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Title Measurement and monitoring of moisture content in timber and investigations of moisture gradients using dielectric measurements

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MEASUREMENT AND MONITORING OF MOISTURE CONTENT IN TIMBER AND INVESTIGATIONS OF MOISTURE GRADIENTS USING DIELECTRIC MEASUREMENTS

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SINA JAZAYERI

A thesis submitted to the University Research Degree Committee in fulfilment of the requirements for the degree of

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1999

To my family:

My parents

Dr. S. K. Jazayeri and Miss E. S. Elmi

brother

Dr. V. Jazayeri

and wife

Miss N. Inoue

whose continuous support through the years has made this possible.

Glossary

ADC	Analogue to digital converter
C/H	Central Heating
DAC	Digital to analogue converter
EMC	Equilibrium moisture content
LC	Inductor-capacitor combination
MC	Moisture content
MORG	Moisture research group
PC	Personal computer
PSPICE	Analogue simulation package
PSU	Power supply unit
PTFE	Polytetrafluoroethylene
PVC	Polyvinyl chloride
Q meter	Quality factor meter
RF	Radio frequency
RH	Relative humidity
Varicap diode	Variable capacitance diode
E_L	Lower extreme value in the data
E_U	Upper extreme value in the data
R	Range = $E_U - E_L$
σ	Standard deviation
μ	Arithmetic mean

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ABSTRACT

This thesis addresses various issues in connection with the measurement of moisture content in timber. The early parts include long term experimentally based studies which culminated in producing recommendations to existing British Standards for **e**quilibrium **m**oisture **c**ontent (EMC) of timber in internal environments. Findings consistently showed lower EMCs than existing recommended values; these are believed to be caused by socio-economic factors.

Intermediate sections of the thesis continue with tests on electrical methods of moisture content measurement to establish a basis for comparability and the claimed accuracy of currently available moisture meters in the market. To this end, the performance of a wide range of resistance-type moisture meters in world-wide use was critically investigated under laboratory conditions – it was established that even under the strict controlled conditions of the study, large discrepancies are not uncommon (as great as 13% moisture content difference was observed). While some instruments consistently underestimated, others overestimated under identical conditions. Lack of agreed standards for species corrections and temperature correction factors were found to be the main cause of disagreement between the meters. Further discussions include the layout for a proposed standard in which agreed values for species and temperature correction factors would be established.

In the latter part of the thesis moisture gradients in timber, the causes and the current methods of assessment are discussed. In particular, the performance of a leading brand capacitance-type moisture meter was systematically investigated both in the absence and in the presence of predetermined moisture gradients. It was established that moisture gradients severely affect the measured moisture content. A computer controlled capacitance measurement system based on resonance detection was developed to initially replicate the behaviour of conventional capacitance-type moisture meters, and to further investigate possible moisture gradient detection protocols. Two electrode designs were used in order to investigate methods by which moisture gradients could be detected. It was shown that a multi-plate electrode can be used to detect moisture gradients in timber to depths of at least 10 mm.

Acknowledgements

Development and progress in a multidisciplinary subject area such as that presented in this thesis would not have been possible without suggestions and constructive criticism from colleges and friends. In particular, Dr Kemal Ahmet (physicist) who supervised and directed the research, Dr Gavin Hall (Technical director, TRADA Technology Ltd.) who contributed by exposing the timber industry's views on the shortcomings of the research area, Dr Rob Hearing (Head of the Electrical and Electronics Department, University of Luton) for reading the electronics contents, Prof. Angus Duncan (Director of research, University of Luton) for commenting on the overall structure, Mr Richard Tomlin (Technician, Moisture Research Group, University of Luton) for directions and assistance in construction of test fixtures and statistical analysis of the data used in Chapter 2, Mr Colin Osborn (Principal Lecturer in Electronics, University of Luton) and Mr Pat Moulseley (Technician, Department of Electrical and Electronics, University of Luton) for their feedback and ideas during the development phase, and the late Dr Roger Harvey (Reader, University of Luton) for his continuous support and leadership for the research project.

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Preface

Humidity, moisture and other water related properties, could generally be thought of as basic and fundamental properties, often taken for granted as areas in which further research could not possibly bring any further benefit. This, in the timber industry, an area in which there has been several decades of world wide research, would even seem more certain.

However, a glimpse into the arena of existing problems soon reveals the scale of problem at hand. Timber, a versatile naturally occurring material with numerous applications, 'reacts' with water readily and exhibits a complex cocktail of problems yet unresolved and all related to the measurement and quantification of moister content.

The work presented in this thesis provides an overview of the main existing problem areas; each chapter details a project undertaken, its aim, objectives and findings. During the course of the research, the author had the privilege of authoring and co-authoring a number of scientific articles with other members of the Moisture Research Group (at The University of Luton) as well as Timber Research and Development Association (TRADA) Technology Limited, who sponsored the EMC project (see Chapter 2), and gave valuable constructive advice during the course of the research. A list of these publications is available in the Appendix F.

Chapter 1

1 Introduction and Basics of the Subject Area

1.1 *Summary*

This introductory chapter introduces the basics of the subject area, and highlights the way in which the moisture content changes the physical properties of timber and hence becomes a critical factor in the timber industry. An in-depth literature search of the current measurement methods, their advantages and disadvantages follows, and finally a more problematic area namely, moisture gradient and its effects on the accuracy of the existing measurement instruments is introduced. The last section of Chapter 1 gives an overview of the projects described in the remainder of the thesis and thus the overall theme of the research carried out.

1.2 *Introduction*

Wood is a renewable, recyclable and biodegradable material and its proper use benefits both the user and the environment. A growing tree is an effective 'carbon sink' whereby carbon dioxide (the main greenhouse gas), is absorbed in exchange for release of oxygen. When a tree is felled the carbon dioxide remains locked in, nevertheless a tree which dies naturally will emit CO_2 as it decays [1]. Full exploitation of forestry can be justified logically, as harvesting mature trees and replantation of younger faster growing trees improves the rate at which the trees absorb CO_2 from the environment.

As the amount of moisture plays an important role in determining the properties of timber components, standards have defined a method for its measurement. Moisture content as defined in the British Standards (e.g. BS 5268) is based on the gravimetric method. The gravimetric method combines the wet mass (M_w) and the oven dry mass (M_d) of timber components to yield the moisture content, as a percentage[1] (MC).

$$MC = 100\times(M_w - M_d)/M_d$$

Water is mainly held in two areas in the structure of wood namely, cell walls and cell cavities.

Figure 1-1 shows a conceptual view of cell structures in timber.

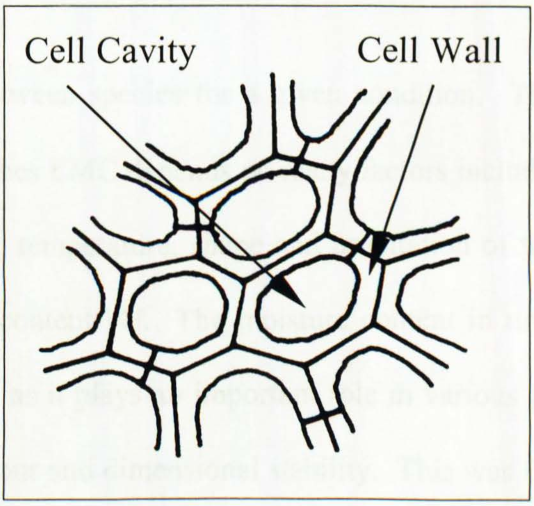


Figure 1-1: Conceptual representation of a wood cell structure

In the living tree, generally the moisture content is 30% or greater [2] and the cell wall (see Figure 1-1) is fully saturated. The cell cavity generally contains some

[1] In accordance with the British Standard BS 5268 : Part 2 : 1991 Appendix H, for the gravimetric method of moisture content measurement the test piece should be weighed to an accuracy of 0.5% and then dried to constant mass in a vented oven at a temperature of 103±2°C. Constant mass is considered to be reached if the loss in mass between two successive measurements carried out at an interval of 6 hours is not greater than 0.5% of the mass of the test piece.

water, the amount of which varies greatly among trees and also among cells in the same tree. This variation can cause a high moisture content in the living tree of around 250% [3]. After the tree is felled however, and due to its hygroscopic nature, the tree gradually loses moisture to equilibrate with the relative humidity of the surrounding environment, viz. desorption. Equilibrium Moisture Content (EMC) is the final moisture content at which the timber settles for a given environment. However, the direct dependency of EMC on relative humidity means the moisture content can fluctuate with a changing environment, and therefore EMC is not, in practice, a static value (see Chapter 2 for typical and recommended EMC values).

The EMC varies between species for a given condition. The speed at which a particular piece reaches EMC depends on many factors including the permeability of the wood species, temperature, shape and orientation of the timber as well as the initial moisture content [4]. The moisture content in timber is of particular commercial interest, as it plays an important role in various properties of timber, such as strength, colour and dimensional stability. This was first realised in 1906, when tests were carried out on variation of moisture content and the corresponding effects on the mechanical properties of timber [5]. The tests established that mechanical properties of timber are affected by the moisture content only below a certain moisture content level. The term *fibre saturation point* was then defined as the moisture content at which the cell cavities contain no liquid water, but the cell walls are fully saturated with water. Figure 1-2 below shows the concept of fibre saturation point (M_f).

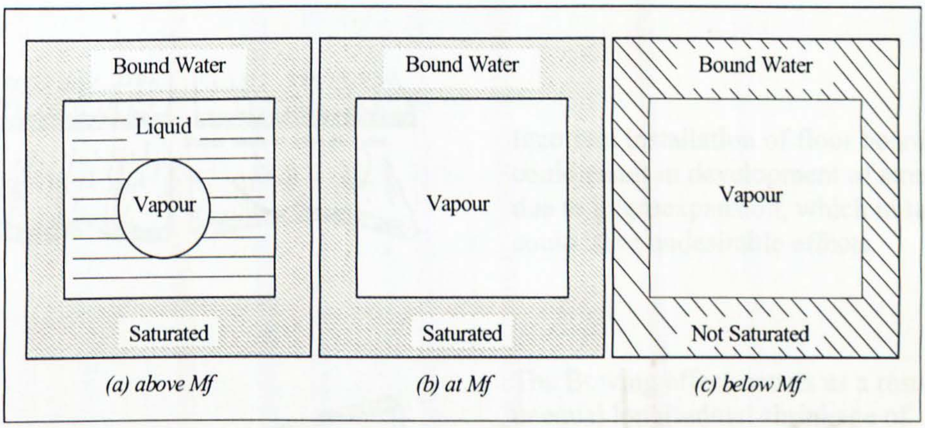
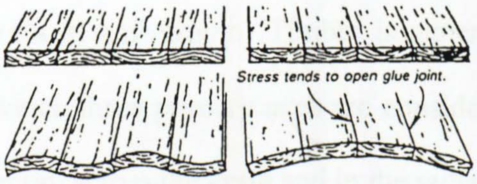
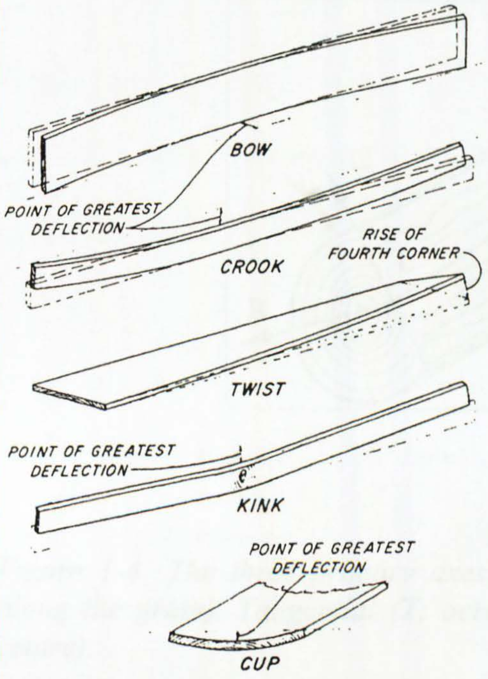


Figure 1-2: An idealised representation of moisture distribution in a wood cell cross-section (a) above, (b) at, and (c) below Mf

Moisture content at fibre saturation point varies from one species to another, nevertheless various figures reported in the literature point to an average of around 27%, well above the required moisture content for typical internal environments (see for example data presented in Table 2-4, page 51). Moisture content fluctuations below this point cause dimensional changes to the timber resulting in undesirable effects to finished products. It is therefore crucial that the timber used for wood products (e.g. furniture, musical instruments or component to be used in the construction industry) have moisture contents corresponding to the mean seasonal EMC of the environment for which they are intended. Failure to season the timber to the correct moisture content could yield destructive irreversible consequences. Warping, twisting and bowing are some of the defects developed when the timber installed in an incorrect environment goes through desorption-adsorption cycles so as to equilibrate with the relative humidity of the surrounding environment (see Figure 1-3).



Incorrect installation of floor boards could result in development of stress due to hygroexpansion, which in turn could have undesirable effects.



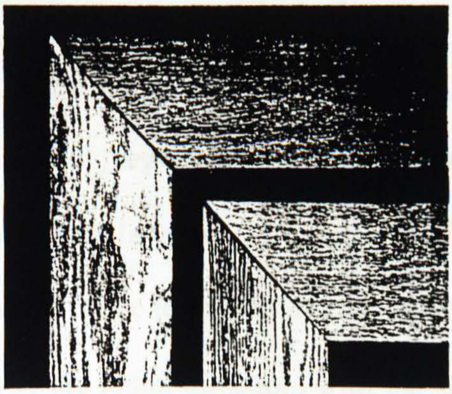
The Bowing effect occurs as a result of unequal longitudinal shrinkage of opposite faces;

Crooking due to unequal longitudinal shrinkage of edges;

Twisting occurs as a result of differential shrinkage or expansion, on plain sawn board, which is not cut parallel to the heart of the tree.

Differential shrinkage or expansion causes a Kinking effect in presence of an area with distorted grain.

The Cupping effect due to excessive tangential shrinkage over radial shrinkage



Moisture movement after installation of timber components could cause joints to break up.

Figure 1-3: Distortion and Warping of timber components and products adapted from [6].

Distortion in timber is caused by non-uniformity of shrinkage along the primary axes of anisotropy. Timber is generally accepted as an orthogonal structure in which three primary axes are considered at right angles to one another along the grain, across the grain and in the radial direction as shown in Figure 1-4.

