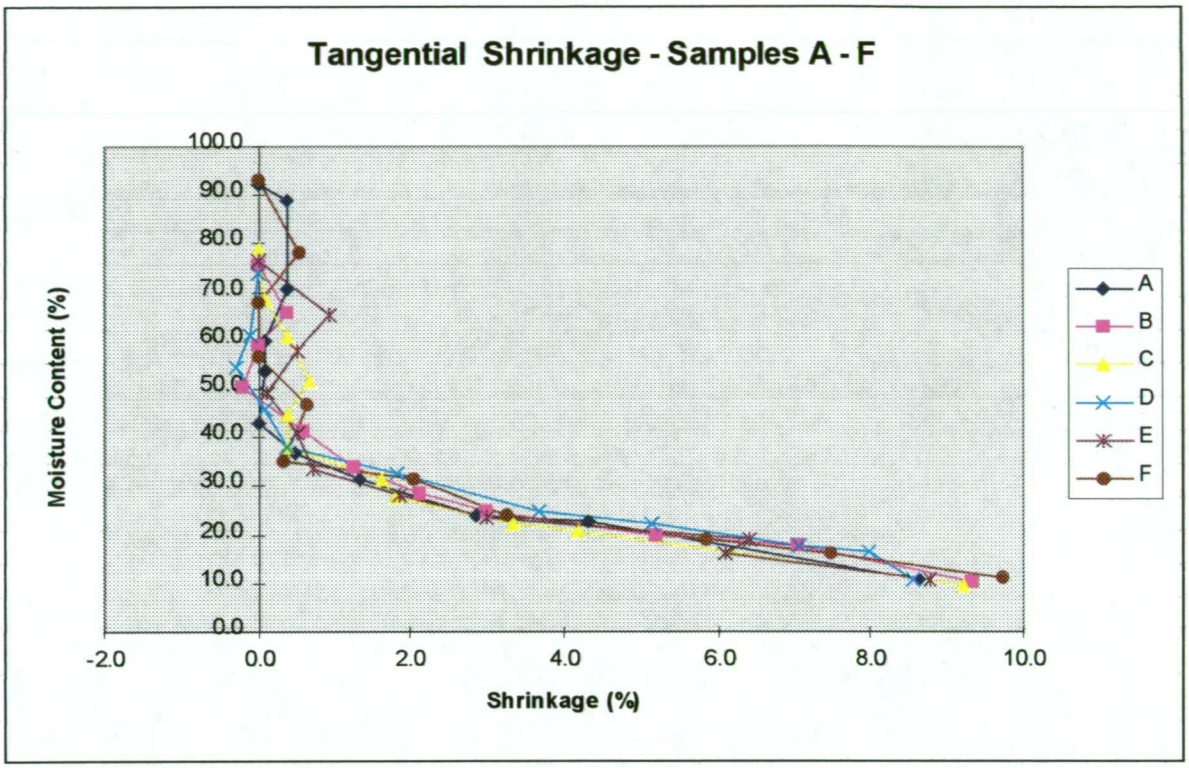
B3 Shrinkage Data

B3.1 Radial Shrinkage Results



Sample	FSP (%)	% Shrinkage	EMC (%)	% Shrinkage
A	30	0.2	10	5.5
B	30	0	9	5.6
C	30	0	10	7.8
D	25	0	8	7.1
E	30	0	9	5.7
F	35	0.2	9	5.8
AVERAGE	30	0.1	9	6.3

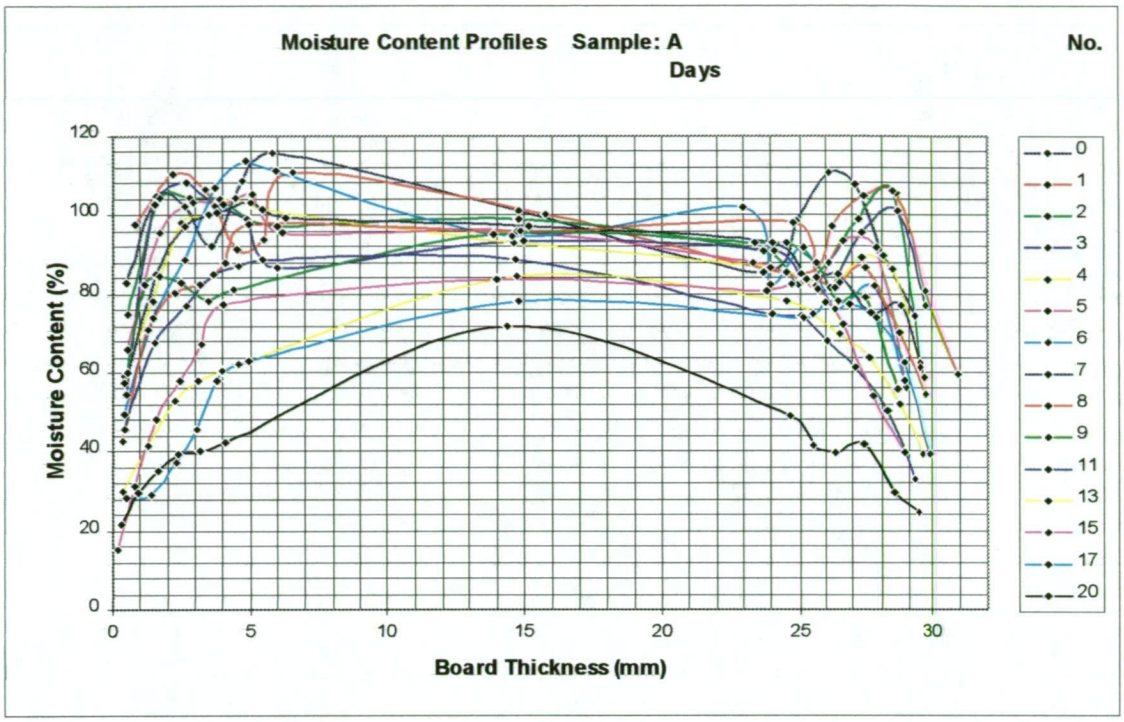
B3.2 Tangential Shrinkage Results



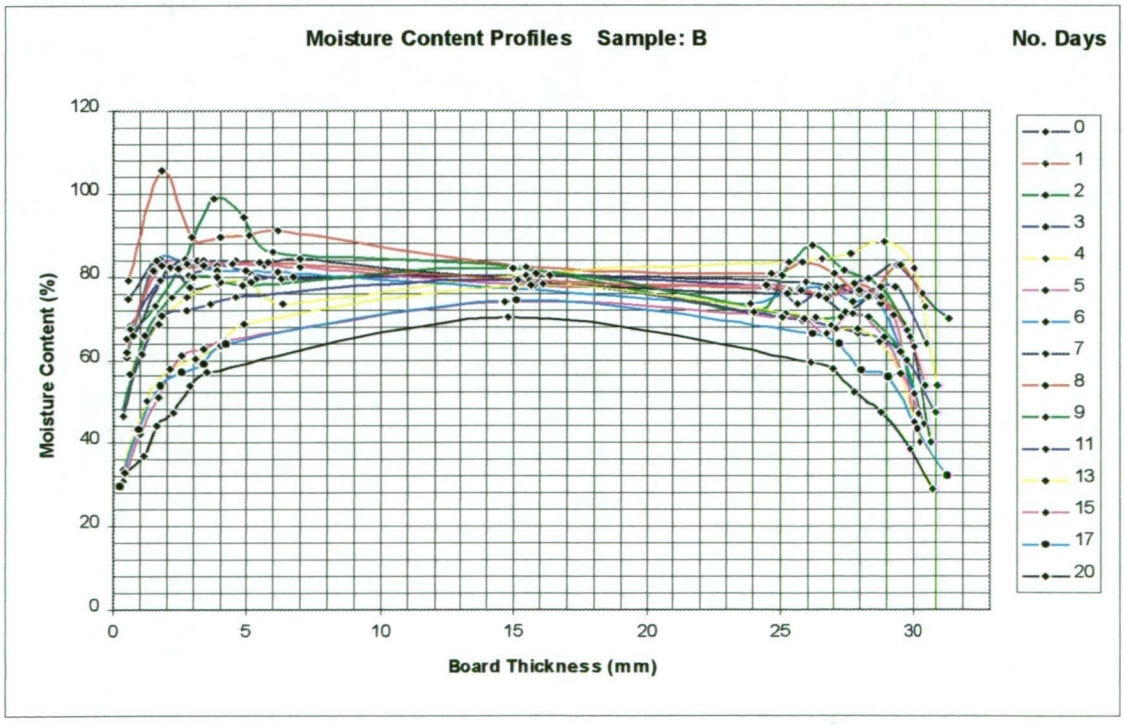
Sample	FSP (%)	% Shrinkage	EMC (%)	% Shrinkage
A	35	0.5	11	8.6
B	35	1	10	9.3
C	35	1	10	9.2
D	35	1	10.5	8.5
E	35	0.8	10.5	8.8
F	35	0.4	11	9.7
AVERAGE	35	0.8	10.5	9.0