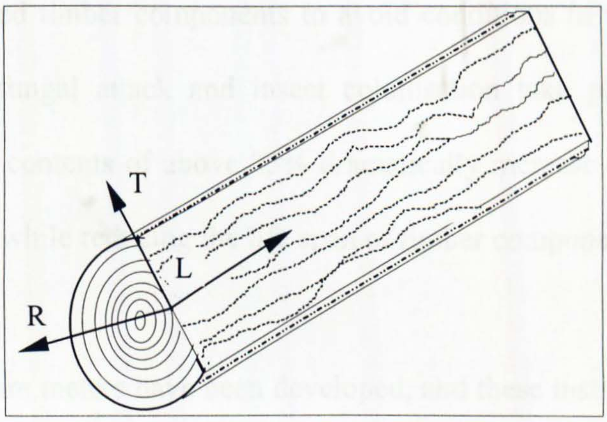


Figure 1-4: The three primary axes of anisotropy in timber; longitudinal (L; along the grain), Tangential (T; across the grain) and Radial (R; through the centre)

Along the grain (in the direction of L in Figure 1-4) hygroexpansion is one to two orders of magnitude less than in the transverse directions (along the direction of T in Figure 1-4), and is usually considered negligible. Most of the distortion in timber is due to the differential shrinkage that occurs across the grain as compared to in the radial direction, with the shrinkage across the grain being a factor of 2 greater.

Further reasons for seasoning which may be important in specific cases include saving weight during transport, ease of machining, facilitating strong glue joints, preservative treatment and increasing the load bearing properties of timber [7]. The importance of the ability to measure (estimate accurately) the moisture content of timber for industrial use can not be over emphasised as the durability could be compromised where due care is not given to maintain and preserve the timber for commercial products. It is equally crucial to monitor the moisture content of installed timber components to avoid conditions in which destructive factors such as fungal attack and insect colonisation take place. Conditions causing moisture contents of above 25% dramatically increase the probability of fungal decay [7], while reducing the life span of timber components.

Hand-held moisture meters have been developed, and these instruments utilise the electrical properties of timber to estimate the moisture content (see section 1.4 (page 10) and section 1.6 (page 19) for further details). These moisture meters have various commercial uses including monitoring and detection of damp surfaces and quality control for seasoned timber for importers and exporters.

However, various problems arise from the dependency of electric properties of timber on factors such as temperature, wood species, density and treatment. This coupled with further complications such as the complexity in the structure of timber and development of moisture *gradients* during or after seasoning, often hinder the accurate measurement of moisture content.

Lack of calibration standards and agreed measurement procedures are additional critical issues which need to be resolved[2].

Issues surrounding the current methods of moisture measurement are discussed in the remainder of this Chapter.

1.3 Measurement of moisture in timber

The gravimetric method defined in section 1.2 (page 2), is destructive, cumbersome and time consuming as it requires a cutting from each sample for oven drying purposes; therefore the procedures followed in this method render it unsuitable for on site measurements. As briefly discussed in section 1.2, the industry has resorted to employing hand-held moisture meters for quick on-site measurements.

Resistance and dielectric properties of timber are employed by hand held moisture meters to estimate the moisture content. Moisture meters rely on the direct correlation between moisture content and the relevant electrical property, however various considerations need to be given; the complex inhomogeneous structure of timber, inter-species and growth dependent variations as well as temperature and density are among factors affecting this correlation, and therefore various correction factors need to be considered at the time of measurement.

---

[2] IMCOPCO, Improvement of moisture content measuring systems and testing strategies to enable precise process and quality control of kiln dried timber, is a Europe wide project. One of the research projects under IMCOPCO deals directly with the accuracy and calibration of moisture content measuring instruments, as well as assessment of innovative measurement procedures and instrumentation.

For example in the case of resistance-type moisture meters variation of the measured moisture content with temperature is a function of moisture content (see Figure 1-7, page 12). However, a rule of thumb frequently used by some manufactures equates to a correction factor of 1% MC per 10 °C above or below 20 °C. This is the calibration temperature for most resistance-type moisture meters.

Kiln dried timber could be at temperatures as high as 100 °C, indicating the importance of the required temperatures compensation (8% MC in the extreme case). Correction factors are further discussed in section 1.4.

1.4 Resistance-type moisture meters

Resistance-type moisture meters use the correlation between moisture content and electrical resistance depicted in Figure 1-5. The shaded area shows the region in which 90% of commercially available species fall [8].

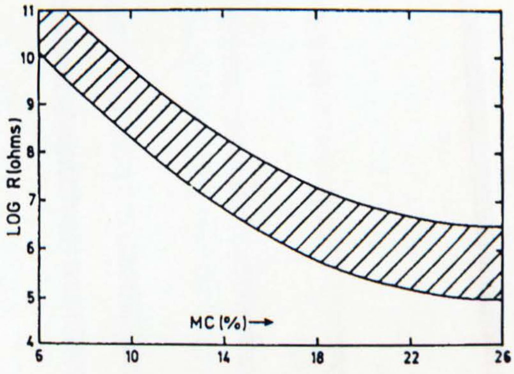


Figure 1-5: Electric resistance (log scale) versus moisture content for most of commercially available wood species [8].

It can be seen from Figure 1-5 that for a given moisture content, the range of measurable resistance varies up to two orders of magnitude. Much of this variability is attributed to the variations in mineral and organic constituents of each species as well as the growth rate [8].

Temperature of the wood also affects the moisture content-resistance relationship, as the conductivity of timber increases with increasing temperature. Therefore, measurement of moisture content at temperatures higher than the calibration temperature of the meter, would produce overestimated values. Similarly, if the temperature of the wood is below the calibration temperature of the meter, then the results will be underestimated.

Accurate measurement of moisture content of "hot lumber" is further complicated by the fact that the temperature of the "lumber" could be rapidly changing, as is the scenario for the lumber that has just come out of a dry kiln. The difficulty in measuring the moisture content of wood with varying temperature has been clearly acknowledged by moisture meter manufacturers (see for example [5]).

Figure 1-6 shows the effect of temperature on the logarithm of resistivity (r) at various moisture contents [9]. It can be observed that an increase in the temperature of wood is followed by a decrease in its resistivity (or an increase in the conductivity). This is why temperature corrections are necessary to compensate for moisture meter readings, where the temperature of the wood under test is considerably different to the calibration temperature of the meter.

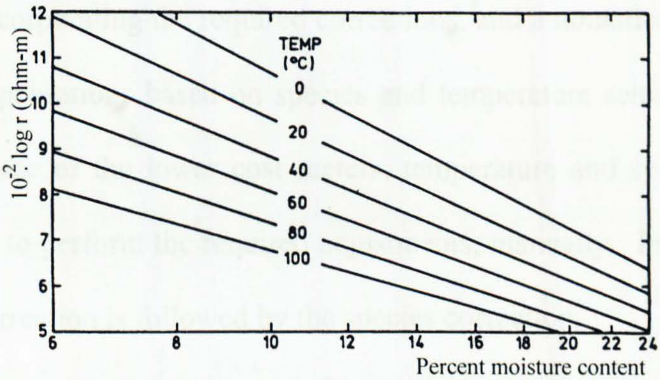


Figure 1-6: Effects of temperature on resistivity of timber at various moisture content (MC) as cited in reference [9].

Figure 1-7 shows the variation in the readings from a typical resistance-type moisture meter for a range of temperatures [9].

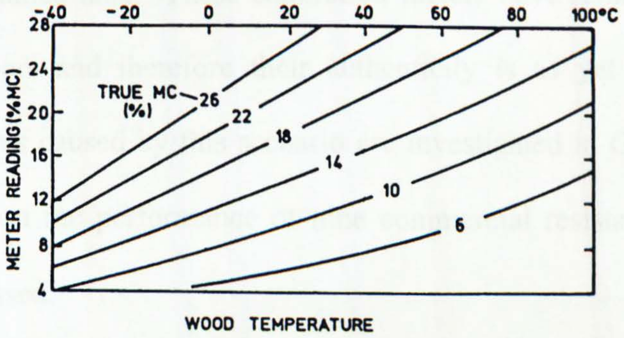


Figure 1-7: The effect of temperature on the readings from a typical resistance-type moisture meter [9]. The moisture contents (o.d. basis) have been shown for comparison.

It is observed that the variation of the meter reading with temperature ($\mathrm{d}(MC)/\mathrm{d}T$) increases with increasing moisture content (o.d. basis). For example, at 20 °C the magnitude of $\mathrm{d}(MC)/\mathrm{d}T$ increases from approximately 0.08 %/°C at MC=6%, to 0.25 %/°C for MC=26%.

In practice, the higher cost more sophisticated moisture meters have embedded facilities for incorporating the required corrections, and automatically perform the necessary compensations based on species and temperature settings adjusted by the user. In case of the lower cost meters, temperature and species correction tables are used to perform the required adjustments, manually. In such cases, the temperature correction is followed by the species correction.

At present, lack of agreed standard calibration values means that the correction factors used by moisture meter manufacturers do not adhere to an agreed criteria [10]. The lack of standardization of resistance type moisture meters has resulted in individual development of moisture meters, calibrated using independent empirically obtained data. These calibration factors have remained the property of the developers and therefore their authenticity is as yet in question [10]. Critical problems caused by this scenario are investigated in Chapter 3, where a detailed study on the performance of nine commercial resistance-type moisture meters is discussed.

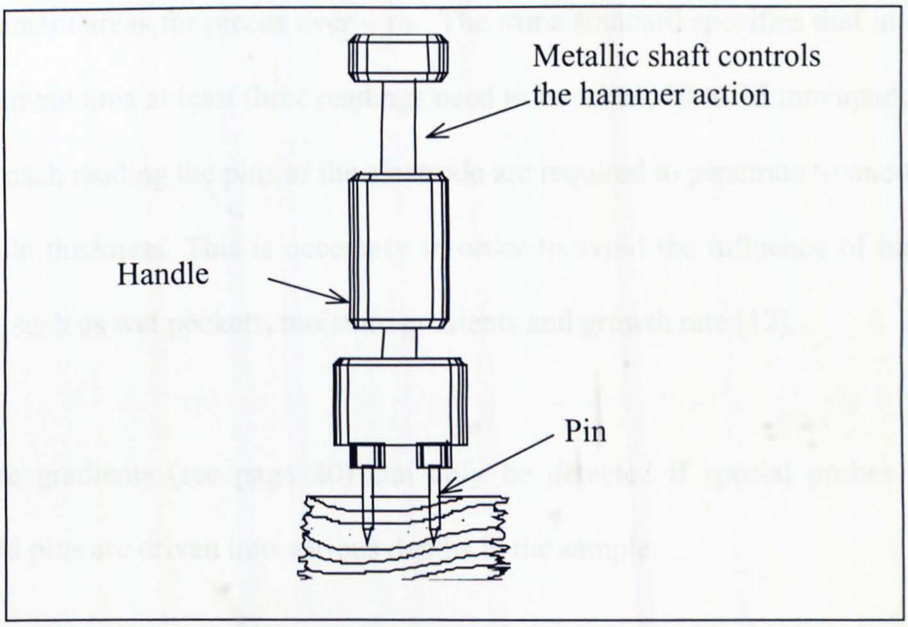


Figure 1-8: A typical hammer-electrode for resistance-type moisture meters; the electric current between the pins gives an estimate of the moisture content in the area of timber between the pins of the electrode.

The electrodes used by the resistance-type moisture meters (Figure 1-8) generally consists of two pins, two to three centimetres apart, inserted along the grain into the timber under test. The moisture meter then applies a set potential difference (usually d.c.) between the tips of the pins, resulting in the flow of electric current between the pins. This electric current directly correlates with the moisture content of the sample, in the electrode area. The use of the resistance-type moisture meters is slightly destructive as the pins of the electrode have to be inserted into the sample under test.

1.4.1 Proposed procedures for measurement of moisture content

Methods of timber moisture measurement in proposed European standards for round and sawn timber [11] specify that two measurement areas are required , at random positions, for pieces between 1.5 m and 2.5 m long, and up to four measurement areas for pieces over 4 m. The same standard specifies that in each measurement area at least three readings need to be taken, 10 to 15 mm apart, and that for each reading the pins of the electrode are required to penetrate to one-third of sample thickness. This is necessary in order to avoid the influence of hidden defects, such as wet pockets, moisture gradients and growth rate [12].

Moisture gradients (see page 20) can only be detected if special probes with insulated pins are driven into various depths in the sample.

The overview of the proposed methods of measurement indicates that measurements performed on large components are inherently labour intensive, as the specified average moisture content requires at least 6 measurement points even for the smaller size samples. Currently and interestingly, there are no provisions for dielectric-type moisture meters in the proposed standards, even though there is insufficient information available on any possible disadvantages of this type of meters over the resistance-type instruments.

The dielectric properties of timber and their uses in the measurement of moisture content are described in section 1.5, page 15.

1.5 Timber and its dielectric properties

Timber is classed as a dielectric material, as it is capable of storing electrical charge on application of an electric field. Dielectric properties of material may be used to describe the interaction of electromagnetic fields with the material. These properties will be utilised in Chapters 4, 5 and 6 where measurement of moisture content in timber through measurement of capacitance is discussed.

From the two components of electromagnetic waves (*electric* and *magnetic* fields) only the influence of the electric component is of interest. The influence of the magnetic field on wood is negligible (as the relative permeability for timber, $\mu_r \approx 1$) and is not taken into consideration for practical purposes [13].

The influence of the electric field on wood is very strong as the interaction between electric field and wood results in the creation of electric currents in the material. The two interactions of primary interest are the absorption or storage or charge in the form of electric potential energy, and dissipation or loss of this energy in the dielectric material in the form of thermal energy. The energy absorbed by a dielectric material is most easily expressed in terms of capacitance, while the loss of energy is usually expressed in terms of loss tangent defined in section 1.5.1 (page 16).

1.5.1 Theory of the relevant dielectric parameters

The dielectric constant (ε') of a material is defined for a parallel plate capacitor arrangement as follows [14].

$$\varepsilon' = C_w / C_v \qquad \textit{Equation 1-1}$$

where C_w is the capacitance of the capacitor with the dielectric (wood) as its insulating medium and C_v is the capacitance of the same capacitor with vacuum (or air) as the insulator. An increase in the moisture content of wood is followed by an increase in its dielectric constant; the water molecules act as storage cells for electric charge increasing the capacitance (C_w) which in turn causes the dielectric constant to increase. Generally the dielectric constant consists of a real and an imaginary part.

The rate of loss of energy in the dielectric is expressed in terms of the loss tangent ($\tan\delta$). If a 'perfect' dielectric material is placed in a sinusoidally varying electric field, a sinusoidally varying current will flow in the material which is pure imaginary and leads the electric field by 90° (quadrature leading). However, in practice when a realistic dielectric material is placed in a sinusoidally varying electric field, there is an additional real component to the current [15].

Figure 1-9 shows the concept of real and imaginary components of current in a real dielectric, such as wood. As illustrated here, the real component is in phase with the applied electric field, and results in energy being dissipated as heat.

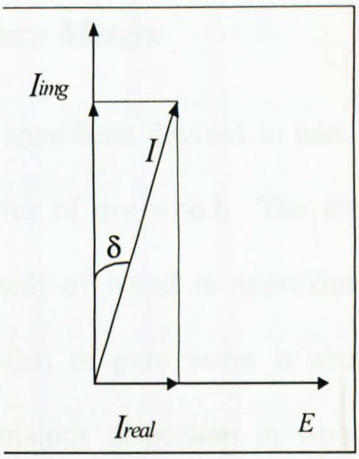


Figure 1-9: Real (I_{rael}) and imaginary (I_{img}) component of current(I) in a dielectric material, subject to a sinusoidally varying electric field (E).

With reference to Figure 1-9 above, the loss tangent is defined in Equation 1-2.

$$\tan\delta = I_{real}/I_{img} \qquad \textit{Equation 1-2}$$

which varies from zero (for a perfect dielectric) to infinity (for a perfect conductor).

Other terms such as dissipation factor (D) and loss factor (ε'') are also used to describe the process of energy transfer in a dielectric material. Loss factor is defined as:

$$\varepsilon'' = \varepsilon' \times \tan\delta \qquad \textit{Equation 1-3}$$

1.6 Dielectric Moisture Meters

Dielectric moisture meters have been devised to take advantage of the effect of water on dielectric properties of dry wood. The intrinsic transverse dielectric constant of the dry cell wall of wood is approximately 4 to 5 in the radio frequency range, whereas that of pure water is about 84. Water also has a pronounced effect on anomalous dispersion in wood, discussed in Chapter 4 (section 4.2.2, page 85).

There are two basic types of *dielectric-type* moisture meters, the capacitance-type primarily affected by the capacitance of the electrode-timber configuration, and the power loss-type which measure the rate of dissipation of electrical energy in the wood, for a given input energy [16].

Dielectric moisture meters respond primarily to the capacitance between the electrodes, which is a function of the electrode type and dielectric constant of the wood. The accuracy of the dielectric moisture meters is dependent on the electrode-wood contact, and the air gap at this interface reduces the sensitivity of the instrument to changes in moisture content.

Measurements carried out using dielectric moisture meters are affected predominantly by two factors namely, density and the moisture content of timber. Although, depending on the choice of electrodes employed, grain orientation may also affect measurements.

Tables of 'density correction' factors are provided by the meter manufacturers as well as other independent research organisations, to facilitate accurate measurement of moisture content [7].

Unlike the resistance-type of instruments, the planar electrode configuration employed by the dielectric moisture meters does not require insertion on pins into the samples. Non-destructive measurements can therefore be performed efficiently, allowing the operator to perform the measurement procedures on a large area of timber in a short time. This in turn, results in a better estimate for the average moisture content of the timber under test.

1.7 Moisture gradient in timber

Measurement of moisture content in timber is associated with various complications, most of which are related to the complex structure of the material. As already mentioned, wood is a multi-component, anisotropic material and reacts hygroscopically to the changes in the relative humidity at various rates, depending on a number of factors including the species, size and orientation of grain and the drying history.

One of the problems associated with the measurement of moisture content in timber is the existence of moisture gradients as a function of depth. The process of commercial timber drying involves evaporating moisture from the surface of the wood. This is usually carried out by heating the timber in a kiln. The deep-seated moisture gradually moves towards the surface, setting up a moisture gradient in the piece - drier towards the outside where the water is being evaporated, wetter towards the centre; this is known as the drying gradient [17]. It is important to monitor the condition of the timber during the seasoning period regularly, so as to stop the heat treatment at the appropriate time. Failure to do so, could affect the final EMC of the timber as well as its physical and aesthetic properties.

Moisture gradients could also occur when low moisture content timber is exposed to high relative humidity, due to lack of adequate packaging, for example. In such cases the moisture gradient is known as the regain gradient in which the outer layers of the timber absorb the moisture from the surrounding environment while the inner layers remain at a lower moisture content. Measurement of moisture content on such timber with the available commercial dielectric moisture meters would give a false indication of the cumulative average moisture content.

Findings of chapters 5 and 6, and the limited published data [20] consolidate the latter.

A current technique used to detect moisture gradients using resistance-type moisture meter involves obtaining two readings for each measurement; one shallow reading which indicates the near surface moisture content and one deep reading using insulated probes which indicates the near centre moisture content. A comparison between the two measurements would indicate the existence of moisture gradient. However, this additional burden to the procedures discussed in section 1.4 (page 10) would render the use of resistance-type moisture meters even more time consuming, labour intensive and therefore less practical.

Extensive literature searches have shown previous work on detection of moisture gradient to have concentrated only on the electrical resistance principle (e.g. see reference [4]). Although the dielectric properties of timber have not been used as means for detection of moisture gradients [18], studies have been carried out on the effects of moisture gradient on various electrode configurations for the measurement of dielectric properties [19]; it has also been shown that moisture gradients affect the accuracy of power-loss moisture meters [20]. These issues will be discussed and further investigated in Chapters 4, 5 and 6.

1.8 Overview of the research

The author has set out to describe various aspects of the research projects in which he was led or extensively involved in during the course of his studies; as in all multidisciplinary subject areas, although there is a general theme - the measurement of moisture content in timber - this general theme was investigated through various avenues.

Initially the aim was to produce a better understanding of the underlying problematic areas, while ultimately the goal was to narrow down and target an unsolved and industrially significant problem in the area with the view to contributing to the subject area by furthering the available knowledge base through theoretical and investigative studies.

Firsthand experience in measurement of moisture in timber during the EMC project (described in Chapter 2) proved invaluable; discrepancies between moisture content values based on the gravimetric calculations and those measured using electrical moisture meters provided the basis of the study fully discussed in Chapter 3, where the performance of a wide range of commercially employed resistance-type moisture meters were put to test in controlled environments. Included in Chapter 4 is a review of the underlying theory behind an alternative electrical method for the measurement of moisture content, namely the dielectric type moisture meters. This is followed by a study into the measurement of capacitance and its correlation with moisture content for a two pole electrode. A commercial capacitance type moisture meter was used during this study so as to provide correlative data for this type of moisture meter. The results from this study are analysed and compared and contrasted with published data.

Chapter 5 concentrates on the performance of the commercial capacitance type moisture meter both in absence and presence of moisture gradients. It is established qualitatively that moisture gradients affect the performance of this type of moisture meters; here the author sets out to investigate further the intrusive effects of moisture gradients on the measurement of moisture content using the capacitance type moisture meters.

In Chapter 6 the effects of moisture gradients on capacitance type moisture meters is taken one stage further. Design of a prototype computer controlled capacitance measurement platform paves the way for the investigation protocols for measurement of moisture gradients.

Chapter 2

2 Evaluation of Moisture Content Standards for Timber in Internal Environments

2.1 *Summary*

The early work performed by the candidate is discussed in Chapter 2 and encompasses various phases in project whose outcome was to define more appropriate equilibrium moisture contents (hereinafter the EMC project). The EMC project, funded by the Department of Environment[1] started in November 1993 at the Moisture Research Group, University of Luton, with the candidate taking effective control of the project several months after the start date. A full account of all the stages in this project is presented.

The project provided the theme for an extensive program of research for systematically investigating the EMC of *in-situ* timber, located in a variety of representative internal environments. This project involved collection of data at regular intervals over a period of 18 months, from over 100 locations using specially prepared sets of timber samples. Data from each location consisted of a range of measurements, two electrical resistance-type moisture meter readings, as well as two readings obtained from two types of embedded electrode pairs (see section 2.3.2, page 39).

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[1] [illegible] contract number: PII 116, Project title: More Appropriate Moisture Content Standards for Timber in Buildings

2 Evaluation of Moisture Content Standards for Timber in Internal Environments

2.1 Summary

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[3] TRADA/DoE contract number: PIF 116, Project title: More Appropriate Moisture Content Standards For Timber In Buildings

The initial work of the candidate incorporated the design and development of a customised spreadsheet to facilitate the storage and analysis of well over 10000 entries. Data was collected by the candidate from remote and local sites on a regular basis through prior arrangements, after which the collected data were checked for abnormalities, and entered into the data base, prior to analysis.

The progress of the EMC project was reported in two stages (see [21] and [22]) and the final dissemination of results was through a detailed report with recommendation for possible revisions of the British Standards (BS1186: Timber for Workmanship and Joinery and BS5268: Structural Use of Timber) submitted to the Department of Environment [23]. It should be stated that the collaborators on this project, Timber **R**esearch **A**nd **D**evelopment **A**ssociation (**TRADA**) Technology Ltd. provided the second part of the aforesaid report comprising recommendations based on actual on-site measurements of in-situ timber components.

The results from this study indicate that the recommended levels of moisture content in the British Standards were in need of modification but not on a universal basis as was anticipated at the start of the study. To this end, a number of recommendations on proposed revisions to the existing Standards are made and further detailed information on moisture regimes and the way they are influenced by building categories[4] and socio-economic factors are discussed.

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[4] All the buildings used for the study were categorised in accordance with the purpose groups as defined in Approved Document B "Fire safety" to Building Regulations 1991.

The findings from the EMC project confirm the (non-empirically based) amendments made to BS1186 Part 1, which formed the basis for the revised standard for timber in joinery, BS EN 942: 1996 which was published prior to the dissemination of the findings from the EMC project.

2.2 Introduction

It is well known that the equilibrium moisture content of timber is not, in reality, an equilibrium quantity at all but a dynamic quantity which can vary considerably with seasonal changes in relative humidity and temperature: the moisture content of timber installed into the internal environment will first tend towards an equilibrium moisture content and then vary according to the temperature and relative humidity of the surroundings. Movement of the timber results from variations in moisture content below the fibre saturation point, as discussed in the introductory chapter.

At the time of this study, in the United Kingdom the recommended average values for the moisture content (MC) of timber to be used for internal joinery consisted of three ranges between the limits of 8% and 17%. The specified range depends on the level of heating within the building (Table 2-1).

Table 2-1: Recommended moisture contents for joinery (extracted from [24])

	Average moisture content (%)
External Joinery	13 – 19
Internal Joinery	
Unheated buildings	13 - 17
Heated to 12 - 21 °C	10 - 14
Heated to above 21 °C	8 - 12

For comparison, Table 2-2 shows average service moisture contents for *structural* timber, although these values are of less importance for the purpose of comparing with the results presented in the next section.

Table 2-2: Recommended moisture contents for the structural use of timber [25]

	Average moisture content (%)
External Joinery, fully exposed	20 or more
Covered but generally unheated	18
Covered and generally heated	15
Internal in continuous heated building	12

These, and other recommendations in the various existing codes are based on surveys carried out by the Building Research Establishment (BRE) and the Timber Research and Development Association (TRADA) on the environmental conditions in a variety of buildings nearly 30 years ago. At present, there are many different building types which are operated under a wide variety of conditions. Most buildings nowadays have central heating and some are air-conditioned. This is in direct contrast to the majority of buildings even twenty years ago. Also, modern buildings and those refurbished to modern standards are typically better insulated, more airtight and heated to higher temperatures than in the past. For these reasons it was important to determine and establish typical EMCs and to understand the annual variations of the moisture content in internal timber. To the authors' knowledge (following extensive literature surveys), no in-depth experiment of this type has previously been carried out in the UK to date. However, relatively small-scale trials have been carried out in parts of the United States of America [26].

2.3 Methodology

In order to systematically measure the EMC of timber, in excess of one hundred sets of timber test samples were installed into a wide range of carefully selected environments. The samples were then periodically monitored for at least one annual climatic cycle before the results were analysed. Various components of the experimental details are now discussed under several headings.

2.3.1 Selection and monitoring of the environments

A wide variety of internal environments were carefully chosen, and permission sought for installation. Locations included dwelling houses, flats, garages, offices, factory workshops, laboratories, retail premises, computer rooms, schools, nursing homes, hospitals, churches, a swimming pool, etc. All the buildings were located in south-east England. The full list of installation sites is provided in Appendix A. A cluster of five timber samples (described in section 2.3.2, page 30) was placed at each location. Particular care was taken to ensure that the chosen positions did not provide atypical conditions for the samples within that particular environment. For example, the use of window sills was avoided as solar heating could generate grossly exaggerated temperatures; also water resulting from condensation on window panes could run onto samples, giving the impression of very humid surroundings.

At the time of installation, all the relevant details were carefully recorded for all the host-locations (for example, whether air-conditioned or centrally heated). Checks were regularly made, and any subsequent changes were logged as appropriate. In addition, for a representative 10% sample of the locations, miniature single channel data-loggers (types RS213-436 and RS216-845) were placed alongside the samples so that the temperature and relative humidity could be continuously recorded.

2.3.2 The test samples

Green beech was chosen as the timber for the test samples primarily due to its high permeability to moisture vapour and its in-depth representative response to changes in the environmental conditions. It is important to stress also that beech is commercially important as it is widely used in the furniture industry.

The timber was obtained in the green state, cut and planed to 300 mm × 30 mm × 25 mm, where the dimensions refer to the cuts along the grain, across the grain and in the radial direction. For identification, every sample was stamped with a unique identification code (see Figure 2-1).