B4 Moisture Profile Graphs - Over 3 Weeks

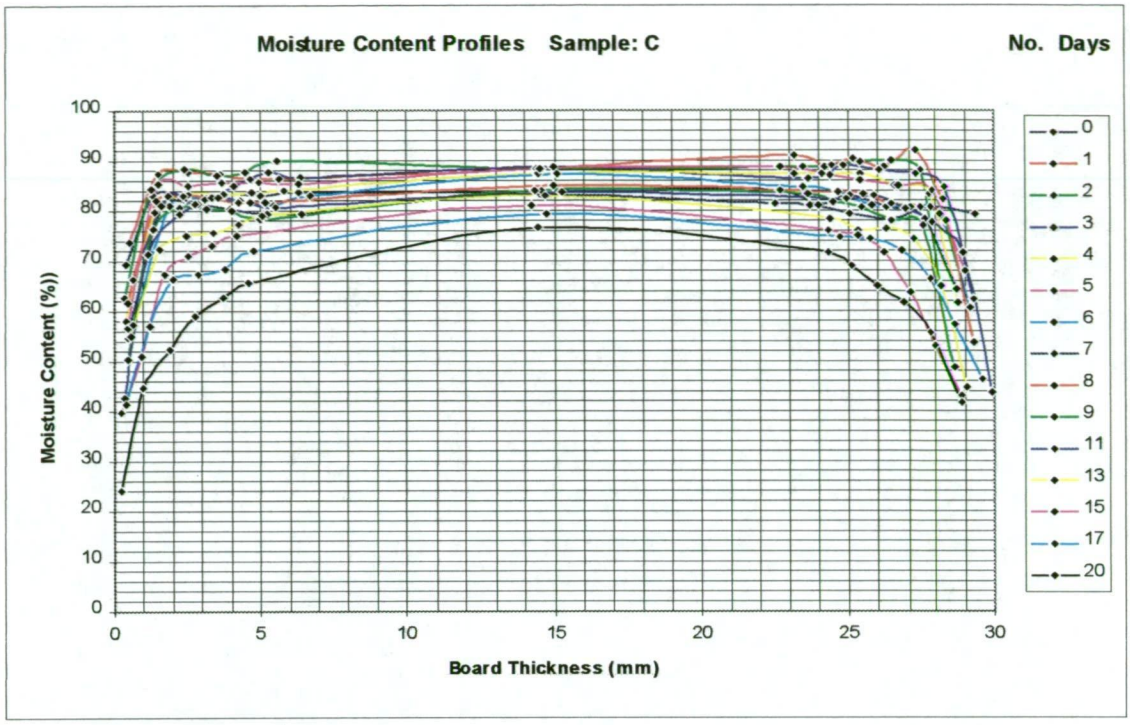
B4.1 Sample A



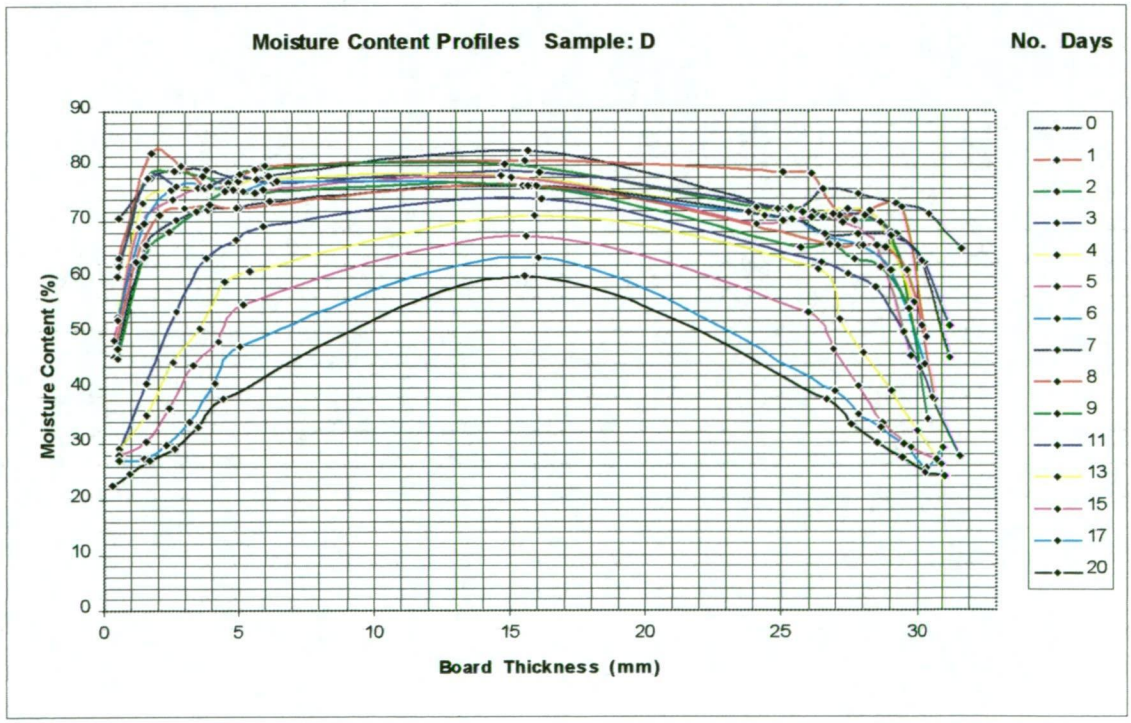
B4.2 Sample B



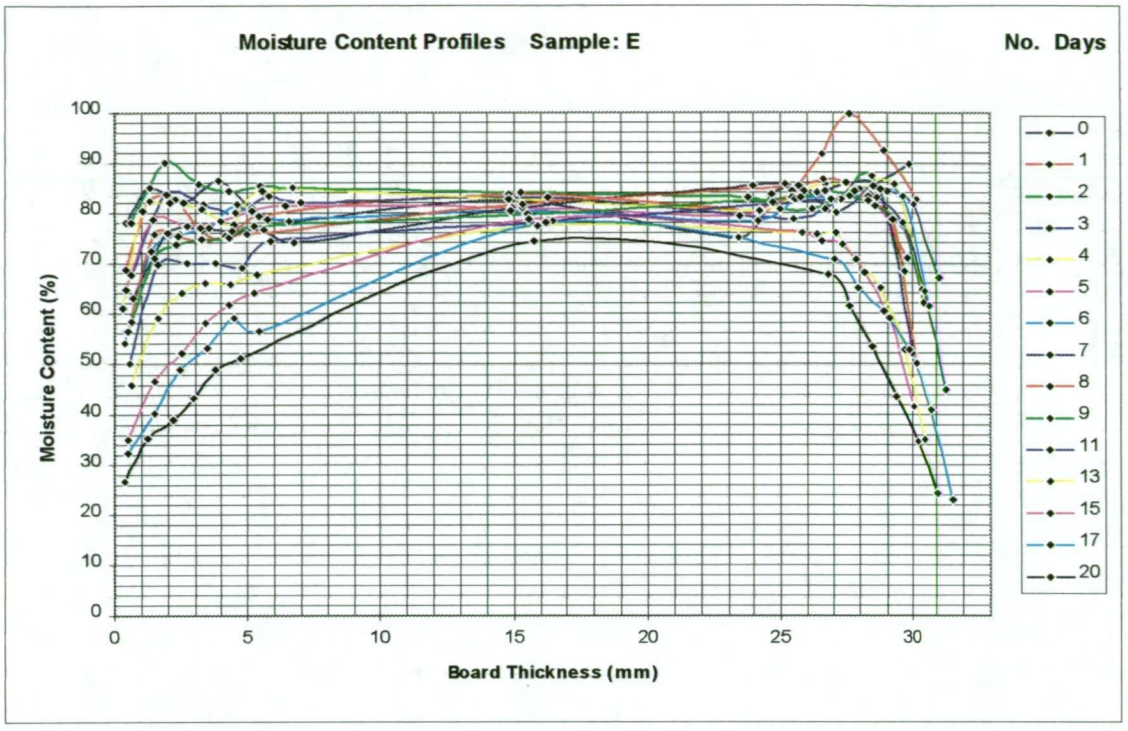
B4.3 Sample C



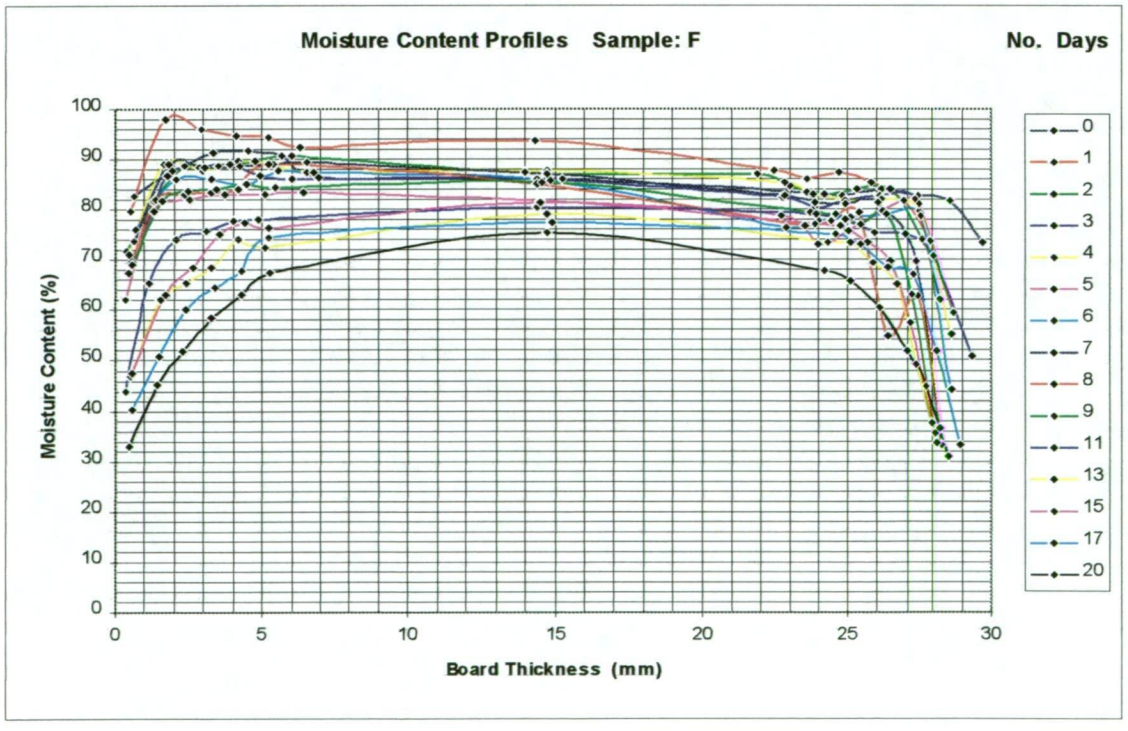
B4.4 Sample D



B4.5 Sample E



B4.6 Sample F



B5 Final Surface Checking and Collapse Results

B5.1 Quartersawn Boards

	Checking ?				Checking ?		
Sample #	Face 1	Face2	Collapse ?	Sample #	Face 1	Face2	Collapse ?
11	Yes	Yes	Yes	89	Yes	Yes	Yes
16	Yes	Yes	Yes	66	No	No	No
21	No	No	Yes	69	No	No	Yes
22	No	No	Yes	67	No	No	Yes
12	Yes	Yes	Yes	65	No	No	Yes
17	No	No	Yes	75	Yes	Yes	Yes
27	No	No	No	73	Yes	Yes	Yes
33	Yes	Yes	Yes	81	Yes	Yes	Yes
24	Yes	Yes	Yes	86	Yes	Yes	No
39	Yes	Yes	Yes	79	Yes	Yes	Yes
28	Yes	Yes	Yes	85	Yes	Yes	No
23	No	No	Yes	87	No	No	Yes
34	Yes	Yes	Yes	78	No	No	Yes
29	No	No	Yes	83	Yes	Yes	Yes
37	No	No	Yes	92	No	No	Yes
35	Yes	No	Yes	89	Yes	Yes	Yes
43	Yes	Yes	Yes	108	Yes	Yes	Yes
45	Yes	Yes	No	99	Yes	Yes	Yes
44	Yes	Yes	Yes	107	No	No	Yes
30	Yes	Yes	Yes	100	Yes	Yes	Yes
41	No	No	Yes	103	No	No	Yes
47	Yes	Yes	Yes	116	Yes	Yes	Yes
42	No	No	No	95	Yes	Yes	Yes
52	Yes	Yes	Yes	112	Yes	No	Yes
48	Yes	Yes	Yes	102	No	No	No
46	No	No	Yes	101	Yes	Yes	Yes
54	Yes	Yes	Yes	109	No	No	Yes
50	No	No	Yes	111	Yes	Yes	Yes
53	No	No	Yes	115	Yes	No	Yes
56	Yes	Yes	Yes	110	Yes	Yes	Yes
55	Yes	Yes	Yes	113	Yes	Yes	Yes
82	Yes	Yes	Yes	114	Yes	No	Yes
61	No	No	Yes	117	No	No	Yes
64	No	No	Yes	118	Yes	Yes	Yes

B5.2 Backsawn Boards

	Checking ?		
Sample #	Face 1	Face2	Collapse ?
139A	Yes	Yes	Yes
135A	Yes	Yes	Yes
141A	Yes	No	Yes
138A	Yes	Yes	Yes
144A	Yes	Yes	Yes
145A	Yes	No	Yes
140A	Yes	Yes	Yes
142A	Yes	Yes	Yes
147A	Yes	Yes	Yes
152A	No	No	Yes
153A	Yes	Yes	Yes
154A	Yes	Yes	Yes
150A	Yes	Yes	Yes
155A	Yes	Yes	Yes
166A	Yes	Yes	Yes
165A	Yes	Yes	Yes
170A	Yes	Yes	Yes
166A	No	No	Yes
173A	Yes	Yes	Yes
175A	Yes	Yes	Yes
177A	Yes	Yes	Yes
178A	Yes	Yes	Yes

Appendix C. Pretreatment Trial data and results

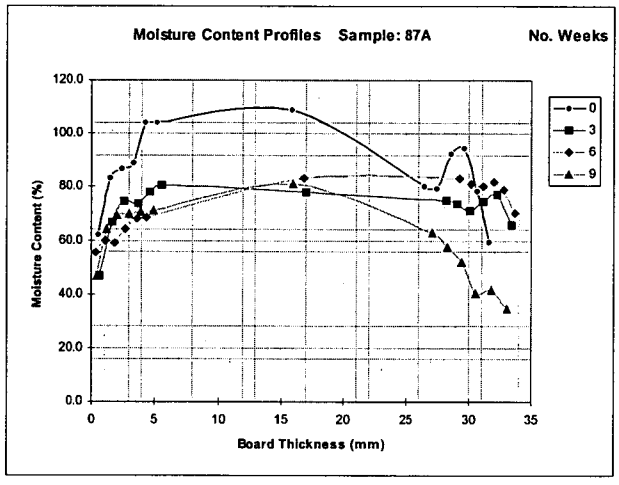
C1 Grading Data

Board #	Sct.	Std.	Ute.	End Split Length a (mm)	End Split Length b (mm)	Board #	Sct.	Std.	Ute.	End Split Length a (mm)	End Split Length b (mm)
1	*			300	0	51		*		400	200
2			*	100	75	52			*	0	610
3		*		125	240	53			*	700	600
4		*		130	0	54		*		400	400
5		*		400	275	55		*		400	0
6		*		475	225	56	*			350	450
7	*			0	0	57	*			0	45
8			*	320	0	58			*	0	300
9		*		500	0	59			*	600	150
10			*	370	0	60		*		150	150
11			*	700	700	61	*			100	300
12		*		100	0	62		*		0	0
13		*		0	0	63		*		0	600
14			*	200	100	64			*	320	500
15			*	350	0	65			*	410	800
16		*		340	0	66			*	500	200
17	*			240	0	67			*	0	0
18		*		220	225	68			*	0	0
19	*			220	225	69			*	500	0
20			*	0	0	70	*			600	50
21			*	300	0	71		*		0	200
22			*	500	225	72			*	0	0
23		*		0	0	73			*	300	300
24		*		300	200	74		*		200	100
25		*		0	100	75		*		0	0
26		*		610	250	76		*		350	150
27		*		300	0	77			*	0	0
28			*	300	150	78			*	300	0
29			*	0	600	79			*	0	450
30	*			0	750	80	*			200	100
31			*	175	600	81	*			300	150
32		*		100	0	82	*			300	300
33			*	200	450	83	*			400	0
34			*	350	300	84		*		520	0
35		*		300	250	85		*		200	0
36		*		300	0	86	*			300	220
37			*	250	0	87	*			300	200
38			*	250	0	88			*	-	300
39		*		350	100	89		*		250	100
40	*			0	150	90		*		0	200
41			*	670	0	91		*		250	200
42			*	700	600	92		*		200	150
43		*		0	300	93	*			250	200
44		*		500	0	94	*			220	100
45	*			200	0	95	*			220	100
46	*			275	0	96		*		0	300
47		*		320	300	97		*		250	150
48		*		0	0	98		*		300	150
49			*	800	610	99		*		0	250
50	*			100	300	100	*			300	0