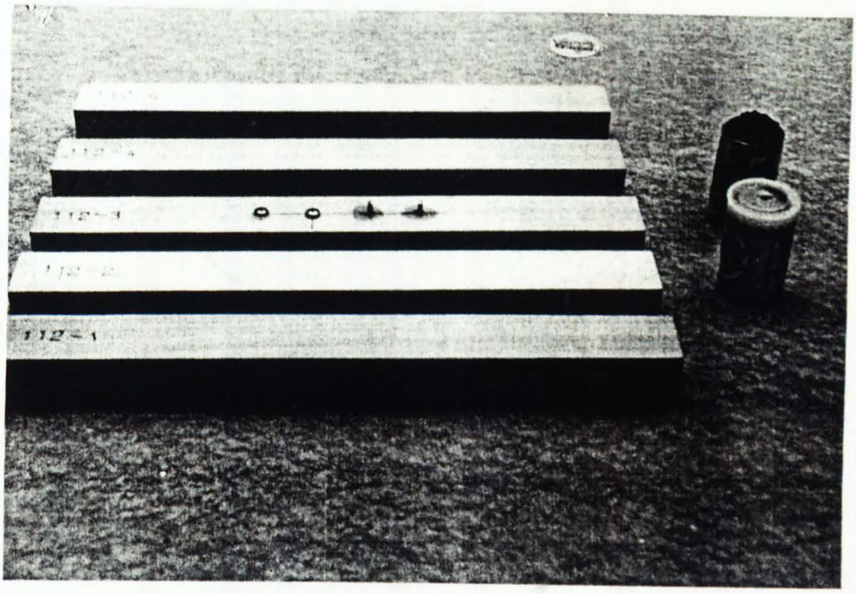

Figure 2-1: A set of samples in situ. The pin and screw electrodes in the middle sample can be clearly seen. Temperature and relative humidity data-loggers are also shown.

Initially, samples were conditioned at 20 °C to relative humidity of 65% for a number of weeks in a conditioning unit until constant mass was achieved.

Immediately following conditioning, all the samples were placed in double polythene bags and sealed. The purpose of the moisture proof membranes was to ensure that the specimens remained at the conditioned EMC until the installation date. Experiments have shown that variation in the moisture content of the samples in the sealed polythene bags is negligible even over time-scales of the order of many months; see Figure 2-2 where control samples remained sealed for over one year.

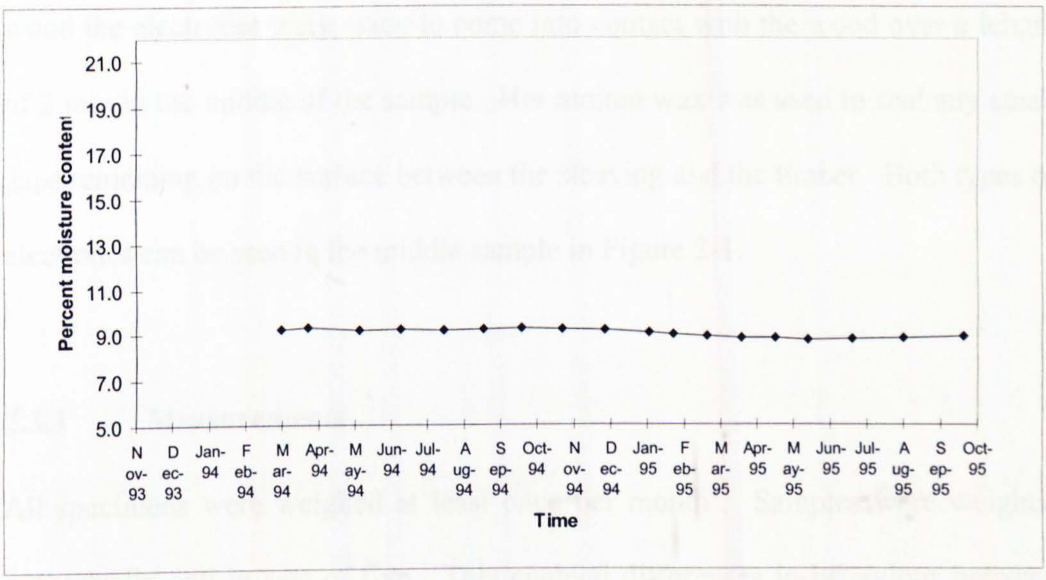

Figure 2-2: Results form one set of samples kept in the polythene bags, for one annual climatic cycles

Although the primary method employed for determination of the moisture content was by mass determination (described in section 1.2, page 2), it was judged important to make measurements by use of conductance-type moisture meters. Additionally, for independent moisture content estimation, two pairs of electrodes were inserted into one sample in each group of five. One electrode type was as recommended by TRADA and the other type by the University of Brighton research group, who used these for studying the effects of moisture content on creep in glulam [27]. The former electrode type (screw electrodes) is a method adapted from TRADA and uses small stainless-steel screws with plastic washers inserted centrally with a separation of 25 mm along the grain. The latter electrode type (pin electrodes) consist of a pair of 1.5 mm diameter stainless-steel pins also at a separation of 25 mm. The pins were first placed inside tight fitting PTFE insulating sleeving and then pushed into pre-drilled holes in the sample which were made along the grain of the wood. By gentle tapping of the pins into the wood the electrodes were made to come into contact with the wood over a length of 2 mm in the middle of the sample. Hot molten wax was used to seal any small gaps remaining on the surface between the sleeving and the timber. Both types of electrodes can be seen in the middle sample in Figure 2-1.

2.3.3 Measurements

All specimens were weighed at least once per month[5]. Samples were weighed individually and in sets of five. This enabled differences in behaviour between individual samples to be monitored, and also helped to assess random errors. Many of the sets of samples installed in dwellings could not be accessed directly due to logistical problems. For this reason, at monthly intervals, participants were instructed to remove samples from their locations, seal them in the polythene bags and dispatch them to the moisture research laboratory. After making the required measurements, samples were returned and reinstalled later the same day.

For mass determination, two Sartorius polyranging balances (type BA3100P) were employed which were calibrated to ±0.01 g. One balance was used for weighing local samples or those brought in by the private participants while the other, which was transportable, was used in the on-site measurements.

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[5]In order to observe short term variations in the moisture content, the mass of one set of samples was monitored continuously for several months by use of computer, sampling approximately twenty times per hour. As expected, the results showed that the moisture content does not suffer from abrupt changes in stable internal conditions.

Both balances were regularly calibrated against standard masses of values 100 g, 500 g and 1000 g. The portable balance was always checked for accuracy before and after transportation, also.

A purpose built case (shown in Figure 2-3) was designed and assembled to facilitate carriage of the instruments to and from remote installation sites, and to reduce the time span taken for recording the data from all sites; the aim was to maximise the comparability of collected data for future analysis in such a way that the annual trends could be extracted based on near identical sampling points.

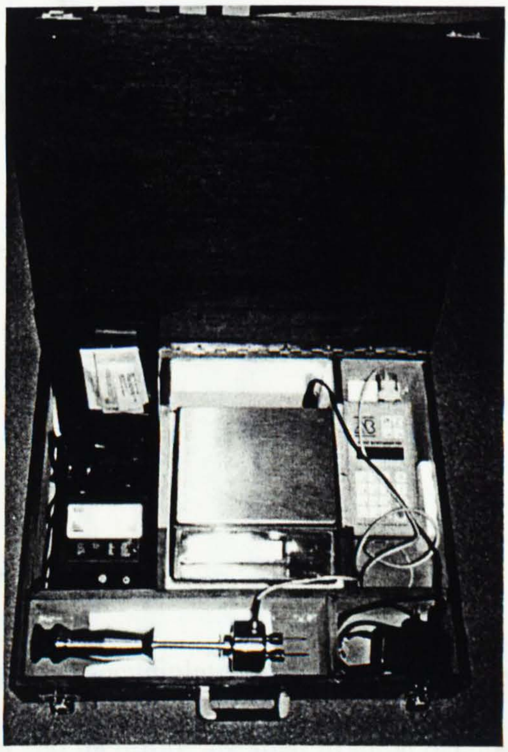

Figure 2-3: The purpose built case, used for transportation of the required instruments

The experiment was deemed complete once all the samples had been *in-situ* for at least one annual climatic cycle, when all the samples were measured for the last time and collected in the sealed moisture proof membranes described in section 2.3.2, page 30. Subsequently, oven drying of the samples was carried out conforming to the required standard and the gravimetric method was used to determine the moisture content of the samples.

For moisture content determination by use of electrical moisture meters, two conductance-type meters, namely the analogue Protimeter Timbermaster (hereinafter PTA meter), and the digital Brookhuis FMD microprocessor controlled moisture meter (hereinafter BH meter), were employed. Direct insertion of the pins electrodes into the timber enabled the measurements to be made, in accordance with each manufacturer's guidelines.

In addition, two independent measurements were then performed using the PTA meter in conjunction with the pin and screw electrodes discussed earlier and seen in Figure 2-1.

2.4 Presentation of results

Data from the survey was accumulated over a period of two years. Although samples were supplied and therefore installed in three batches, it was ensured that all sets remained *in-situ* for well in excess of one annual climatic cycle, as previously mentioned.

Figure 2-4 to Figure 2-10 show a representative selection of the results (for full set of plots see reference [28]), where the moisture content is plotted as a function of time. All the results presented below are those obtained by the gravimetric method which is generally accepted as the most accurate method of timber moisture measurement.

2.4.1 Domestic sites

2.4.1.1 Unheated environments

Starting with environments that generally yielded higher moisture contents, Figure 2-4 shows the results for a typical unheated internal environment (the environment here is a domestic conservatory with no heating).

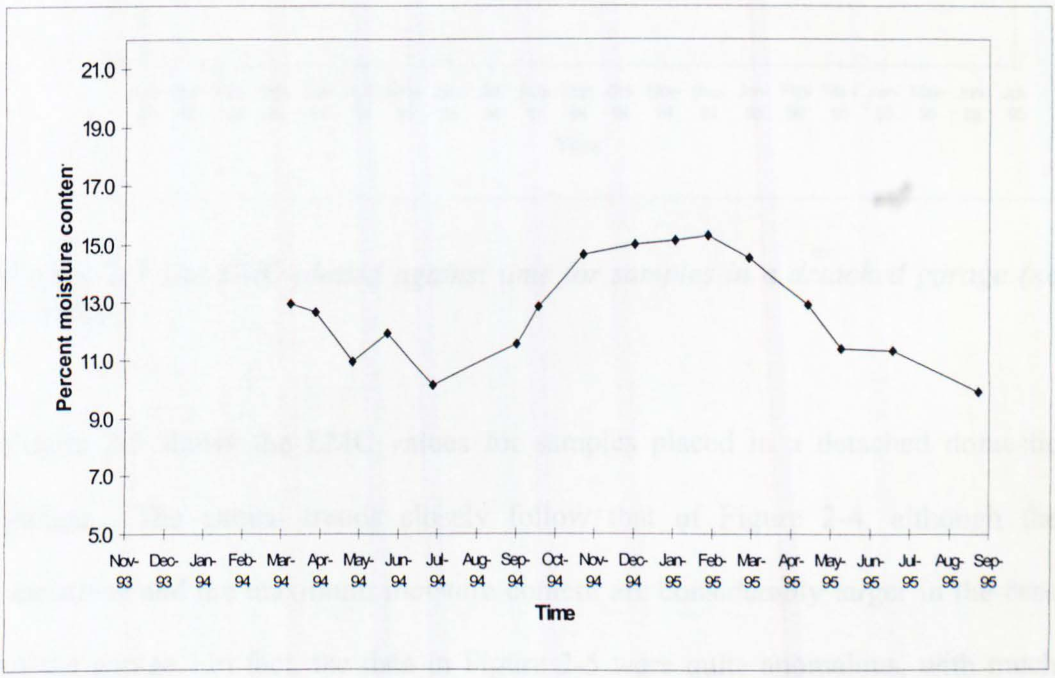

Figure 2-4 The EMC plotted against time, where the test samples were situated in a conservatory (no heating).

There are clear, systematic changes in the moisture content during the year, with the minimum and maximum values about 10% and 15%, respectively. The annual variations observed are as anticipated: in the absence of heating, winter conditions provide high humidity levels, while a pronounced drop is observed during the summer. As the moisture content is predominantly dependent on the relative humidity, these observations are to be expected.

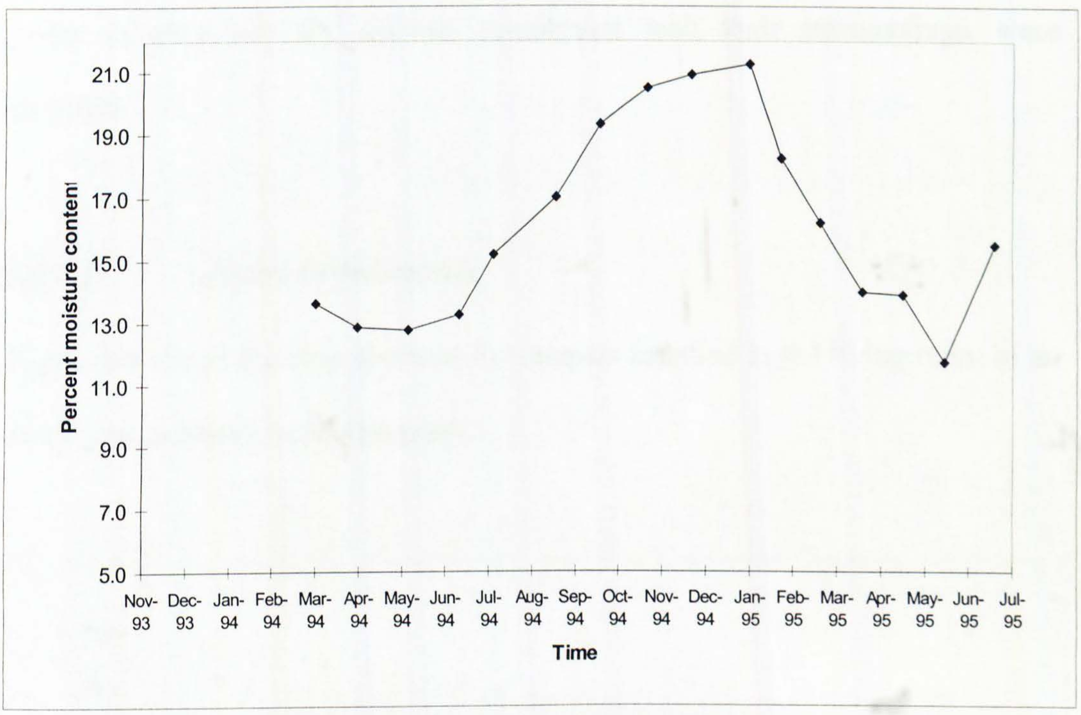

Figure 2-5 The EMC plotted against time for samples in a detached garage (no heating).