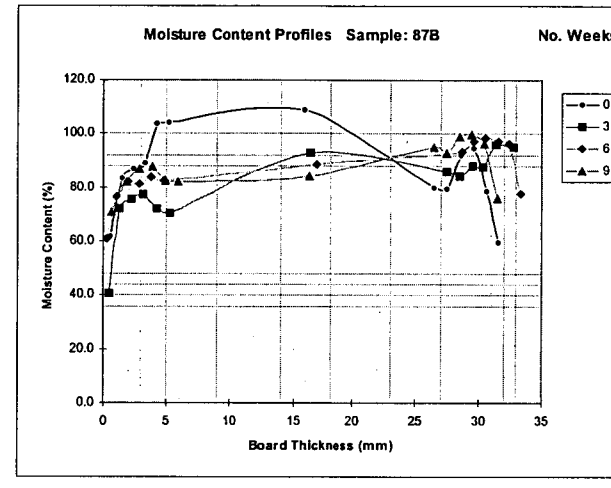
C2 Progressive Moisture Content Profile Graphs

C2.1 Salt/Hessian Regime and Control Graphs

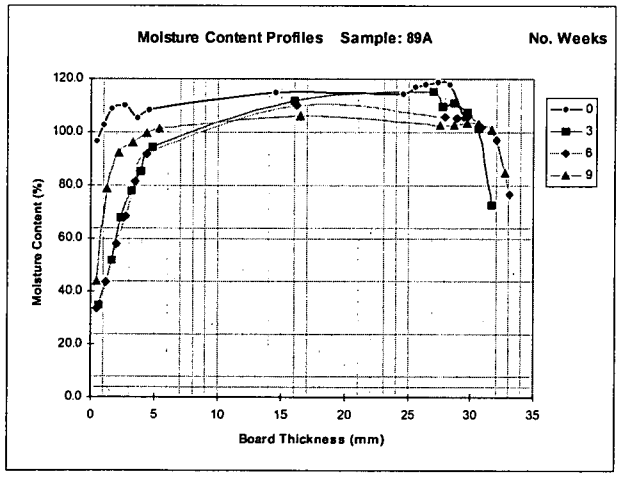
Regime Sample No. 87A



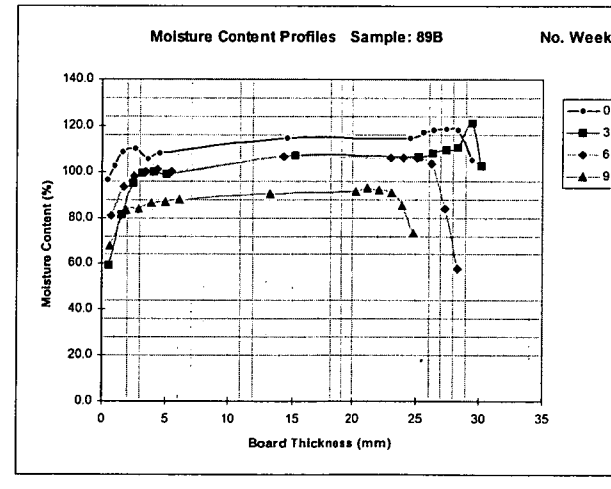
Control Sample No. 87B



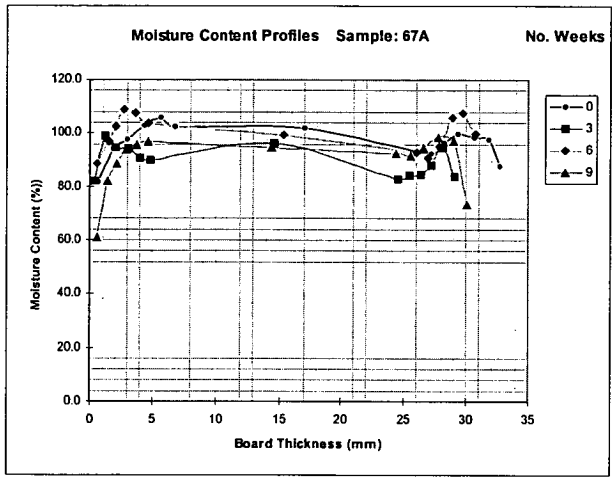
Regime Sample No. 89A



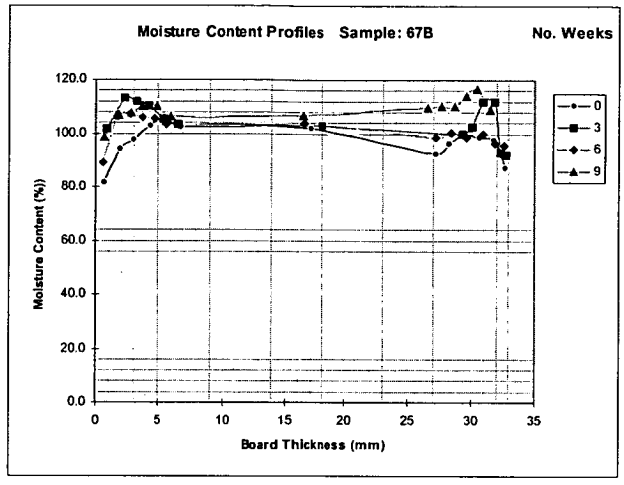
Control Sample No. 89B



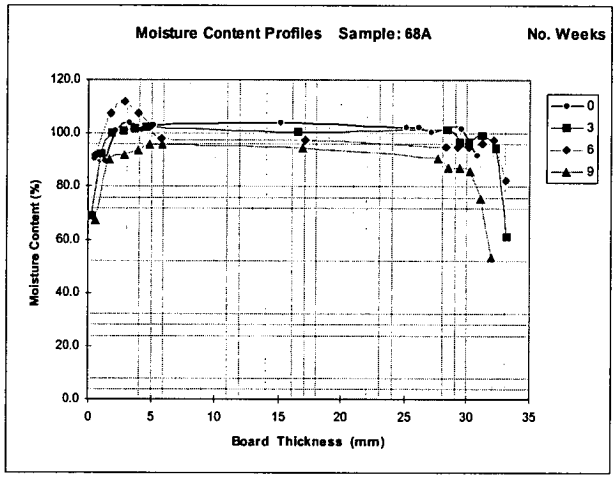
Regime Sample No. 67A



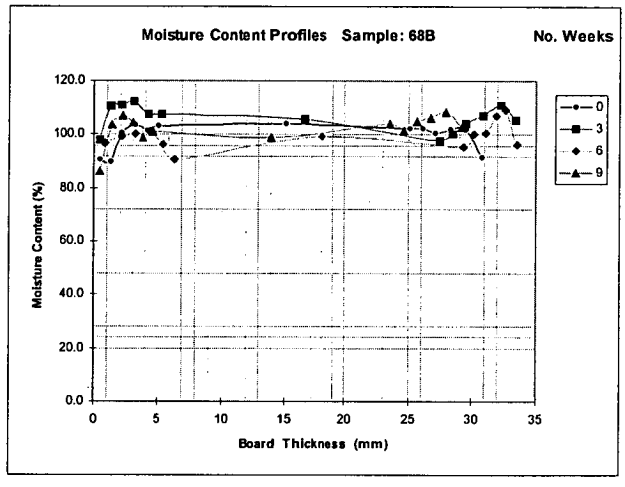
Control Sample No. 67B



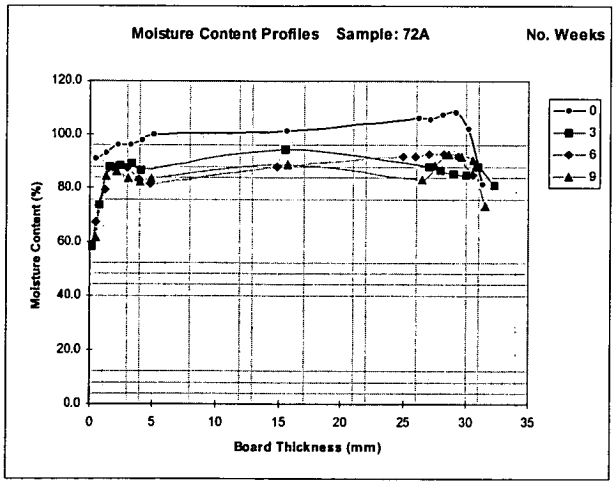
Regime Sample No. 68A



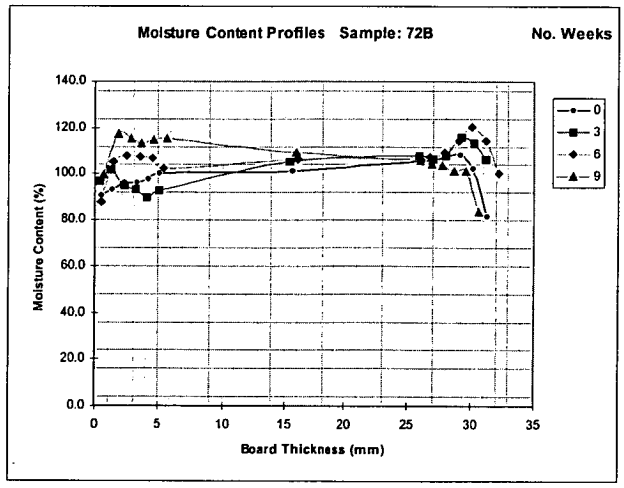
Control Sample No. 68B



Regime Sample No. 72A

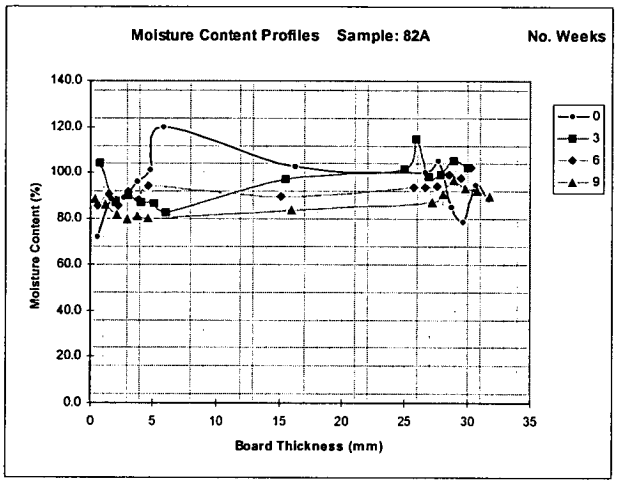


Control Sample No. 72B

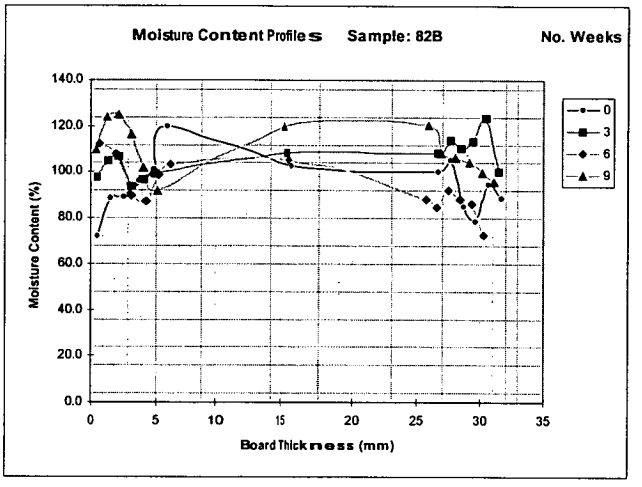


C2.1 Salt Solution Regime and Control Graphs

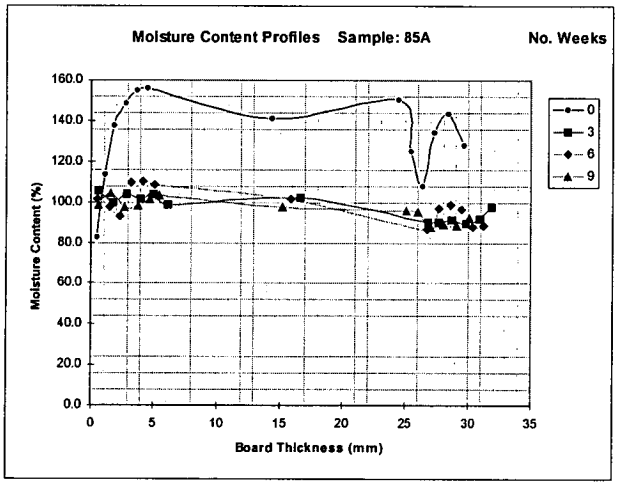
Regime Sample No. 82A



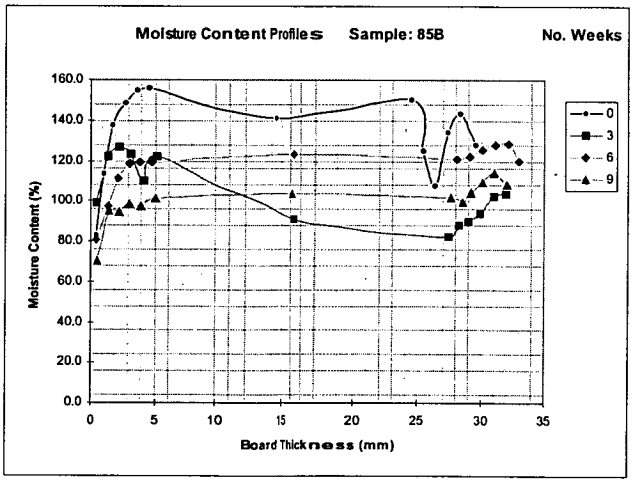
Control Sample No. 82B



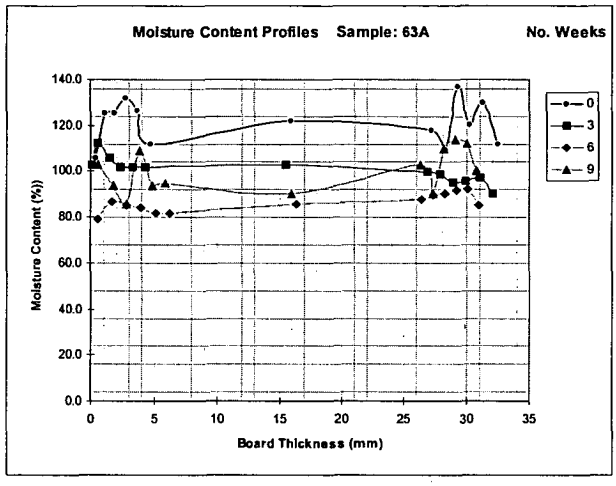
Regime Sample No. 85A



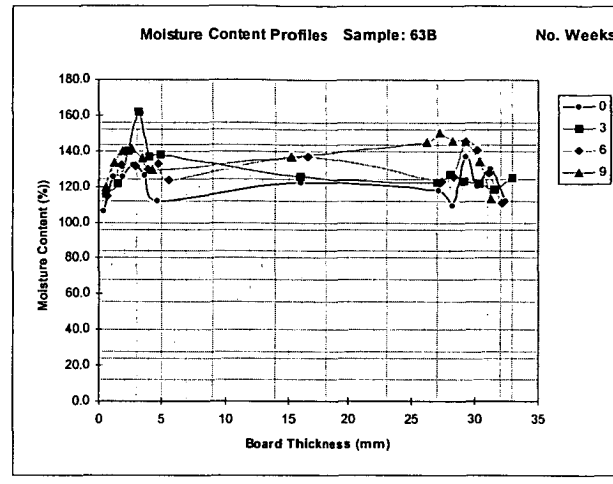
Control Sample No. 85B



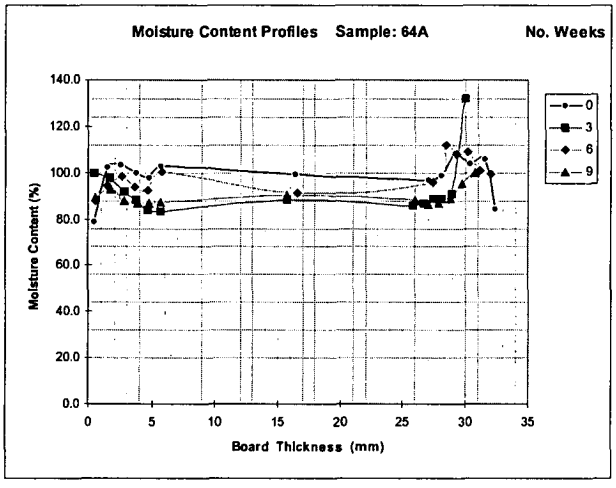
Regime Sample No. 63A



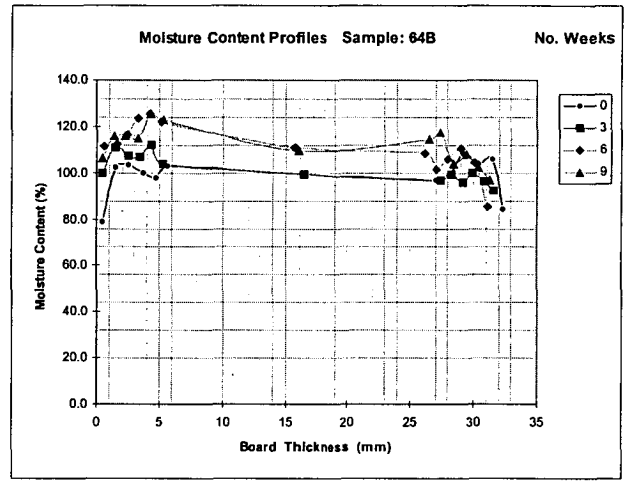
Control Sample No. 63B



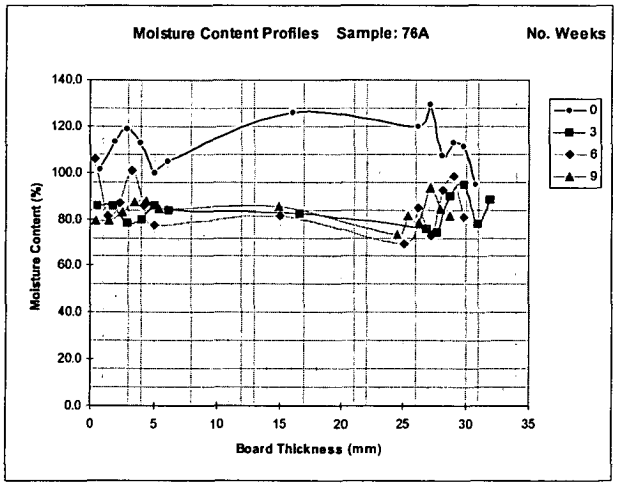
Regime Sample No. 64A



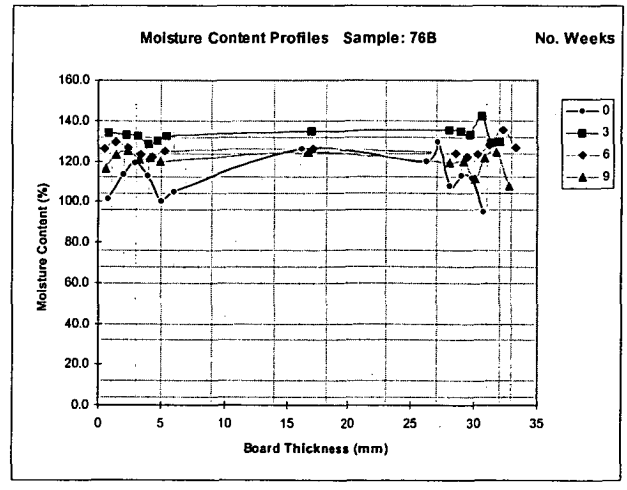
Control Sample No. 64B



Regime Sample No. 76A



Control Sample No. 76B



C3 Progressive Average Moisture Content and Basic Density Results

C3.1 Progressive Average MC Results

	Moisture Content (%)			
Sample #	Week 0	Week 3	Week 6	Week 9
87A	88.57	74.74	78.26	63.39
89A	111.69	82.96	87.25	90.85
72A	103.80	86.47	89.64	85.62
67A	104.77	92.62	100.71	91.83
68A	104.99	93.44	97.12	84.64

Salt/Hessian Regime

	Moisture Content (%)			
Sample #	Week 0	Week 3	Week 6	Week 9
87B	88.57	89.64	89.65	89.61
89B	104.33	102.27	103.44	104.11
72B	103.80	105.83	102.59	109.94
67B	104.77	105.2	103.94	111.29
68B	104.99	107.39	104.68	104.78

Salt/Hessian Control

	Moisture Content (%)			
Sample #	Week 0	Week 3	Week 6	Week 9
82A	102.18	97.73	95.7	90.26
64A	104.61	92.14	98.35	93.24
76A	120.38	86.18	84.94	89.16
63A	122.83	104.00	90.98	101.27
85A	134.96	103.62	103.6	101.64

Salt Solution Regime

	Moisture Content (%)			
Sample #	Week 0	Week 3	Week 6	Week 9
82B	102.18	106.45	103.12	105.44
64B	104.61	102.88	111.13	111.35
76B	120.38	130.84	128.77	125.51
63B	122.83	126.94	134.35	133.14
85B	125.85	121.13	120.46	124.46

Salt Solution Control

C3.2 Progressive Average Basic Density Results

	Basic Density (kg/m^3)			
Sample #	Week 0	Week 3	Week 6	Week 9
72A	505.7	538.8	536.2	538.5
89A	499.1	519.1	545.0	536.0
68A	540.3	524.1	529.5	536.2
67A	541.7	557.2	555.2	556.3
87A	570.5	597.4	596.5	643.1

Salt/Hessian Regime

	Basic Density (kg/m^3)			
Sample #	Week 0	Week 3	Week 6	Week 9
72B	505.7	515.5	522.7	486.3
89B	523.0	527.4	521.1	513.1
68B	540.3	527.4	551.0	540.1
67B	541.7	544.7	552.3	553.4
87B	570.5	576.4	580.3	577.4

Salt/Hessian Control

	Basic Density (kg/m^3)			
Sample #	Week 0	Week 3	Week 6	Week 9
85A	446.8	559.7	550.4	562.5
63A	496.0	544.3	563.3	548.4
64A	557.3	565.2	551.3	566.4
82A	498.0	578.3	581.8	605.2
76A	494.2	591.4	589.1	591.5

Salt Solution Regime

	Basic Density (kg/m^3)			
Sample #	Week 0	Week 3	Week 6	Week 9
82B	498.0	503.4	493.6	475.8
64B	557.3	551.73	545.3	540.1
76B	494.2	475.6	480.5	486.3
63B	496.0	487.8	468.3	464.6
85B	498.6	501.2	493.4	513.1

Salt Solution Control

C3.4 Presoaked Regime - Initial average moisture content and basic density results.

Sample #	M.C. (%)	Basic Density (kg/m^3)
101	108.64	495.6
102	104.52	520.0
103	91.08	539.4
104	103.06	532.7
105	91.21	546.0

C4 Collapse and Checking Data - Pre-reconditioning

C4.1 Salt/Hessian Regime

	Collapse? Y/N		Collapse? Y/N	
Board #	Side 1	Side 2	Side1	Side2
6	Y	Y	Y	Y
7	N	N	N	N
8	Y	Y	Y	N
9	N	Y	Y	Y
10	Y	Y	Y	Y
11	Y	Y	Y	Y
12	N	N	Y	Y
13	Y	N	N	N
14	Y	Y	N	N
15	Y	Y	N	Y
26	Y	Y	N	N
27	Y	Y	Y	Y
28	Y	Y	Y	Y
29	N	Y	N	N
30	N	Y	N	N
31	Y	Y	Y	Y
32	Y	N	Y	Y
33	N	N	N	Y
34	N	Y	N	Y
35	Y	Y	Y	Y
46	N	Y	N	Y
47	Y	N	N	N
48	N	N	N	Y
49	Y	Y	N	N
50	Y	N	Y	Y
51	Y	Y	Y	Y
52	N	N	N	N
53	N	Y	Y	Y
54	N	N	Y	N
55	Y	Y	Y	Y
66	Y	Y	Y	Y
69	Y	Y	N	N
70	N	N	N	N
71	N	Y	Y	N
73	N	N	N	N
74	N	N	Y	Y
75	Y	Y	N	N
86	Y	Y	Y	Y
88	Y	Y	Y	Y
90	Y	Y	Y	Y
91	Y	Y	Y	Y
92	Y	N	N	Y
93	Y	N	N	Y
94	Y	Y	Y	Y
95	N	N	N	N