Figure 2-5 shows the EMC values for samples placed in a detached domestic garage. The annual trends closely follow that of Figure 2-4, although the variations and the maximum moisture content are considerably larger in the case of the garage. In fact, the data in Figure 2-5 were quite anomalous, with much higher maximum moisture content than the majority of the other unheated environments monitored. It transpired that part of the brickwork for this garage is below ground level and the absence of water-proofing results in moisture penetrating through the masonry into the interior; this explains the unusually higher moisture content of the timber. Nevertheless, even including this anomaly, the data from all the unheated environments provided *mean* values spanning 10% to 16% moisture content. The *mean* was calculated by obtaining the average of the data points over one annual cycle. The data obtained early in the experiment, where samples had not reached equilibrium with their surroundings, were excluded.

2.4.1.2 Heated environments

Figure 2-6 shows the data obtained for samples installed in the living room of an older type, centrally heated property.

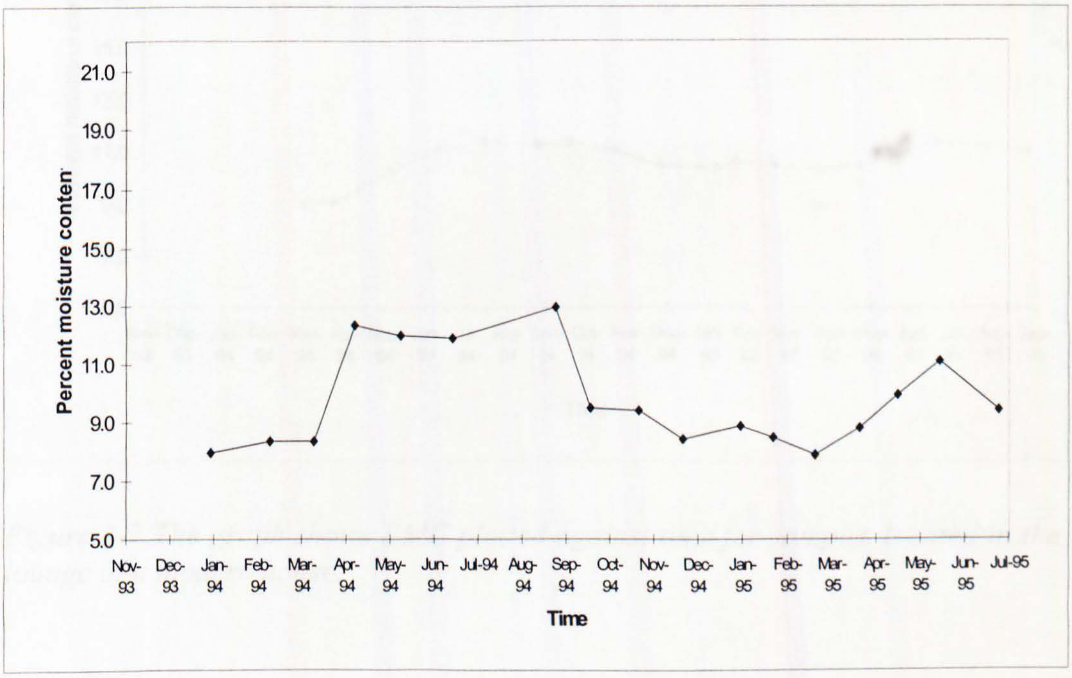

Figure 2-6 Equilibrium moisture content variations against time for an older type, centrally heated, house.

As can be observed, the annual trend here is that the moisture content is at a maximum during the summer months and falls during winter. The data for all similar environments showed this trend, although in most cases the fluctuations in the moisture content were on a much smaller scale.

Contrasting Figure 2-4 (heated environment) with Figure 2-6 (unheated environment), the two curves are roughly one half-cycle out of phase with each other, further confirming the effect of heating during the winter months in the heated environments.

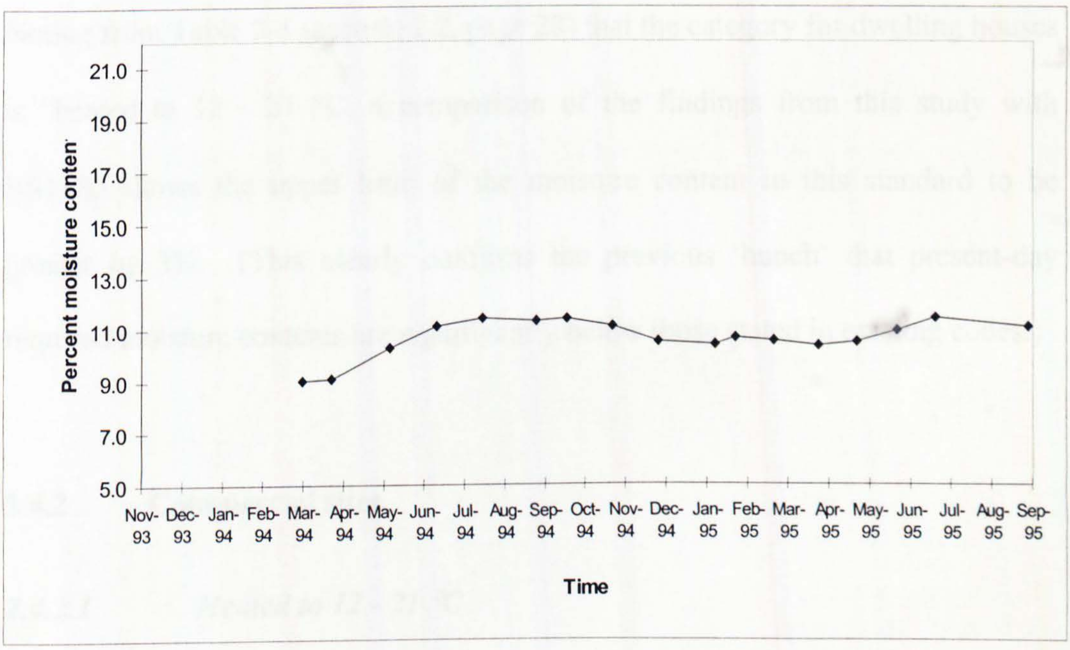

Figure 2-7 The graph shows EMC plotted against time for samples located in the lounge of a modern house.

It was found (see Figure 2-7, for instance), that where samples were *in-situ* in the lounge of a modern domestic property, the fluctuations were of much smaller amplitudes. This plot is far more representative of the data collected. The observed annual trends are consistent with the drying effect of heating during the winter months.

From the analysis of all data from domestic-type properties, it is concluded that the mean value of moisture content over one annual climatic cycle spans 9% to 11%. These figures have been deduced having employed a wide variety of domestic buildings for the samples, ranging from flats to large houses, from terraced to detached buildings. Centrally-heated and non centrally-heated houses were also used in the survey; fuel types included both gas and electricity. There were samples located in kitchens, lounges and bedrooms.

Noting from Table 2-1 (section 2.2, page 28) that the category for dwelling houses is "heated to 12 - 21 °C, a comparison of the findings from this study with BS1186 shows the upper limit of the moisture content in this standard to be greater by 3%. (This clearly confirms the previous 'hunch' that present-day required moisture contents are significantly below those stated in existing codes.)

2.4.2 Commercial sites

2.4.2.1 Heated to 12 - 21 °C

Moving onto commercial-type environments, Figure 2-8 and Figure 2-9 show moisture content variations for typical offices.

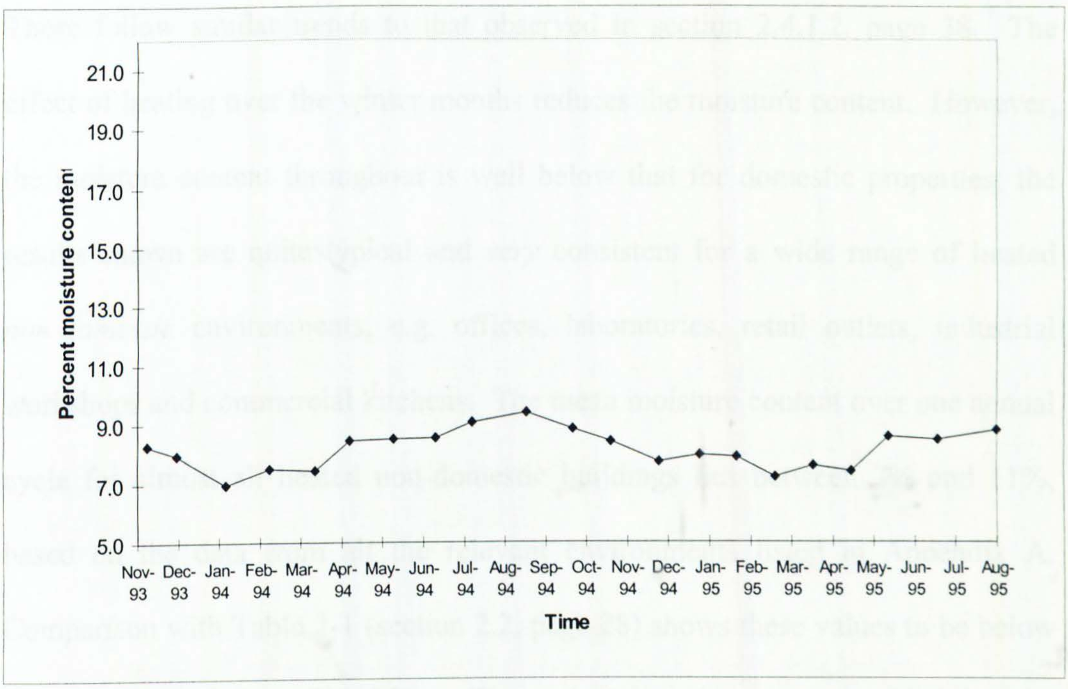

Figure 2-8 Time variations in EMC for samples in a large drawing office in industrial premises.

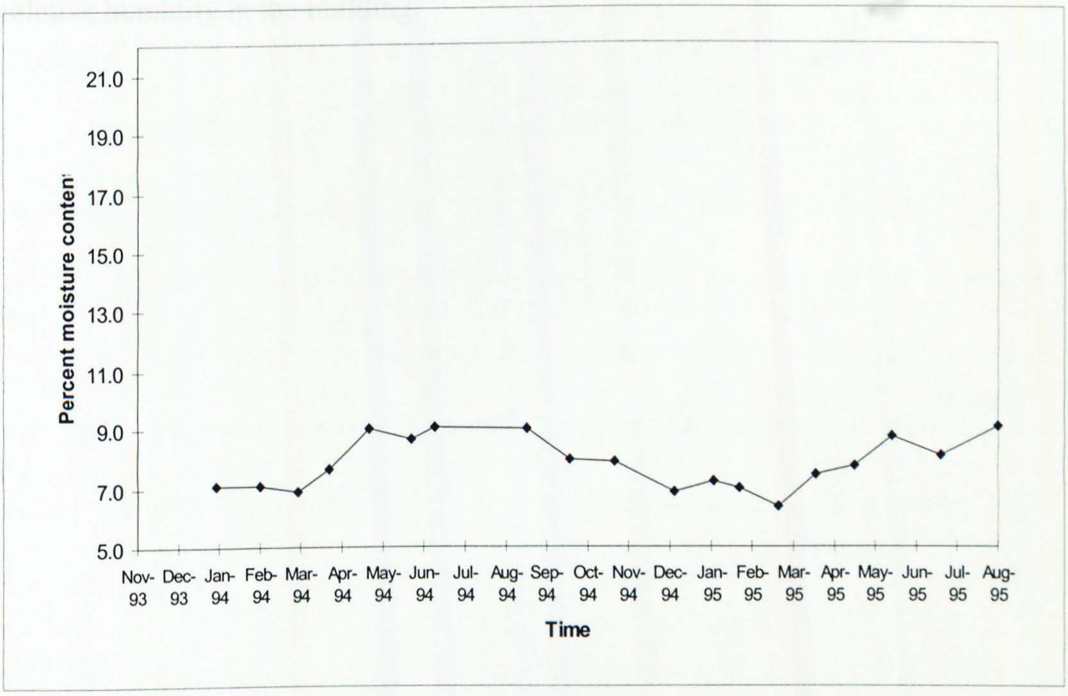

Figure 2-9 Time variations in EMC for samples in a small office in an educational establishment.

These follow similar trends to that observed in section 2.4.1.2, page 38. The effect of heating over the winter months reduces the moisture content. However, the moisture content throughout is well below that for domestic properties; the results shown are quite typical and *very* consistent for a wide range of heated *non-domestic* environments, e.g. offices, laboratories, retail outlets, industrial workshops and commercial kitchens. The mean moisture content over one annual cycle for almost all heated non-domestic buildings lies between 7% and 11%, based on the data from all the relevant environments listed in Appendix A. Comparison with Table 2-1 (section 2.2, page 28) shows these values to be below those in BS1186 by 3% MC. The only exception was provided by the environment of an indoor swimming pool, where the mean moisture content was 13% - this high mean EMC is not difficult to explain in the presence of the high relative humidity in the building.

2.4.2.2 Heated to above 21 °C

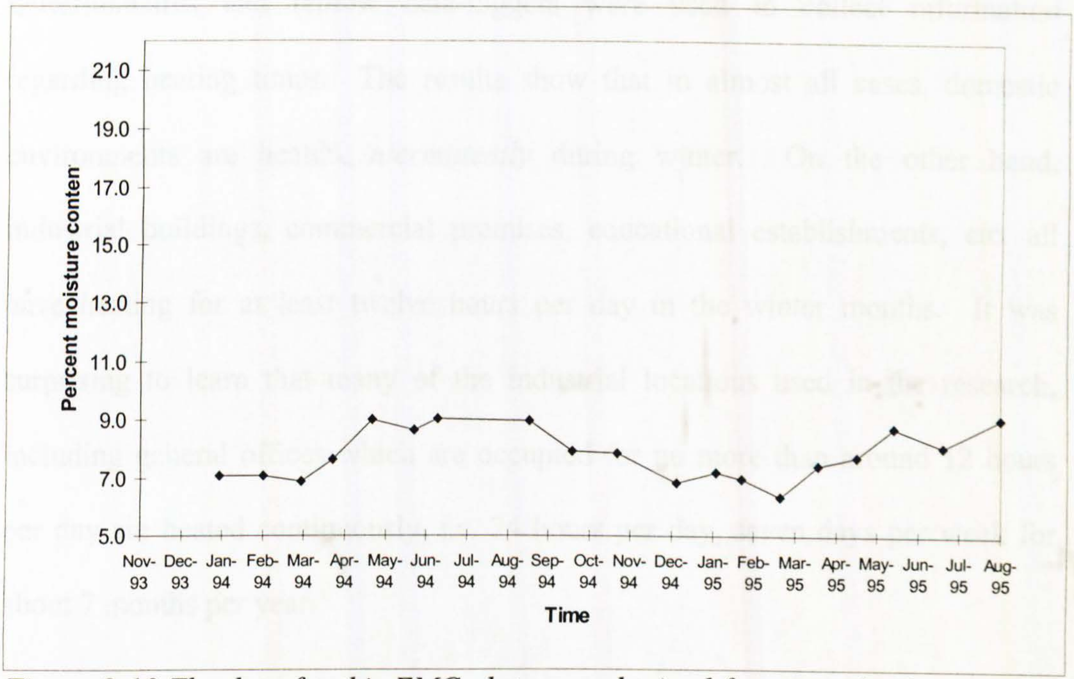

Figure 2-10 The data for this EMC plot were obtained from samples located in a hospital ward.

Figure 2-10 shows values of moisture content and the trends for a hospital environment, where heating is continuous and in the "above 21 °C" category in Table 2-1 (section 2.2, page 28). Samples situated in wards and store rooms all yielded similar moisture contents and trends. The samples placed in various locations within nursing homes showed similar behaviour. The mean value of moisture content over one annual cycle for this type of environment was found to be in the range 7% and 10%. This is consistent with the observed high temperatures and low relative humidity, typically around 25 °C and 40%, respectively.

2.4.3 Relative humidity and temperature trends

Questionnaires and remote data-loggers were used to collect information regarding heating times. The results show that in almost all cases, domestic environments are heated *intermittently* during winter. On the other hand, industrial buildings, commercial premises, educational establishments, etc. all have heating for at least twelve hours per day in the winter months. It was surprising to learn that many of the industrial locations used in the research, including general offices which are occupied for no more than around 12 hours per day are heated continuously, i.e. 24 hours per day, seven days per week for about 7 months per year.

The recorded trends on the data-loggers showed that over a six month period, September 1994 to March 1995, the mean relative humidity for the domestic environments sampled was between about 45% and 65%. Likewise, the mean values of relative humidity for typical 'office-type' environments was between about 35% and 45% (see Appendix B, for example). Conversely, temperatures were generally a few degrees lower in domestic buildings. The effect of increasing the temperature in a given environment is to reduce the relative humidity. This is what is being unambiguously observed: in office environments, continuous heating results in depressed values of relative humidity which in turn reduces the timber moisture content. However, higher relative humidity in the domestic environment also results from higher levels of moisture production: cooking, bathing, washing are examples of moisture production which are generally absent in most commercial-type environments.

2.4.4 Results from moisture meter readings

As already discussed (in section 2.3.3, page 30) electrical moisture meters were also employed for moisture content measurement. Figure 2-11 shows a frequency histogram comparing the results from the BH[6] meter (where the meter pins were driven directly into the timber) with the moisture content (o.d. basis). A characteristic 'bell-shaped' distribution is observable.

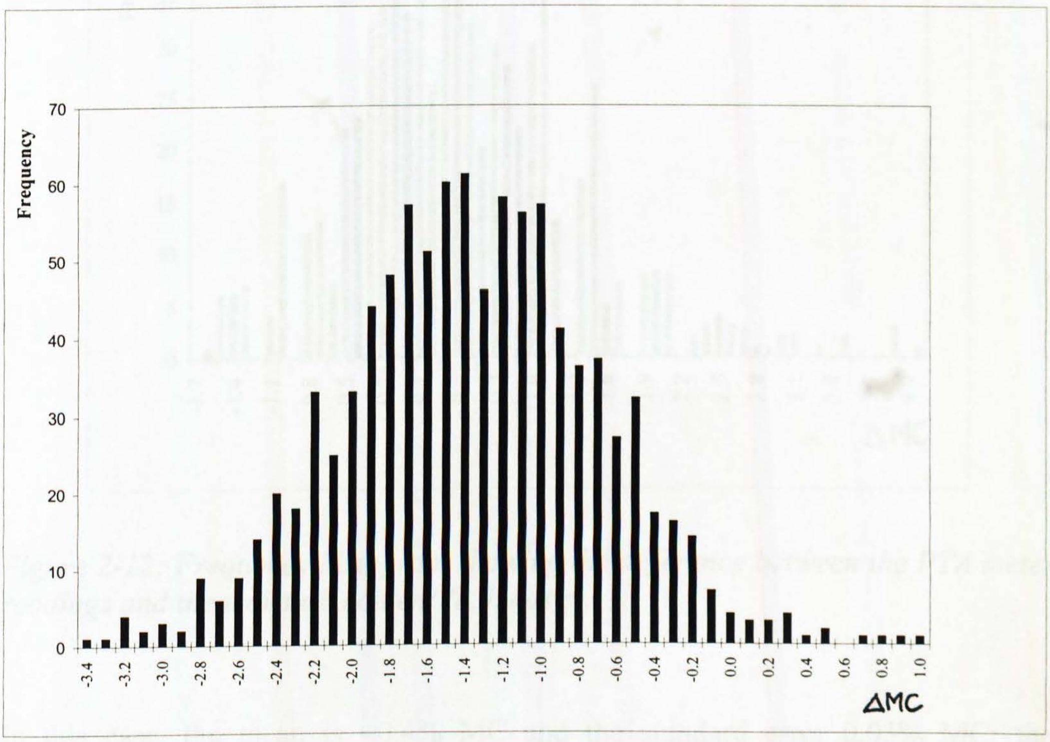

Figure 2-11: Frequency histogram showing the difference between the BH meter readings and the moisture content (o.d. basis).

The quantity displayed by the histogram is (MC_{meter}–$MC_{oven\text{-}dry}$). The mean value is –1.3% MC (i.e. the instrument readings are on average below moisture contents

[6] The BH meter already mentioned in section 2.3.3, is an advanced digital resistance-type moisture meter capable of moisture content measurements in the range of 5% to 99% for the general species "wood" at 20 °C (specified in FMD User guide: Technical specifications).

(o.d. basis) by this value), and the standard error in the mean is around 0.02% MC. The standard deviation of the distribution is about 0.8% MC. A similar plot for the PTA[7] meter (where the shallow pins were directly inserted into the timber) revealed a broader distribution (see Figure 2-12).

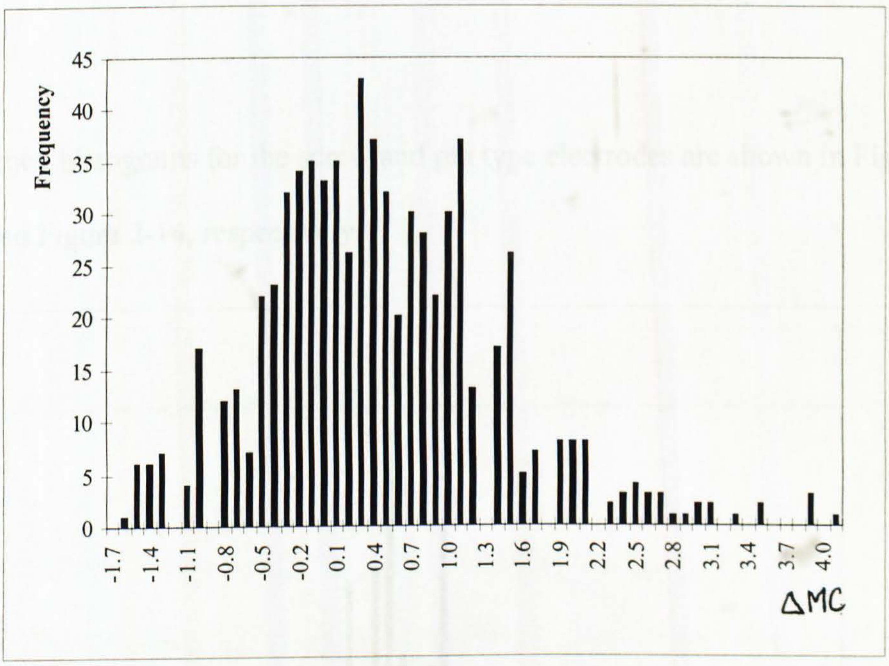

Figure 2-12: Frequency histogram showing the difference between the PTA meter readings and the moisture content (o.d. basis).

In this case, the mean is +0.4% MC and the standard error 0.03% MC; the standard deviation is about 0.9% MC Clearly, there are significant differences in not only the mean moisture content from the two meters, but also between the moisture content (o.d. basis)s and those indicated by the meters[8].

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[7] The PTA meter briefly introduced in section 2.3.3 is a commonly employed analogue conductance-type moisture meter with a specified measurement range of 7% MC to 28% MC, approximately.

[8] Although resistance-type moisture meters are widely used for moisture content determination, considerable variations can occur between different brands of instruments because at present there exist no standards for the calibration of the meters. Further discussion, and a comparison of meters, is available in [21] and in Chapter 3.

2.4.4.1 Comparison of the electrode types

The presented results in section 2.4.4 (page 45) are based on the use of the electrodes provided by each manufacturer and direct contact with the sample. However, the results from the two independent electrode types discussed in section 2.3.2 (page 30) are summarized here.

Frequency histograms for the screw and pin type electrodes are shown in Figure 2-13 and Figure 2-14, respectively.

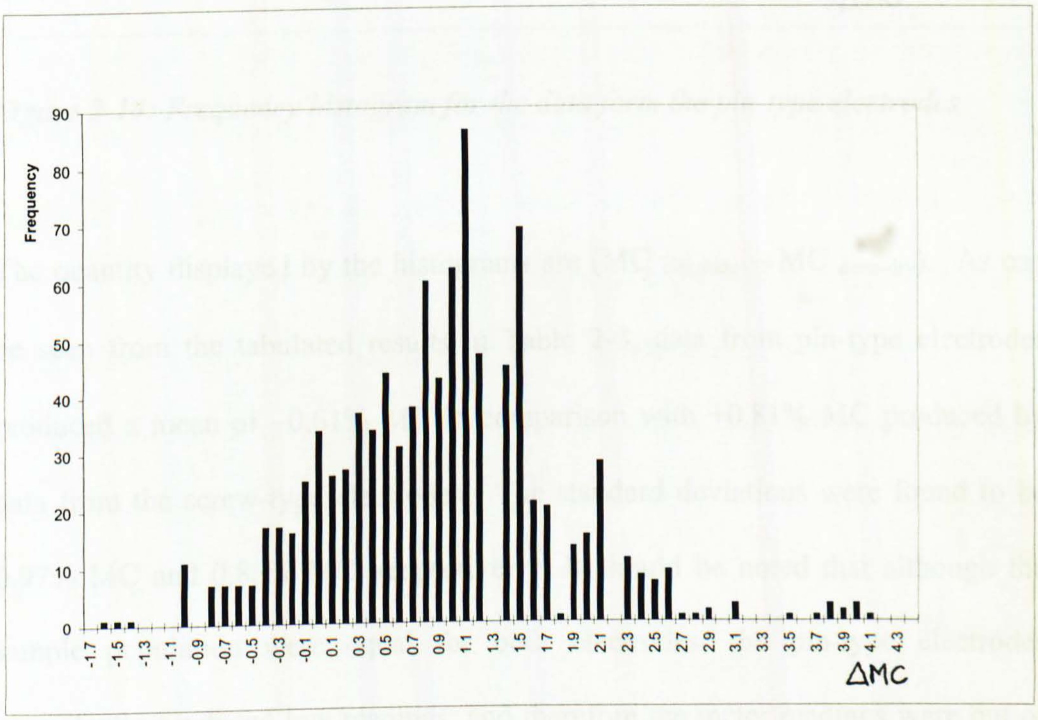

Figure 2-13: Frequency histogram for data from the Screw-type electrodes.

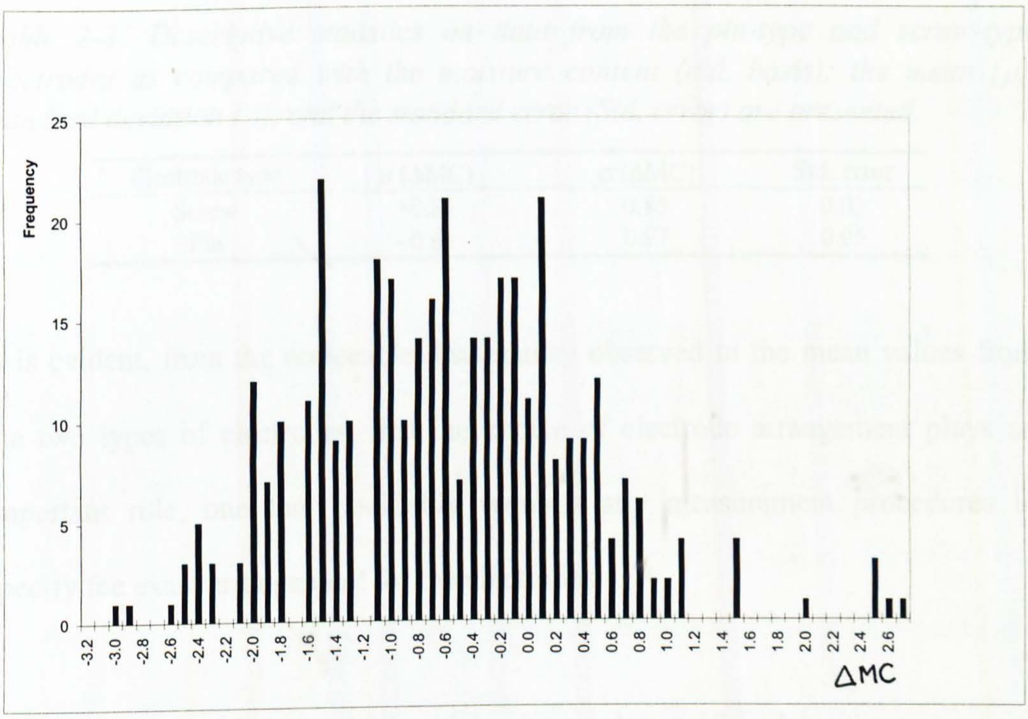

Figure 2-14: Frequency histogram for the data form the pin-type electrodes

The quantity displayed by the histograms are ($MC_{electrode} - MC_{oven\text{-}dry}$). As can be seen from the tabulated results in Table 2-3, data from pin-type electrodes produced a mean of –0.61% MC in comparison with +0.81% MC produced by data from the screw-type electrodes. The standard deviations were found to be 0.97% MC and 0.85% MC, respectively. It should be noted that although the sample population were equal for both electrodes, the pin-type electrodes consistently produced low readings, and therefore the meter readings were out of range for some of the drier environments. In such cases it was clearly not possible to take reliable measurements, and therefore data from such cases were ignored during the analysis.