C4.2 Salt/Hessian Control

	Collapse? Y/N		Collapse? Y/N	
Board #	Side 1	Side 2	Side1	Side2
6B	Y	Y	Y	Y
7B	Y	Y	N	N
8B	Y	N	Y	Y
9B	Y	Y	N	N
10B	Y	Y	Y	Y
11B	N	N	Y	Y
12B	N	N	N	Y
13B	Y	Y	N	N
14B	Y	N	Y	Y
15B	Y	Y	Y	Y
26B	Y	N	N	N
27B	Y	Y	Y	Y
28B	N	Y	Y	Y
29B	N	Y	Y	Y
30B	N	Y	Y	Y
31B	Y	Y	Y	Y
32B	Y	Y	N	N
33B	Y	Y	Y	Y
34B	Y	Y	Y	Y
35B	Y	N	N	N
46B	N	N	Y	N
47B	Y	Y	N	Y
48B	N	N	Y	Y
49B	Y	Y	Y	Y
50B	N	Y	Y	Y
51B	N	Y	Y	Y
52B	Y	Y	Y	Y
53B	Y	Y	Y	Y
54B	Y	Y	Y	Y
55B	Y	Y	Y	Y
66B	Y	Y	N	N
69B	Y	Y	Y	Y
70B	Y	Y	N	Y
71B	Y	Y	N	Y
73B	Y	Y	Y	Y
74B	Y	Y	Y	Y
75B	Y	Y	Y	Y
86B	Y	Y	Y	Y
90B	N	Y	N	N
91B	N	Y	N	N
93B	Y	Y	Y	Y
94B	Y	Y	Y	Y
95B	Y	Y	Y	Y

C4.3 Salt Solution Regime

	Collapse? Y/N		Collapse? Y/N	
Board #	Side 1	Side 2	Side1	Side2
1	Y	Y	Y	Y
2	Y	Y	Y	Y
3	Y	Y	Y	Y
16	Y	Y	Y	Y
17	N	Y	Y	Y
18	Y	Y	Y	Y
19	Y	Y	Y	Y
20	Y	Y	Y	Y
21	Y	Y	Y	Y
22	Y	Y	Y	Y
23	Y	Y	Y	Y
24	Y	Y	Y	Y
25	Y	Y	Y	Y
36	Y	Y	Y	Y
37	Y	Y	Y	Y
38	Y	Y	Y	Y
39	Y	Y	Y	Y
40	Y	Y	Y	Y
41	Y	Y	Y	Y
42	Y	Y	Y	Y
43	Y	Y	Y	Y
44	Y	Y	Y	Y
45	Y	Y	Y	Y
56	Y	Y	Y	Y
57	Y	Y	Y	Y
58	Y	Y	Y	Y
59	Y	Y	Y	Y
60	Y	Y	Y	Y
76	Y	Y	Y	Y
77	N	N	Y	Y
78	Y	Y	Y	Y
79	Y	Y	Y	Y
80	Y	Y	Y	Y
81	Y	Y	Y	Y
82	Y	Y	Y	Y
83	Y	Y	N	Y
84	Y	Y	Y	Y
85	Y	Y	Y	Y
96	Y	Y	Y	Y
97	Y	Y	Y	Y
98	Y	Y	Y	Y
99	Y	Y	Y	Y
100	Y	Y	Y	Y

C4.4 Salt Solution Control

	Collapse? Y/N		Collapse? Y/N	
Board #	Side 1	Side 2	Side1	Side2
1B	N	N	Y	Y
2B	N	N	Y	Y
3B	N	N	Y	Y
4B	Y	Y	Y	Y
5B	Y	Y	Y	Y
16B	Y	Y	Y	Y
17B	N	N	N	Y
18B	Y	Y	Y	Y
19B	Y	Y	Y	Y
20B	Y	Y	Y	Y
21B	Y	Y	Y	Y
22B	Y	Y	Y	Y
23B	Y	Y	Y	Y
24B	Y	Y	N	Y
25B	N	N	N	N
36B	Y	Y	Y	Y
37B	Y	Y	Y	Y
38B	Y	Y	Y	Y
39B	Y	Y	Y	Y
40B	N	N	Y	Y
41B	Y	Y	Y	Y
42B	Y	Y	Y	Y
43B	Y	Y	Y	Y
44B	Y	Y	N	Y
45B	N	N	Y	Y
56B	Y	Y	Y	Y
57B	N	N	Y	Y
58B	Y	Y	Y	Y
59B	Y	N	N	N
60B	N	Y	Y	Y
61B	N	Y	Y	Y
62B	N	N	Y	Y
65B	Y	Y	N	N
77B	N	N	Y	Y
78B	Y	Y	Y	Y
79B	N	Y	N	N
80B	Y	Y	Y	Y
81B	Y	N	Y	N
83B	Y	N	Y	N
84B	Y	N	Y	Y
96B	Y	Y	Y	Y
97B	N	N	N	N
98B	N	N	Y	Y
99B	Y	Y	N	Y
100B	Y	Y	N	N

C4.5 Presoaked Regime

	Collapse? Y/N		Collapse? Y/N	
Board #	Side 1	Side 2	Side1	Side2
106	Y	Y	Y	Y
107	Y	Y	Y	Y
108	Y	N	N	N
109	Y	Y	N	N
110	N	N	Y	Y
111	Y	N	N	N
112	N	N	N	N
113	Y	Y	Y	Y
114	N	N	Y	N
115	N	N	Y	Y
116	Y	N	Y	Y
117	Y	N	N	Y
118	Y	N	Y	Y
119	Y	N	Y	Y
120	Y	N	N	N
121	Y	Y	N	Y
122	Y	Y	N	Y
123	Y	Y	Y	N
124	Y	Y	Y	N
125	Y	Y	Y	Y
126	Y	Y	Y	Y
127	Y	Y	Y	Y
128	N	Y	Y	Y
129	Y	Y	N	Y
130	Y	Y	N	Y
131	Y	Y	N	Y
132	N	Y	Y	Y
133	Y	Y	Y	Y
134	Y	Y	N	N
135	N	Y	Y	Y
137	N	N	N	N
138	Y	Y	Y	Y
139	Y	Y	Y	Y
140	Y	Y	Y	Y
141	N	Y	N	N
142	Y	Y	N	N
143	Y	Y	Y	Y
144	Y	Y	Y	Y
145	Y	Y	Y	Y
146	Y	Y	N	N
147	N	Y	Y	Y
148	Y	Y	N	Y
149	Y	Y	N	N
150	Y	Y	N	Y

C5 Checking Penetration Data

C5.1 Salt/Hessian Regime

Board #	Checking Length along Board mm					
	Up Side 25mm	Down Side 25mm	Up Side 22mm	Down Side 22mm	Up Side 19mm	Down Side 19mm
6	0	110	0	0	0	0
7	550	140	0	0	0	0
8	1930	1370	800	670	440	130
9	1670	2400	450	220	370	0
10	480	2400	0	270	0	110
11	940	1160	270	380	90	0
12	2110	100	730	50	0	0
14	2400	860	1550	460	440	120
15	1220	2400	1140	130	980	90
26	470	130	480	0	250	0
27	2400	2400	2400	2400	2400	760
28	2400	2400	2400	2400	1390	370
29	0	1260	0	0	0	0
30	590	730	0	210	0	0
31	580	900	0	0	0	0
32	0	0	0	0	0	0
33	1580	2400	310	750	0	0
34	1900	1230	740	350	570	310
35	0	690	0	0	0	0
46	2050	1490	1410	740	1680	630
47	2400	1610	0	0	0	0
48	1230	1670	0	0	0	0
49	850	730	0	0	0	0
50	0	0	0	0	0	0
51	0	1450	0	0	0	0
52	1930	1370	200	260	150	40
53	1260	1500	820	940	910	340
54	440	2400	280	240	110	0
55	730	180	0	0	0	0
66	260	2180	200	90	70	0
69	250	870	270	0	0	0
70	2400	2300	1970	2200	1190	340
71	1650	770	590	320	0	0
72	2400	1000	1040	310	550	320
73	1870	2400	1080	2400	950	460
74	2400	2400	2400	2330	2400	1620
75	160	660	0	0	0	0
86	2400	2400	1820	760	370	530
88	2160	1350	0	0	0	0
90	2400	1690	1230	390	850	60
93	0	0	0	0	0	0
94	2400	2120	1140	810	1020	330
95	2400	2400	1870	2400	720	1080

C5.2 Salt/Hessian Control

Board #	Checking Length along Board mm					
	Up Side 25mm	Down Side 25mm	Up Side 22mm	Down Side 22mm	Up Side 19mm	Down Side 19mm
6B	1710	910	520	800	30	150
7B	1420	0	100	0	0	0
8B	1670	130	730	0	370	0
9B	0	170	0	0	0	0
10B	670	270	70	0	0	0
11B	450	200	300	40	100	0
12B	70	0	0	0	0	0
13B	600	730	0	310	0	0
14B	160	170	0	0	0	0
15B	870	180	820	0	500	0
26B	0	330	0	0	0	0
27B	1600	2800	1420	1960	260	300
28B	2800	310	2800	0	420	0
29B	510	700	540	630	520	550
30B	300	300	0	0	0	0
31B	0	2470	0	0	0	0
32B	0	0	0	0	0	0
33B	230	430	160	240	440	80
34B	450	460	380	410	750	270
35B	0	170	0	0	0	0
46B	640	2800	120	1780	120	470
47B	200	170	0	0	0	0
48B	160	230	60	0	60	0
49B	840	250	440	170	320	0
50B	0	500	0	0	0	0
51B	0	2470	0	0	0	0
52B	290	0	650	0	120	0
53B	1750	1780	1720	660	820	110
55B	1020	70	830	0	830	0
66B	1250	90	910	50	230	0
69B	920	1970	660	1120	370	1000
70B	2800	1430	1340	1420	670	1110
71B	110	1520	0	270	0	100
73B	1350	2800	870	2510	780	2140
74B	2410	2240	1180	1450	570	960
75B	380	0	0	0	0	0
86B	2800	2510	1790	1880	1000	630
88B	0	100	0	0	0	0
90B	2800	2150	2800	640	2800	370
91B	2740	2800	1680	2800	540	2800
92B	2380	1920	2260	1380	1700	460
93B	440	0	0	0	0	0
94B	2800	2170	2800	1900	1790	500
95B	2800	2800	1320	2800	990	1490

C5.3 Salt Solution Regime

	Checking Length along Board mm					
Board #	Up Side 25mm	Down Side 25mm	Up Side 22mm	Down Side 22mm	Up Side 19mm	Down Side 19mm
1	0	200	0	0	0	0
2	610	1360	860	1000	930	1090
3	0	710	0	700	0	770
4	1250	500	580	410	400	350
5	100	0	0	0	0	0
16	550	1710	700	930	900	610
17	0	0	0	0	0	0
18	100	350	100	400	0	300
19	540	110	280	500	200	0
20	0	0	0	0	0	0
21	1020	1110	670	560	570	430
22	790	1100	220	1020	0	900
23	550	380	240	840	200	450
24	0	1010	0	190	0	0
25	0	0	0	0	0	0
36	640	2400	220	1140	0	880
37	0	0	0	0	0	0
38	650	480	640	640	500	600
39	680	950	660	450	450	260
40	0	480	0	0	0	0
41	0	0	0	0	0	0
42	800	0	410	0	240	0
43	670	400	180	580	100	60
44	0	0	0	0	0	0
45	1140	2400	500	2400	250	900
56	1600	990	810	470	240	80
57	1670	1800	1750	2100	890	1520
58	2040	2400	1830	1640	1470	1600
59	1410	2400	120	360	0	0
60	640	1260	310	360	0	0
61	0	2400	0	240	0	0
62	1690	360	1700	1350	1370	150
65	1710	1090	1630	1020	1420	820
77	1450	0	0	0	0	0
78	640	2050	0	220	0	0
79	0	0	0	0	0	0
80	2400	2400	1550	1140	1100	1160
81	1010	1860	780	780	690	560
83	0	0	0	0	0	0
84	0	2010	0	1630	0	1060
96	1900	1260	330	740	240	650
97	630	0	0	0	0	0
98	1950	2280	1770	2240	1600	2250
99	680	1260	440	90	0	0
100	360	1270	310	310	0	350

C5.4 Salt Solution Control

	Checking Length along Board mm					
Board #	Up Side 25mm	Down Side 25mm	Up Side 22mm	Down Side 22mm	Up Side 19mm	Down Side 19mm
1B	2800	1100	2140	290	580	0
2B	2800	720	2800	510	1710	250
3B	1050	2800	430	2800	240	1660
4B	2800	2110	1450	500	1000	0
5B	2800	2800	2300	1340	80	1010
16B	1860	2800	160	2800	190	2800
17B	980	950	0	0	0	0
18B	2800	2800	2800	780	2800	0
19B	1230	2800	130	2800	0	2800
21B	2800	2800	2800	2240	2800	610
22B	1300	2800	550	2680	400	960
23B	2800	2800	2800	1710	800	850
24B	740	1750	130	1420	70	660
25B	0	0	0	0	0	0
36B	1190	2800	620	2800	290	2800
37B	280	2800	0	2800	0	2800
38B	2800	2800	2800	200	2800	100
39B	2800	1540	810	0	210	0
40B	1200	2600	650	1290	260	340
42B	2800	2800	1090	2800	1020	250
43B	0	2800	0	890	0	90
44B	990	280	0	0	0	0
45B	2800	1340	180	0	0	0
56B	2800	2800	2800	1130	1650	370
57B	2700	2280	1070	1500	180	1400
58B	2800	2200	2800	0	2600	0
59B	0	500	0	110	0	0
60B	2470	2800	1360	2800	1020	1980
61B	840	1540	0	410	0	0
62B	520	2800	160	0	60	0
65B	0	2000	0	0	0	0
77B	880	670	620	150	440	50
78B	1480	2580	890	1970	700	2060
79B	2090	460	1800	90	50	70
80B	1090	2080	300	1800	290	930
81B	790	2800	600	2650	290	1490
83B	570	90	0	0	0	0
84B	680	110	0	0	0	0
96B	1630	1100	980	620	350	150
97B	2640	1010	1060	380	230	80
98B	800	2800	200	480	100	180
99B	1790	60	50	0	0	0
100B	0	100	0	0	0	0

C5.5 Presoaked Regime

	Checking Length along Board mm					
Board #	Up Side 25mm	Down Side 25mm	Up Side 22mm	Down Side 22mm	Up Side 19mm	Down Side 19mm
109	3000	3000	2670	200	2110	0
110	460	90	0	0	0	0
111	3000	3000	3000	800	3000	0
112	690	980	440	160	70	0
113	860	3000	520	1250	0	930
114	3000	2600	3000	420	3000	0
115	2410	0	1280	0	0	0
116	2020	3000	970	1920	0	0
117	2940	3000	3000	3000	3000	3000
118	1070	3000	180	490	0	120
119	0	200	0	0	0	0
120	2210	1500	1380	70	0	0
121	0	3000	0	0	0	0
122	800	1980	0	0	0	0
123	220	1970	500	1310	0	0
124	1720	3000	650	0	0	0
125	0	1170	0	0	0	0
126	60	3000	0	2670	0	1800
127	3000	3000	300	0	60	0
128	2150	220	610	100	0	0
129	220	1580	0	0	0	0
130	210	3000	320	1180	0	570
131	200	720	0	0	0	0
132	3000	3000	3000	3000	890	1400
133	240	250	0	0	0	0
134	1720	2890	1560	1460	1500	0
135	3000	0	200	0	0	0
136	1270	260	330	0	0	0
137	190	1160	0	60	0	0
138	220	1880	0	0	0	0
139	1980	3000	170	0	0	0
140	3000	1940	2750	820	1880	260
141	490	860	0	0	0	0
142	980	1470	390	880	0	0
143	3000	2820	3000	800	3000	590
144	0	1800	0	0	0	0
145	2690	3000	1490	130	800	0
146	1040	3000	980	90	0	0
147	120	1030	0	250	0	250
148	650	1440	0	350	0	0
149	170	3000	0	0	0	0
150	80	1320	0	0	0	0

C6 Internal Checking Data

C6.1 Salt/Hessian Regime

Board #	Cut (a)			Cut (b)			Cut (c)			Cut (d)		
	# Checks	Ring Width	# Rings	# Checks	Ring Width	# Rings	# Checks	Ring Width	# Rings	# Checks	Ring Width	# Rings
10	4	4.03	1	5	3.91	1	3	2.99	3	-	-	-
27	8	2.42	1	3	2.52	1	-	-	-	-	-	-
35	-	-	-	1	2.88	1	-	-	-	1	7.07	1
46	-	-	-	3	3.05	2	3	2.97	1	1	2.51	1
50	-	-	-	5	7.16	2	1	4.26	1	1	3.44	1
72	2	4.67	2	2	4.12	1	18	4.83	2	15	4.68	4
90	-	-	-	3	3.65	1	6	3.49	2	7	2.59	2
93	-	-	-	2	3.74	1	2	3.66	1	1	3.62	1
94	7	3.2	2	9	3.98	3	12	4.21	3	4	7.92	2
95	10	3.18	3	14	3.51	2	13	4.19	2	3	4.76	1

C6.2 Salt/Hessian Control

Board #	Cut (a)			Cut (b)			Cut (c)			Cut (d)		
	# Checks	Ring Width	# Rings	# Checks	Ring Width	# Rings	# Checks	Ring Width	# Rings	# Checks	Ring Width	# Rings
15B	-	-	-	-	-	-	-	-	-	1	4.23	1
34B	-	-	-	-	-	-	-	-	-	1	4.28	1
70B	-	-	-	-	-	-	3	2.13	1	3	3.15	1
90B	4	3.74	2	1	3.95	1	-	-	-	-	-	-
94B	-	-	-	4	4.87	2	4	8.51	2	2	7.5	1
95B	-	-	-	3	4.24	1	4	4.31	1	-	-	-

C6.3 Salt Solution Regime

Board #	Cut (a)			Cut (b)			Cut (c)			Cut (d)		
	# Checks	Ring Width	# Rings	# Checks	Ring Width	# Rings	# Checks	Ring Width	# Rings	# Checks	Ring Width	# Rings
2	4	2.46	1	5	2.77	1	9	3.34	2	2	3.37	1
3	1	2.22	1	1	2.34	1	3	3.43	1	5	2.81	3
5	4	3.75	2	4	3.16	2	4	4.49	3	13	4.92	6
16	3	2.58	1	10	3.48	2	4	2.7	3	10	3.48	2
17	8	1.81	3	-	-	-	6	2.44	2	5	3.13	3
18	-	-	-	4	3.7	3	2	1.96	1	-	-	-
19	1	4.81	1	8	2.48	3	13	2.27	4	10	2.15	3
21	7	3.43	4	-	-	-	2	2.82	2	7	3.25	4
23	8	3.22	2	6	2.23	1	5	2.22	1	1	3.12	1
36	2	3.53	1	2	2.8	1	3	3.07	1	2	2.87	1
37	1	3.12	1	-	-	-	3	2.52	2	-	-	-
39	5	3.56	2	6	3.88	3	2	3.89	1	5	3.91	3
43	11	3.63	2	16	4.86	3	12	3.9	4	1	3.02	1
45	3	2.81	1	8	2.26	3	7	2.92	2	4	3.08	2
58	9	2.7	2	4	2.48	1	15	4.57	5	9	4.86	3
59	1	2.22	1	-	-	-	-	-	-	-	-	-
60	-	-	-	-	-	-	6	2.91	2	6	3.38	2
65	6	3	4	16	3.23	4	5	3.54	2	4	5.76	3
80	11	1.77	1	3	1.84	2	5	2.77	2	4	2.47	1
81	1	2.2	1	7	2.48	1	4	3.55	1	4	3.12	1
84	27	3.6	5	2	3.84	1	14	5.24	4	2	6.12	2
98	6	2.35	1	-	-	-	46	4.9	5	16	6.43	5

C6.4 Salt Solution Control

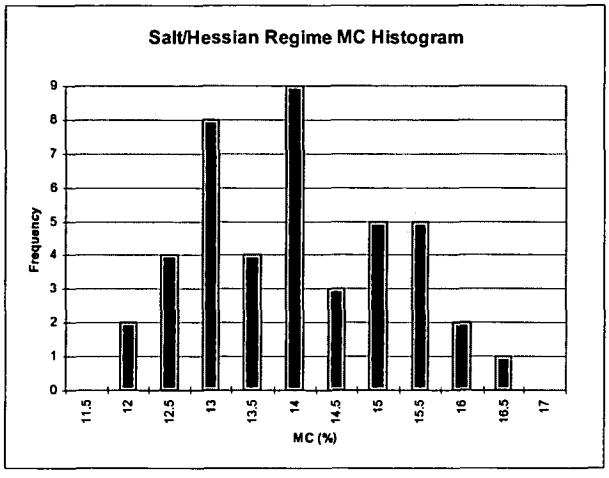
Board #	Cut (a)			Cut (b)			Cut (c)			Cut (d)		
	# Checks	Ring Width	# Rings	# Checks	Ring Width	# Rings	# Checks	Ring Width	# Rings	# Checks	Ring Width	# Rings
18B	-	-	-	-	-	-	4	2.86	1	-	-	-
23B	3	5.25	1	-	-	-	-	-	-	-	-	-
40B	2	2.33	1	2	2.12	1	-	-	-	-	-	-

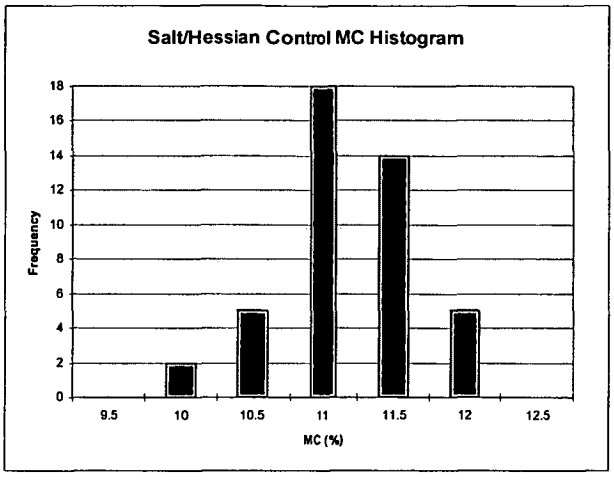
C6.5 Presoaked Regime

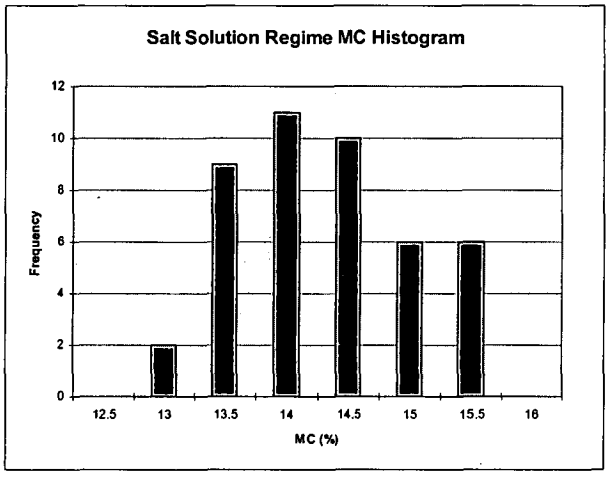
Board #	Cut (a)			Cut (b)			Cut (c)			Cut (d)		
	# Checks	Ring Width	# Rings	# Checks	Ring Width	# Rings	# Checks	Ring Width	# Rings	# Checks	Ring Width	# Rings
121	2	2.82	1	3	3.06	1	12	7.26	1	4	3.71	1

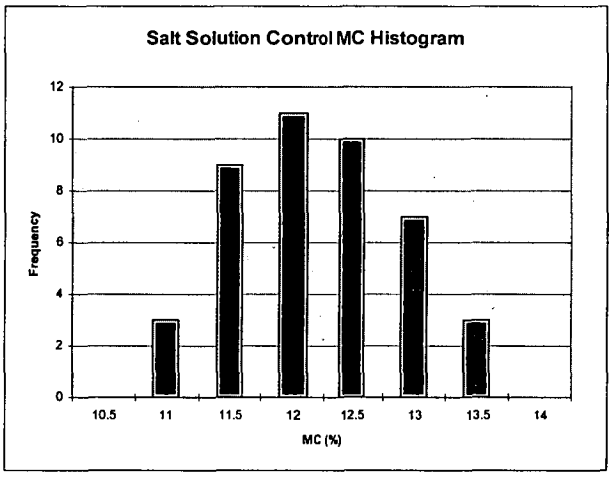
C7 Final Average MC and Dry Density Data