Table 2-3: Descriptive statistics on data from the pin-type and screw-type electrodes as compared with the moisture content (o.d. basis); the mean (μ), standard deviation (σ), and the standard error (Std. error) are presented.

Electrode type	μ (ΔMC)	σ (ΔMC)	Std. error
Screw	+0.81	0.85	0.03
Pin	−0.61	0.97	0.05

It is evident, from the noticeable discrepancy observed in the mean values from the two types of electrodes, that the choice of electrode arrangement plays an important role, one that justifiably requires any measurement procedures to specify the exact arrangement for the electrodes.

With reference to Table 2-3, the high mean value produced by the screw-type electrodes is due to the relatively large contact area between the conducting regions of the screws and the timber, compared with that of the insulated pins. The insulating sleeves used in the construction of the pin-type electrodes (discussed in section 2.3.2, page 30) limits the conduction path to between the tips of the pins only, whereas in the case of the screw-type electrodes the conduction path is the 'path of least resistance' anywhere between the (relatively) large surface area of the screws.

2.5 *Further discussion*

The findings place still greater importance on the accepted, yet seldom observed, practice of specifying timber for internal environments according to an *appropriate* moisture content range so as to minimize excessive movement and distortion in response to large and sudden moisture losses. Specifiers should be mindful of the moisture regimes likely to occur in certain environments and stipulate realistic moisture ranges for components in specific environments. Although heating regimes are the main factor responsible for moisture trends within buildings, one must not lose sight of the potential influence in achieving a *stable* equilibrium moisture content by optimum insulation, ventilation and good building design. Not only is consideration of EMC important where newly installed timber is concerned, but the maintenance of a stable EMC over the annual cycle is just as important if long-term problems with distortion and movement are to be avoided. While it may not be reasonable to expect too high a level of stability, particularly in environments vulnerable to sharp humidity changes, consideration of good design is nonetheless vital if large-scale fluctuations in moisture content are to be avoided.

Data from the conductance-type moisture meters used in the study revealed that the users of such meters need to be aware of the exact measurement methodologies employed, and that in scenarios whereby results from independent manufacturer's moisture meters are to be compared, high tolerance levels should be allowed. This is typically the case for shipments of imported timber; quality assurance agents checking (in a "accept / reject" scenario) the moisture content for a batch of timber against that specified. In such cases, unless detailed agreed quality assessment criteria (which specify the exact moisture meter brand) are used by both the supplier and the buyer, then the chances of moisture content mismatch are high, as a direct consequence of the lack of calibration standards in the moisture meter industry.

2.6 *Conclusion*

2.6.1 Recommendations

Based on exhaustive data-taking over a two year period, using a wide range of internal environments, the findings of the survey showed that the values of mean moisture content as quoted in BS1186 were consistently higher than those observed. Based on the results of this survey, the mean moisture contents as measured by the oven-dry method are summarized in Table 2-4.

Table 2-4 Summary of results from the study

Internal environment	Span of mean of moisture contents (%)
Unheated	10 - 16
Heated (domestic)	9 - 11
Heated (commercial)	7 - 11
Heated (high temperature environments)	7 - 10

These findings were compiled as the first part of a report for the Depart of Environment (DoE), which was complemented by a second part based on data from actual on-site measurements by TRADA Technology Ltd. (TTL), and submitted to the DoE in April 1996.

Findings from the on-site measurements (carried out by TTL) similarly indicated that in general recommendation set out in BS 1186 are set too high or at too great a range of tolerance for current building practices and lifestyles (see reference [23], page 32).

2.6.2 Revisions to British Standard BS1186

The British Standard BS EN 942:1996 was introduced in the early 1996 as replacement for BS1186 Part 1. The new recommended levels of moisture content for timber to be installed in buildings are shown in Table 2-5.

Table 2-5: Current recommendations in BS EN 942 (adapted from [29])

Category	Sub-category based on service climates	Average moisture content (%)
External joinery		12 – 19
Internal joinery	Unheated buildings	12 – 16
	Buildings with heating providing room temperatures of 12 - 21 °C	9 – 13
	Buildings with heating providing room temperatures in excess of 21 °C	6 –10

The underlying trend in the modifications introduced in BS EN 942 confirm the recommendations put forward by this study (refer to page 51). Figure 2-15 shows the comparison between the recommended levels of moisture content in BS1186, the revised version of this standard BS EN 942 and findings of the EMC project.

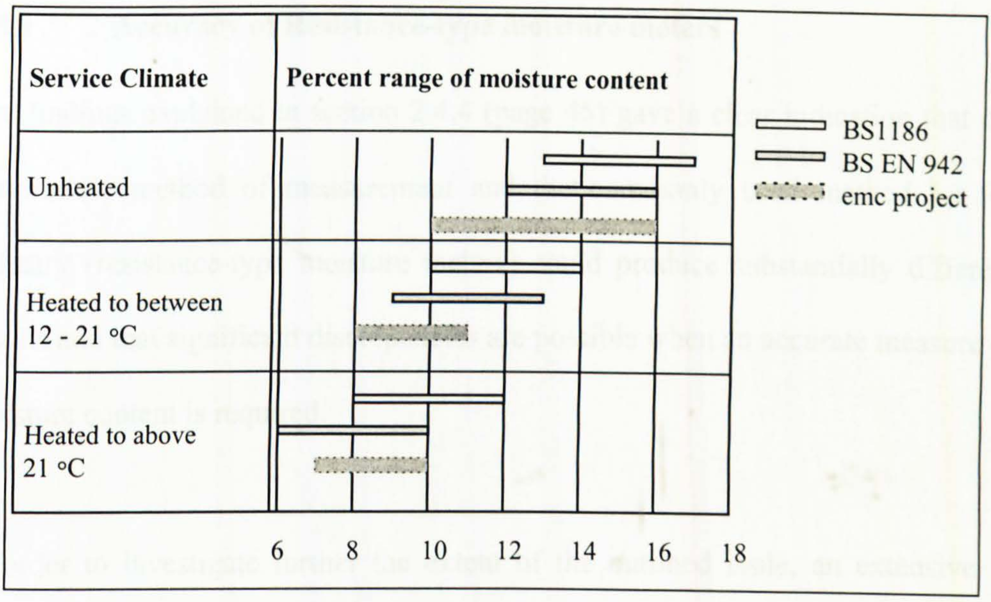

Figure 2-15: Comparison between the levels of moisture content specified in BS1186, BS EN 942 and the empirically determined levels from the EMC project

It is deduced from Figure 2-15 that for the first two categories (unheated and heated to between 12 and 21°C) both the upper and lower limits of the recommended moisture content in BS 1186, have been reduced by 1% MC; the upper and lower limits reduction for the third category (heated to above 21°C) is 2% MC. It is important to emphasis that the recommended levels of moisture content in BS EN 942 were made prior to the submission of the results from the EMC project, and therefore where not based on collected data [30], but more on the general understanding that such changes were necessary given the evolution of socio-economic factors since the last revision of the British Standards nearly 30 years ago.

2.6.3 Accuracy of Resistance-type moisture meters

The findings explained in section 2.4.4 (page 45) gave a clear indication that the gravimetric method of measurement and the commonly used method by the industry (resistance-type moisture meters) could produce substantially different results and that significant discrepancies are possible when an accurate measure of moisture content is required.

In order to investigate further the extent of the outlined issue, an extensive in depth analysis on the performance of nine commercially used resistance type moisture meters was carried out; this is fully discussed in Chapter 3.

Chapter 3

3 A Comparative Study in The Performance of Nine Commercially Used Conductance-type Moisture Meters

3.1 Summary

The performance of nine commercial conductance-type moisture meters, in common use in Europe and North America, was investigated under laboratory conditions. The performance criteria used included temperature and species correction data provided by each manufacturer. To this end, a range of temperatures, spanning –10 °C to 80 °C, and ten commercially important species were used in the study.

The findings indicate that significant discrepancies are possible between the readings obtained for identical species, under identical conditions.

The lack of standards for global calibration of conductance-type moisture meters is discussed; this is followed by a proposed methodology for the standardization and calibration procedures.

3.2 *Introduction*

Hand-held conductance-type (also referred to as resistance-type) moisture meters are the most widely used type of moisture meters, and currently the most popular method for on-site moisture content measurements. They are used by producers, processors and consumers in the timber industry. Although, as previously explained (see page 15) other types of moisture meters are available, the current standards specify only the use of resistance-type moisture meters[9], for electrical method of moisture content measurement.

Quality control is one of the most important applications for hand-held moisture meters. It is inevitable that in such situations various brands of moisture meters may be used; it is desirable that such variation of brand should not introduce significant levels of uncertainty in the measured values. However, some concern has been voiced by industry leaders that this may not necessarily be the case today, see for example [31].

Manufacturers frequently emphasize that their meters can measure to ±0.1% moisture content; however during each measurement the operator must take account of three variables, namely the temperature of the wood, the species under test and the depth at which the measurement is carried out.

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[9] Currently, National standards are being replaced by European standards. Comité Europeene de Normalisation (CEN) responsible for the European Standards drafted a proposal, prEN(175-13.01), in which only the resistance-type moisture meters were specified for electrical measurement of moisture content.

In reality, because of the variable nature of timber it has been estimated that under the best conditions these moisture meters can read to within ±1% moisture content accuracy in 95% of readings [32]. In any case, quotes to 1 decimal point are probably not meaningful under normal use.

3.3 Methodology

3.3.1 Preparation of moisture meters for testing

Nine conductance-type moisture meters[10] were obtained for the tests from six manufacturers. These were labelled as A, B, C, D1, D2, E1, E2, F1 and F2, where the letter refer to a particular manufacturer (and calibration). Instruments D1, E1 and F1 were all analogue read out, while D2, E2, and F2 were their digital readout counterparts. All instruments were either new or in excellent condition, the latter having previously been used only in the laboratory environment. Where available, meters were checked against appropriate external/internal calibrators. Likewise, calibration tests were frequently made to instruments where check-facilities were available within the instrument. Throughout all the subsequent tests, power supplies to the moisture meters were regularly checked to ensure correct input voltages. For all tests, the appropriate electrodes supplied by the manufacturers were used.

[10] A list of the meters used is given in Appendix C. However, the order is randomised to ensure that no data can be linked directly to a brand.

3.3.2 Preparation of samples

3.3.2.1 Supply and selection of species

Representative samples from ten different commonly used softwoods and hardwoods were used. These are listed in Table 3-2, page 69. Ten species were chosen to keep the experimental work within reasonable limits. The timber was obtained untreated and cut and planed to 130 mm × 72 mm × 22 mm (along the grain, across the grain and in the radial direction, respectively). Four end-matched samples of each species were obtained from the same length of timber.

3.3.2.2 Modifications for temperature measurement

The temperature of each sample was monitored 2 mm below the surface, and also in the centre of each sample. A small hole was drilled from the side, into the centre to enable the penetration of a thermocouple insertion probe (type K). A small hole was also made to a depth of 2 mm below the surface in the middle of one of the large surfaces to enable insertion of a second thermocouple. These holes enabled the central and external temperatures of each sample to be checked during subsequent measurements.

3.3.2.3 Conditioning

Each set of ten samples was conditioned at 20 °C to one of four relative humidities, namely, 30%, 45%, 65% and 85% and labelled as sets 1 to 4, respectively, using commercial conditioning chambers[11].

The conditioned timber provided a range of moisture contents (o.d. basis) spanning 6% to 22%. During conditioning, the mass of each sample was monitored every day using a scale to a precision of 2 decimal points. Samples were deemed to have reached equilibrium in moisture content when the changes in mass became negligible[12]. At the end of the conditioning period, the mass of each sample was again determined and the individual samples were then immediately placed into several layers of polyethylene film (previous tests had shown that the moisture content in the arrangement used remains constant to a very good approximation, see page 32).

3.3.3 Measurement procedure

The measurements were carried out at four temperatures, –10, 5, 20 and 80 °C. The selected temperature are representative of various possible climatic conditions with the exception of the 80°C where the results are relevant for kiln-drying only. In order to ensure that the measurements were carried out at the correct

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[11] The 45% and 85% relative humidity (at 20 °C) conditions were available at conditioning rooms utilized at the Building Research Establishment (BRE) and the remaining two conditions at conditioning chambers of TRADA Technology Limited (TTL).

[12] The criterion for emc was a change in mass of less than or equal to 0.1%, for two successive weighing or three fluctuations.

temperatures, arrangements were made to carry out the measurements *within* each environment[13]. A list of each measurement environment at the relevant temperature is given in Table 3-1.

Table 3-1: The range of temperatures and measurement environments used in the study

Temperature[14] (°C)	Measurement environment
−10	Commercial walk-in freezer
5	Commercial walk-in cold store
20	Laboratory environment
80	1kW microwave heater

The measurements at 80 °C required particular care. It was critical to maintain the moisture content of the samples, and yet raise the temperature to high values. The only way to achieve this was to employ a 'rapid' method of heating the timber. A Pilot study was undertaken using similar sample sizes to those used in the study in conjunction with the microwave heater used in the main study, to obtain the correct time required for samples to reach 80 °C carried out on a species-by-species basis.

Except for the 80 °C measurements when the heating time was very short (about 40 second), the samples sealed in the polyethylene film were placed into the appropriate environment 24 hours before testing. Near surface and deep

[13] Except for the tests carried out at 80 °C; it should also be stated that large uncertainties were likely for the latter tests due to the nature of these tests explained in the next section.

[14] Calibrators were used at each temperature to ensure that the meters were functioning correctly (no 'electronics' problems were encountered).

thermocouples were placed into each sample prior to testing to ensure the equilibrium temperature had been achieved. Where small discrepancies from the nominal temperature occurred, corrections were later made in accordance with the meter manufacturer's instructions. Where meters were equipped with temperature and/or species correction facilities, the dials were set as appropriate before measurements were made otherwise 'manual' corrections were made in accordance with the meter instructions.