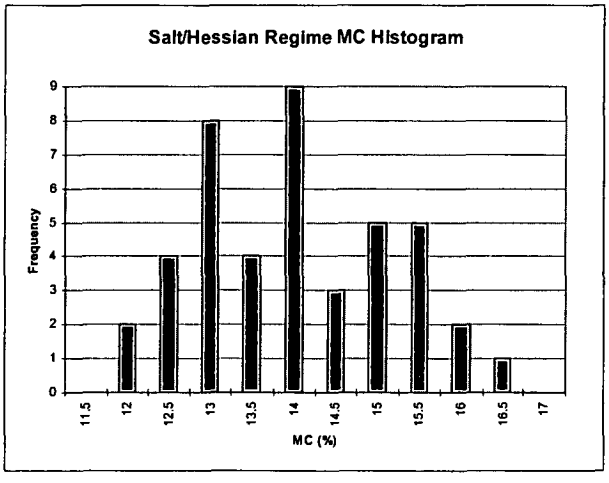
C7.1 MC Histograms



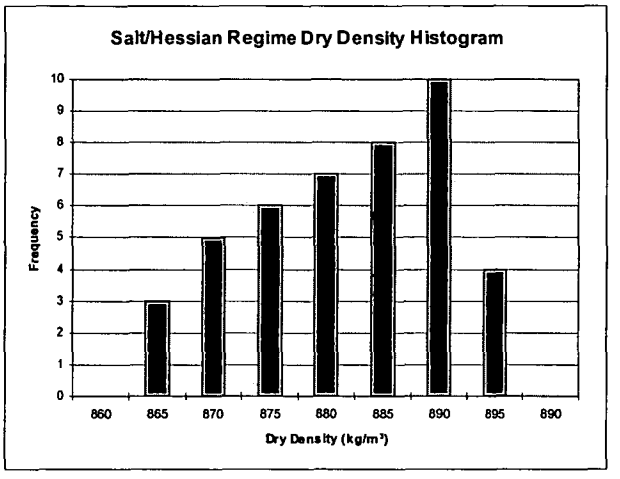


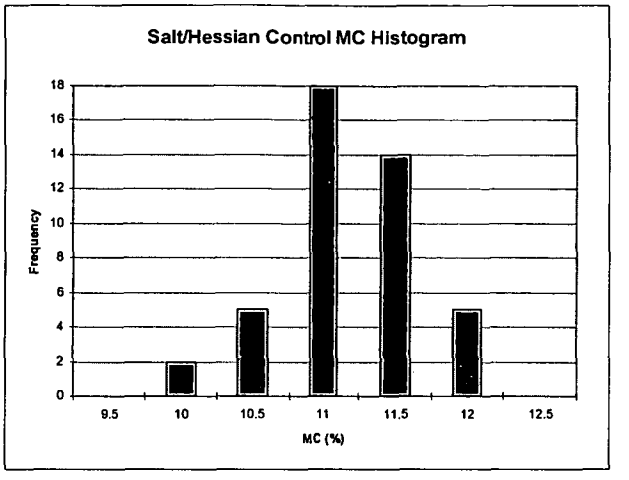


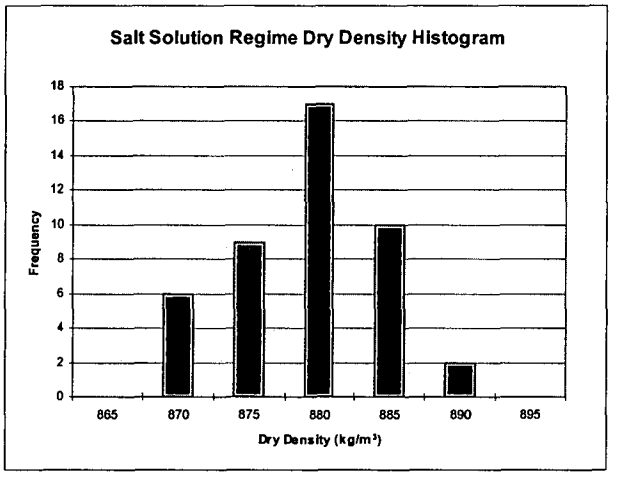


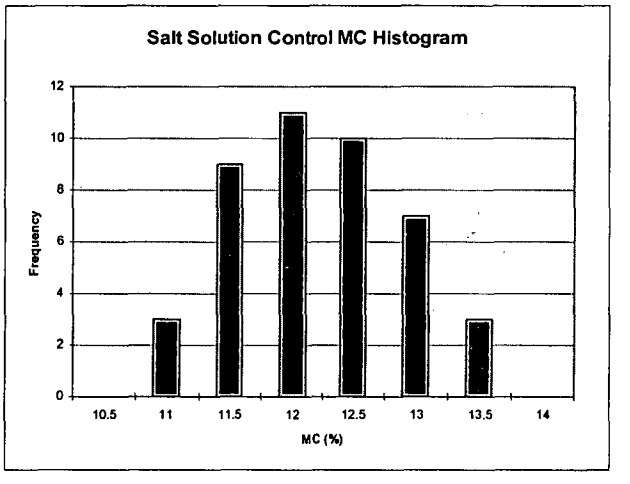


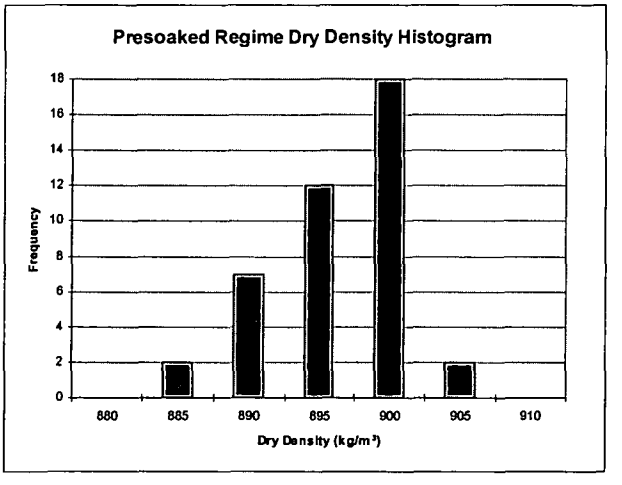
C7.2 Dry Density Histograms











Appendix D. Moisture Meter Species Correction Data

D1 Initial MC, BD and Predicted Oven Dry Weight Results

	Basic Density & Initial MC -Small Sample				Oven Dry Weight -large sample	
Sample #	M_w (g)	M_d (g)	B.D. (kg/m^3)	MC (%)	$M_{initial}$ (g)	O.D.W (g)
A1	61.15	53.46	758	14.4	415.98	363.70
A2	65.22	57.05	751	14.3	428.90	375.20
A3	58.96	51.57	747	14.3	411.41	359.85
A4	65.14	56.96	741	14.4	397.15	347.28
A5	63.65	55.68	737	14.3	405.13	354.42
B1	55.62	48.60	738	14.4	390.40	341.13
B2	61.83	54.02	738	14.4	405.44	354.26
B3	55.86	48.67	737	14.8	388.12	338.15
B4	62.39	54.42	741	14.7	378.85	330.44
B5	61.08	53.24	736	14.7	386.93	337.24
C1	50.01	43.83	703	14.1	354.22	310.46
C2	56.96	49.95	729	14.0	364.27	319.43
C3	51.31	45.02	747	14.0	360.84	316.59
C4	59.38	52.03	759	14.1	357.55	313.27
C5	58.45	51.22	772	14.1	368.30	322.74
D1	64.20	56.23	775	14.2	414.86	363.39
D2	67.33	58.91	771	14.3	421.67	368.95
D3	56.78	49.61	764	14.5	415.39	362.94
D4	63.62	55.56	752	14.5	420.30	367.05
D5	52.22	45.66	760	14.4	420.41	367.61
E1	57.28	50.09	700	14.4	372.76	325.97
E2	60.63	53.06	712	14.3	383.00	335.17
E3	51.82	45.26	724	14.5	381.19	332.97
E4	59.86	52.29	742	14.5	401.47	350.71
E5	49.52	43.34	764	14.3	402.03	351.84
F1	58.68	51.33	772	14.3	384.00	335.92
F2	62.58	54.81	777	14.2	387.53	339.40
F3	52.22	45.74	771	14.2	384.65	336.95
F4	59.20	51.79	764	14.3	387.60	339.11
F5	47.38	41.40	746	14.4	384.56	336.01
G1	46.76	40.84	733	14.5	369.02	322.29
G2	49.89	43.60	743	14.4	357.68	312.58
G3	53.62	46.87	728	14.4	367.66	321.36
G4	52.05	45.49	741	14.4	363.99	318.12
G5	51.45	45.04	733	14.2	367.47	321.68
H1	50.23	43.98	726	14.2	394.65	345.57
H2	53.74	47.05	727	14.2	385.02	337.10
H3	58.35	51.05	720	14.3	396.24	346.66
H4	56.02	48.99	737	14.4	389.36	340.49
H5	56.34	49.30	737	14.3	401.71	351.50

Averages	743.8	14.3

D2 Meter calibration results at approximately 18% MC

		Resistance Type-model					Capacitance Type-model				
		G-30 MC(%)		RC-IC MC(%)			M10-1 MC(%)		M10-2 MC(%)		
Sample #	Approx. MC(%)	Side 1	Side 2	Side 1	Side 2	AVE.	Side 1	Side 2	Side 1	Side 2	AVE.
A1	18.4	15.0	15.1	14.9	15.2	15.1	21.0	20.5	20.0	20.5	20.5
A2	18.3	15.1	15.1	15.1	15.2	15.1	21.0	21.5	20.5	21.5	21.1
A3	18.3	15.1	15.1	15.1	15.2	15.1	20.5	21.0	20.0	21.0	20.6
A4	17.8	14.9	14.8	14.9	14.8	14.9	20.0	20.0	19.5	20.0	19.9
A5	17.5	14.6	14.6	14.7	14.6	14.6	19.5	20.0	19.5	19.5	19.6
B1	18.6	15.5	15.5	15.5	15.5	15.5	21.0	22.0	20.0	21.0	21.0
B2	18.5	15.5	15.5	15.5	15.5	15.5	21.0	22.0	20.5	21.0	21.1
B3	18.8	15.1	15.0	15.2	15.1	15.1	21.0	21.5	20.5	21.5	21.1
B4	18.0	14.7	14.5	14.6	14.5	14.6	21.0	21.0	21.0	21.0	21.0
B5	18.7	15.0	15.0	14.9	15.0	15.0	21.0	21.5	21.0	21.5	21.3
C1	17.9	16.5	16.6	16.5	16.6	16.6	19.0	19.0	19.0	19.0	19.0
C2	18.2	17.0	17.0	16.8	17.0	17.0	20.0	19.5	19.0	19.5	19.5
C3	18.2	16.7	17.0	16.6	16.9	16.8	19.5	20.0	19.5	20.0	19.8
C4	17.9	16.0	16.7	16.5	16.6	16.5	21.0	21.0	20.5	20.0	20.6
C5	17.5	16.2	16.3	16.2	16.4	16.3	21.0	21.0	20.5	21.0	20.9
D1	18.0	15.2	15.2	15.3	15.3	15.3	20.5	20.5	20.5	20.0	20.4
D3	18.3	15.5	15.1	15.5	15.2	15.3	22.0	20.5	21.5	20.5	21.1
D4	18.3	15.9	15.1	15.9	15.1	15.5	21.0	20.5	20.5	20.0	20.5
D5	18.1	15.1	15.1	15.2	15.2	15.2	20.5	20.5	20.5	20.5	20.5
E1	17.5	16.5	16.8	16.6	16.6	16.6	19.0	18.5	19.5	18.0	18.8
E2	18.6	17.5	17.5	17.7	17.7	17.6	21.0	20.0	20.5	20.0	20.4
E3	17.8	16.9	16.8	16.8	16.8	16.8	20.0	20.0	20.0	20.0	20.0
E4	17.7	17.0	17.0	17.0	17.0	17.0	21.5	20.5	21.0	20.0	20.8
E5	17.6	16.9	16.2	16.9	16.3	16.6	21.0	21.0	21.0	21.0	21.0
F1	18.3	15.1	15.1	15.1	15.1	15.1	22.0	21.0	22.0	21.0	21.5
F2	17.6	14.6	15.0	14.7	15.1	14.9	21.0	19.5	20.0	19.5	20.0
F4	17.6	14.6	14.8	14.5	14.8	14.7	20.5	19.5	20.5	19.5	20.0
F5	17.8	14.5	14.9	14.3	14.9	14.7	20.5	20.0	20.0	20.0	20.1
G1	18.9	15.3	15.2	15.2	15.1	15.2	22.0	22.0	22.0	22.0	22.0
G2	18.7	15.2	15.2	15.2	15.1	15.2	22.0	21.5	21.0	21.0	21.4
G3	18.2	14.5	15.0	14.5	15.0	14.8	20.5	21.0	20.5	20.5	20.6
G4	18.9	15.0	15.0	15.1	15.1	15.1	22.0	21.0	21.5	21.0	21.4
G5	18.8	15.1	15.1	15.1	15.1	15.1	21.5	20.5	21.5	20.5	21.0
H1	18.4	17.8	17.7	17.8	17.8	17.8	21.0	21.0	20.0	20.0	20.5
H2	18.4	16.8	17.5	17.0	17.5	17.2	19.5	20.0	20.0	19.5	19.8
H3	18.1	17.0	17.0	17.0	17.0	17.0	20.0	20.0	19.5	20.0	19.9
H5	18.2	16.2	16.5	16.2	16.5	16.4	20.0	20.0	19.5	21.0	20.1

D3 Meter calibration results at approximately 13% MC

		Resistance Type-model					Capacitance Type-model				
		G-30 MC(%)		RC-IC MC(%)			M10-1 MC(%)		M10-2 MC(%)		
Sample #	Approx. MC(%)	Side 1	Side 2	Side 1	Side 2	AVE.	Side 1	Side 2	Side 1	Side 2	AVE.
A1	14.0	11.3	11.5	11.3	11.5	11.4	16.5	16.5	16.5	16.5	16.5
A2	13.6	11.8	11.8	11.8	11.8	11.8	16.5	16.5	16.5	16.5	16.5
A3	13.8	11.0	11.5	11.0	11.5	11.3	17.0	17.0	17.0	17.0	17.0
A4	13.6	11.5	11.5	11.5	11.5	11.5	16.5	16.5	16.0	16.5	16.4
A5	13.6	11.5	12.0	11.5	12.0	11.8	17.0	17.0	17.0	17.0	17.0
B1	13.8	11.3	11.3	11.3	11.3	11.3	17.0	17.5	17.0	17.5	17.3
B2	13.5	11.3	11.5	11.5	11.5	11.4	17.5	17.5	17.5	17.5	17.5
B3	13.9	11.0	11.0	11.0	11.0	11.0	17.5	17.0	17.5	17.0	17.3
B4	13.7	11.5	11.3	11.8	11.3	11.4	17.0	17.0	17.0	16.5	16.9
B5	13.8	11.0	11.0	11.0	11.0	11.0	16.5	17.0	16.5	17.0	16.8
C1	13.6	12.0	12.0	12.0	12.0	12.0	16.0	16.0	16.0	16.0	16.0
C2	13.1	11.8	11.8	11.8	11.8	11.8	16.0	16.0	16.0	16.0	16.0
C3	13.3	11.8	12.0	11.8	12.0	11.9	15.5	15.5	15.5	15.5	15.5
C4	13.7	12.0	12.3	12.0	12.3	12.1	17.0	17.0	17.5	17.0	17.1
C5	13.6	12.5	12.5	12.5	12.5	12.5	17.0	17.0	17.0	17.0	17.0
D1	13.6	11.0	11.0	11.0	11.0	11.0	18.0	17.5	18.0	17.5	17.8
D3	13.8	11.3	11.5	11.3	11.8	11.4	17.0	17.0	17.0	17.0	17.0
D4	13.8	11.3	11.3	11.3	11.3	11.3	16.5	16.5	16.5	16.5	16.5
D5	13.7	11.5	11.3	11.5	11.5	11.4	17.0	17.0	17.0	17.0	17.0
E1	13.9	12.5	13.0	12.5	13.0	12.8	15.5	17.0	15.5	16.5	16.1
E2	13.8	12.5	12.5	12.8	12.8	12.6	16.5	17.5	16.5	17.5	17.0
E3	13.7	12.0	12.5	12.0	12.5	12.3	17.0	17.0	17.0	17.0	17.0
E4	13.6	12.3	11.8	12.3	11.8	12.0	17.5	17.5	17.5	17.5	17.5
E5	13.4	12.3	12.5	12.3	12.8	12.4	17.5	17..5	17.0	17..5	17.3
F1	13.6	11.3	11.0	11.3	11.0	11.1	17.0	16.5	17.0	16.5	16.8
F2	13.6	11.0	11.3	11.0	11.3	11.1	17.0	17.0	17.0	17.0	17.0
F4	14.2	11.8	11.8	11.8	11.8	11.8	16.5	16.5	16.5	16.5	16.5
F5	13.5	11.0	11.0	11.0	11.0	11.0	16.5	16.5	16.5	16.5	16.5
G1	14.0	11.5	11.3	11.5	11.3	11.4	18.5	18.5	18.5	18.5	18.5
G2	14.1	11.5	11.5	11.5	11.5	11.5	17.5	17.5	17.5	17.5	17.5
G3	14.1	11.5	11.5	11.5	11.5	11.5	17.5	17.5	17.5	17.5	17.5
G4	14.1	11.3	11.5	11.3	11.5	11.4	18.0	18.5	18.0	18.5	18.3
G5	13.8	11.3	11.0	11.3	11.3	11.2	17.0	17.0	17.0	17.0	17.0
H1	14.0	12.8	12.8	12.8	12.8	12.8	16.5	16.0	16.0	16.0	16.1
H2	13.5	12.5	12.5	12.5	12.5	12.5	16.0	16.5	16.0	16.5	16.3
H3	13.7	12.8	12.3	12.8	12.3	12.5	16.5	16.5	16.5	16.5	16.5
H5	13.8	12.5	12.8	12.5	12.8	12.6	16.5	17.0	16.5	17.0	16.8

D3 Meter calibration results at approximately 8% MC

		Resistance Type-model					Capacitance Type-model				
		G-30 MC(%)		RC-IC MC(%)			M10-1 MC(%)		M10-2 MC(%)		
Sample #	Approx. MC(%)	Side 1	Side 2	Side 1	Side 2	AVE.	Side 1	Side 2	Side 1	Side 2	AVE.
A1	8.8	7.8	8.0	7.8	7.8	7.8	13.0	13.0	13.5	13.0	13.1
A2	9.5	7.8	7.8	7.8	7.8	7.8	13.5	14.0	13.5	14.0	13.8
A3	8.5	7.2	8.0	7.5	8.0	7.7	13.0	13.0	13.0	13.0	13.0
A4	8.3	7.5	7.3	7.3	7.3	7.3	12.5	12.5	12.5	12.5	12.5
A5	8.6	7.5	7.5	7.5	7.5	7.5	13.5	13.5	13.5	13.5	13.5
B1	9.5	8.5	8.5	8.0	8.3	8.3	14.0	14.5	14.0	14.5	14.3
B2	9.5	8.0	7.8	7.8	7.5	7.8	14.0	14.0	14.0	13.5	13.9
B3	8.6	7.5	7.5	7.5	7.5	7.5	13.0	13.5	13.0	13.5	13.3
B4	8.7	7.5	7.5	7.5	7.5	7.5	13.5	13.5	13.5	13.5	13.5
B5	9.0	8.0	8.0	7.8	8.0	7.9	13.5	13.5	13.0	13.5	13.4
C1	9.3	8.5	8.0	8.8	8.0	8.3	13.0	13.0	13.0	13.0	13.0
C2	8.5	8.0	8.0	7.8	8.0	7.9	12.5	12.5	12.5	12.5	12.5
C3	9.2	9.0	8.8	8.8	8.8	8.8	13.5	13.5	13.5	13.5	13.5
C4	8.4	8.0	8.0	7.8	8.0	7.9	13.5	13.5	13.5	13.5	13.5
C5	9.5	8.3	8.5	8.0	8.5	8.3	15.0	15.0	15.0	15.0	15.0
D1	8.6	7.8	8.5	7.8	7.5	7.9	13.0	13.0	13.0	13.0	13.0
D3	9.0	7.5	7.5	7.5	7.5	7.5	13.5	14.0	13.5	14.0	13.8
D4	8.7	7.5	7.5	7.5	7.5	7.5	13.0	13.0	13.0	13.0	13.0
D5	8.5	7.3	7.5	7.5	7.5	7.4	14.0	14.0	14.0	14.0	14.0
E1	8.6	8.5	8.0	8.5	8.0	8.3	13.0	13.5	13.0	13.5	13.3
E2	8.5	8.0	7.8	7.8	7.8	7.8	12.5	12.5	12.5	12.5	12.5
E3	9.5	8.5	8.0	8.3	8.0	8.2	13.5	13.5	13.5	13.5	13.5
E4	9.3	8.5	8.8	8.5	8.5	8.6	14.0	14.0	13.5	14.0	13.9
E5	9.3	8.8	8.8	8.8	8.8	8.8	14.5	14.5	14.5	14.5	14.5
F1	8.8	7.8	7.8	7.5	7.8	7.7	13.5	13.5	13.5	13.5	13.5
F2	9.4	8.0	8.3	7.8	8.0	8.0	13.5	14.0	13.5	14.0	13.8
F4	9.9	8.3	8.5	8.3	8.3	8.3	14.0	13.5	14.0	13.5	13.8
F5	8.9	7.8	7.8	7.8	7.8	7.8	13.0	13.0	13.0	13.0	13.0
G1	9.0	7.5	7.5	7.5	7.5	7.5	13.5	13.5	13.5	13.5	13.5
G2	9.7	8.0	8.5	8.0	8.5	8.3	14.0	13.5	13.5	13.5	13.6
G3	9.0	7.5	7.5	7.5	7.5	7.5	13.0	13.5	13.0	13.5	13.3
G4	9.9	8.5	8.3	8.3	8.0	8.3	14.0	14.0	14.0	14.0	14.0
G5	8.9	7.5	7.5	7.5	7.5	7.5	13.0	13.0	13.0	13.0	13.0
H1	9.5	8.3	8.8	8.5	8.8	8.6	13.5	13.5	13.5	13.5	13.5
H2	9.4	9.0	9.0	9.0	9.0	9.0	13.0	13.5	13.5	13.5	13.4
H3	8.7	8.3	8.3	8.0	8.0	8.1	12.5	12.5	12.5	12.5	12.5
H5	9.5	8.5	8.8	8.5	8.5	8.6	13.5	13.5	13.5	13.5	13.5

D4 Moisture Meter Calibration Results

		MC's at approx 18%			MC's at approx 13%			MC's at approx 8%		
Sample #	O.D.W (g)	Oven Dry	Resistance	Capacitance	Oven Dry	Resistance	Capacitance	Oven Dry	Resistance	Capacitance
A1	366.16	17.6	15.1	20.5	13.2	11.4	16.5	8.0	7.8	13.1
A2	377.27	17.7	15.1	21.1	13.0	11.8	16.5	8.9	7.8	13.8
A3	361.35	17.8	15.1	20.6	13.4	11.3	17.0	8.0	7.7	13.0
A4	348.40	17.4	14.9	19.9	13.2	11.5	16.4	8.0	7.3	12.5
A5	355.35	17.2	14.6	19.6	13.3	11.8	17.0	8.3	7.5	13.5
B1	342.25	18.2	15.5	21.0	13.4	11.3	17.3	9.1	8.3	14.3
B2	356.27	17.8	15.5	21.1	12.9	11.4	17.5	8.8	7.8	13.9
B3	340.30	18.0	15.1	21.1	13.2	11.0	17.3	7.9	7.5	13.3
B4	331.67	17.6	14.6	21.0	13.3	11.4	16.9	8.3	7.5	13.5
B5	338.93	18.1	15.0	21.3	13.3	11.0	16.8	8.4	7.9	13.4
C1	311.97	17.3	16.6	19.0	13.1	12.0	16.0	8.8	8.3	13.0
C2	320.26	17.9	17.0	19.5	12.0	11.8	16.0	8.3	7.9	12.5
C3	317.95	17.7	16.8	19.8	13.6	11.9	15.5	8.7	8.8	13.5
C4	315.05	17.2	16.5	20.6	13.0	12.1	17.1	7.8	7.9	13.5
C5	324.97	16.7	16.3	20.9	12.8	12.5	17.0	8.8	8.3	15.0
D1	365.64	17.2	15.3	20.4	12.9	11.0	17.8	7.9	7.9	13.0
D3	364.18	17.9	15.3	21.1	13.4	11.4	17.0	8.6	7.5	13.8
D4	369.50	17.5	15.5	20.5	13.0	11.3	16.5	8.0	7.5	13.0
D5	369.26	17.6	15.2	20.5	13.2	11.4	17.0	8.0	7.4	14.0
E1	327.44	16.9	16.6	18.8	13.4	12.8	16.1	8.1	8.3	13.3
E2	336.01	18.3	17.6	20.4	13.5	12.6	17.0	8.2	7.8	12.5
E3	334.19	17.4	16.8	20.0	13.2	12.3	17.0	9.1	8.2	13.5
E4	352.53	17.1	17.0	20.8	13.0	12.0	17.5	8.7	8.6	13.9
E5	352.94	17.2	16.6	21.0	13.1	12.4	17.3	9.0	8.8	14.5
F1	337.41	17.8	15.1	21.5	13.1	11.1	16.8	8.4	7.7	13.5
F2	340.47	17.2	14.9	20.0	13.2	11.1	17.0	9.1	8.0	13.8
F4	341.46	16.8	14.7	20.0	13.4	11.8	16.5	9.2	8.3	13.8
F5	337.67	17.2	14.7	20.1	13.0	11.0	16.5	8.4	7.8	13.0
G1	324.36	18.2	15.2	22.0	13.3	11.4	18.5	8.3	7.5	13.5
G2	315.05	17.8	15.2	21.4	13.3	11.5	17.5	8.9	8.3	13.6
G3	323.86	17.3	14.8	20.6	13.2	11.5	17.5	8.1	7.5	13.3
G4	320.51	18.0	15.1	21.4	13.3	11.4	18.3	9.1	8.3	14.0
G5	323.39	18.2	15.1	21.0	13.2	11.2	17.0	8.3	7.5	13.0
H1	348.14	19.2	17.8	20.5	13.1	12.8	16.1	8.7	8.6	13.5
H2	338.71	17.8	17.2	19.8	12.9	12.5	16.3	8.8	9.0	13.4
H3	347.93	17.7	17.0	19.9	13.3	12.5	16.5	8.3	8.1	12.5
H5	354.2	17.3	16.4	20.1	12.9	12.6	16.8	8.7	8.6	13.5

Average	366.16