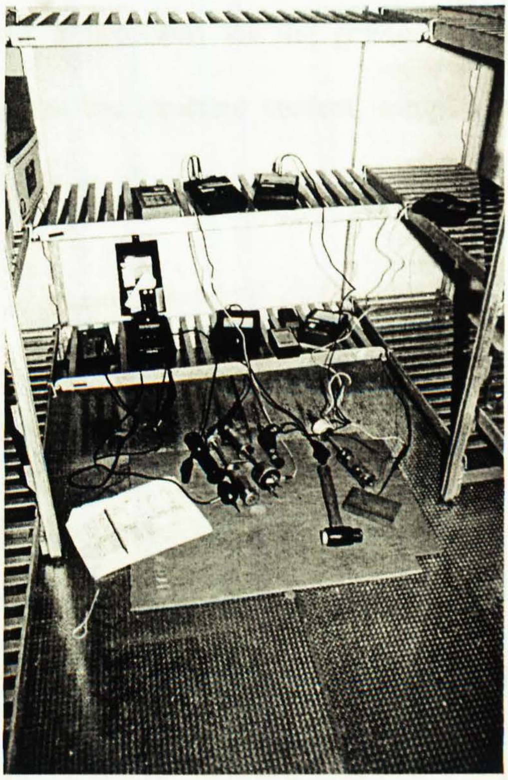


Figure 3-1: Resistance-type moisture meters in the walk-in freezer environment (–10 °C temperature)

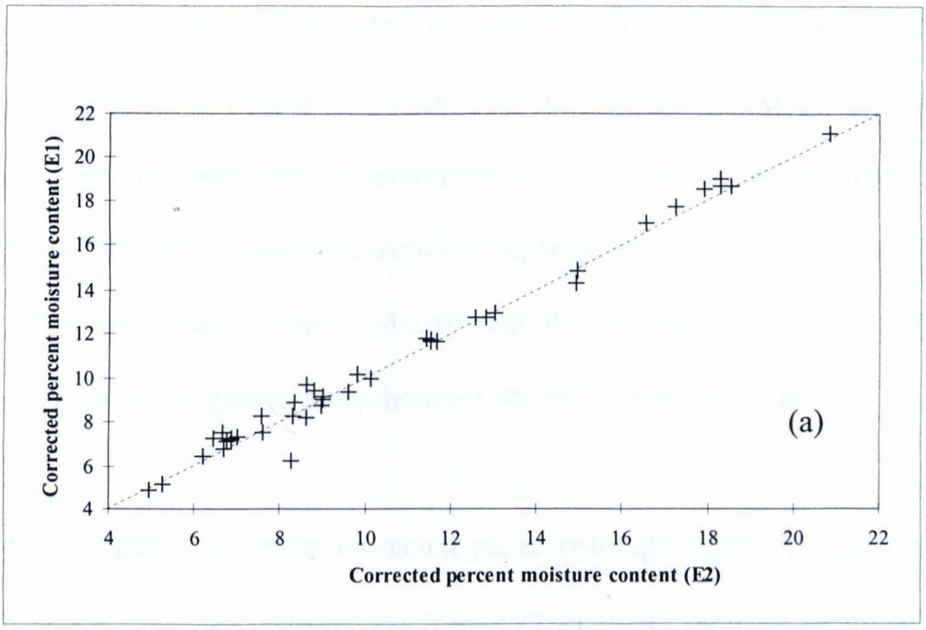
Each moisture meter, in turn, was used to measure the moisture content of each sample. Precautions were taken to avoid condensation on electrodes by ensuring that electrodes were in steady state condition, where extreme temperatures were involved.

The penetration of electrodes was 6 mm ±1 mm (about 1/3 of sample depth) with the electrodes pins inserted along the grain of the timber on one of the larger faces (in the LT plane, see Figure 1-4 page 7). To ensure consistency in readings, several measurements were taken from each sample and the mean value was subsequently recorded. Samples were weighed at the time of measurements to check for any small variations in the mass and hence moisture content during the tests and this enabled comparisons via the gravimetric method. In order to minimize the changes in the moisture content, samples were kept within the polyethylene membranes at all times except when measurements were being made.

3.4 Results and analysis

The representative data presented here have been processed to include all the corrections required for species and temperature as instructed by the relevant manufacturer. The term *corrected* moisture content is used hereinafter to refer to the processed data.

Figure 3-2 (a) compares readings made using meters E1 and E2 at 20 °C . The dashed line is the ideal, perfect agreement between the meters. The line of best fit to the data points (not shown), obtained by linear regression has a gradient of 1.00 with a y-intercept of 0.35% MC. Clearly, the agreement is quite striking apart from the small but obvious systematic relative off-set between the two sets of values. Similar analysis of the data produced by meters D1 and D2 resulted in a gradient of 1.07 and y-intercept of –1.21% MC (Figure 3-2 (b)).



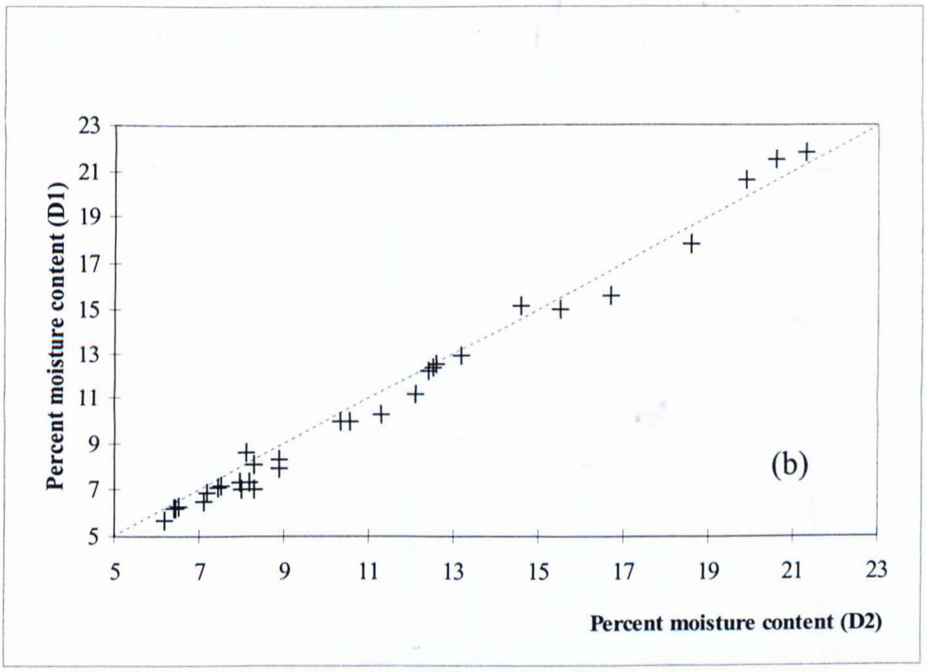
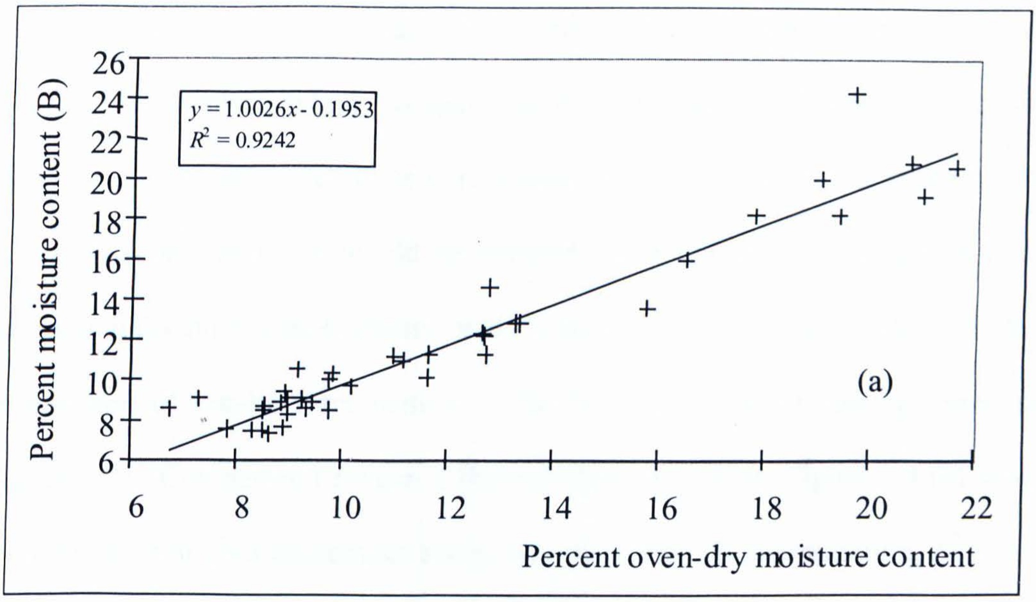


Figure 3-2 (a) and (b): Typical results showing corrected moisture contents where moisture meters of the same brand were compared at 20 °C.

Agreement was similarly very good when the instruments F1 and F2 were compared. All these results show remarkably close agreement between the pairs of meters of the same brand. These data enabled the uncertainties associated with our measurements to be estimated by observing the differences between the moisture content measured by each pair of meters. Using the data of Figure 3-2(a), the mean absolute deviation is 0.38% MC while that from Figure 3-2(b) is 0.58% MC. Assuming zero discrepancy in the calibration between the pairs of meters, these values indicate that the measurements were suffering random errors of not greater than about ±0.5% MC during the tests.

To follow, Figure 3-3 shows corrected meter readings versus moisture content (o.d. basis) for the two instruments, B and F2 at 20 °C showing relatively good and poor agreement, respectively.



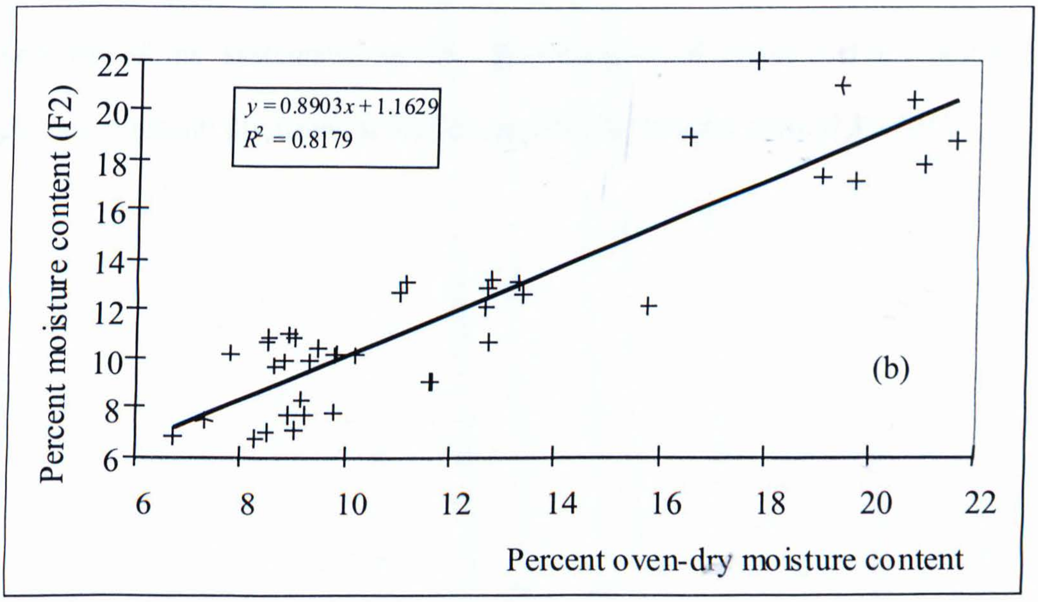
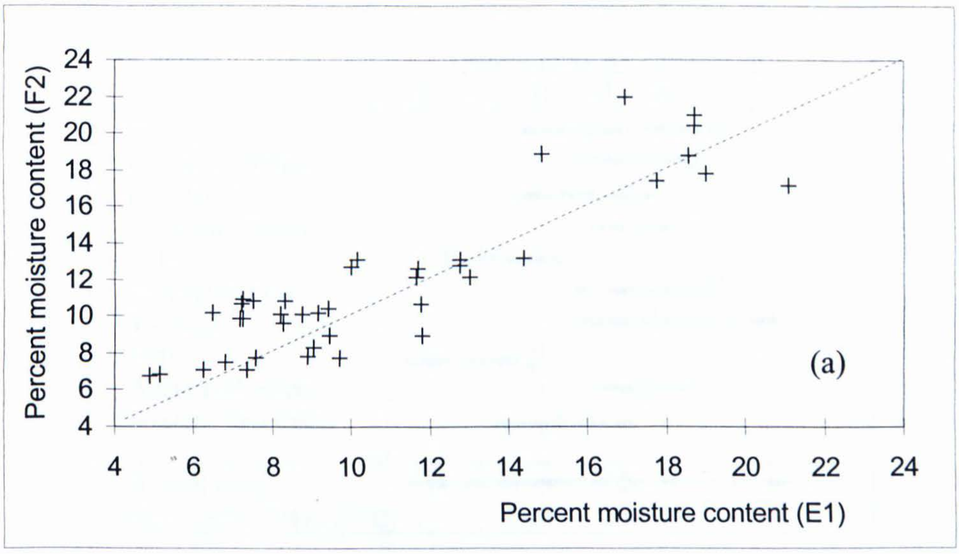


Figure 3-3: corrected meter readings versus MC (oven-dry basis) for (a) relatively good agreement (instrument B) and (b) poor agreement (instrument F2) at 20 °C

Comparisons made using instruments from different manufacturers contrast quite dramatically with Figure 3-2; typical examples follow. Figure 3-4 (a) shows the corrected readings from meter F2 when plotted against those from meter E1.

Likewise Figure 3-4 (b) compares corrected moisture contents for instruments B and E2. These plots, which compare instrument readings, highlight substantial discrepancies between (corrected) readings obtained by moisture meters under laboratory conditions. It should be stressed that the scatter of the points is not random; individual measurements were repeatable to around ±0.5% as indeed comparison of results from meters of the same brand-name clearly show (see Figure 3-2). Comparing between different brands of meters, Figure 3-4 (a) shows a typical case of poor agreement where the coefficient of determination, $R^2 = 0.79$ (correlation coefficient r = 0.89), while Figure 3-4 (b) shows relatively good correlation. The results in Figure 3-4 (b) yield $R^2 = 0.94$ ($r = 0.97$) nevertheless, because of the systematic relative displacement of results certain points still deviate substantially from the line of agreement, by up to around 3% MC.



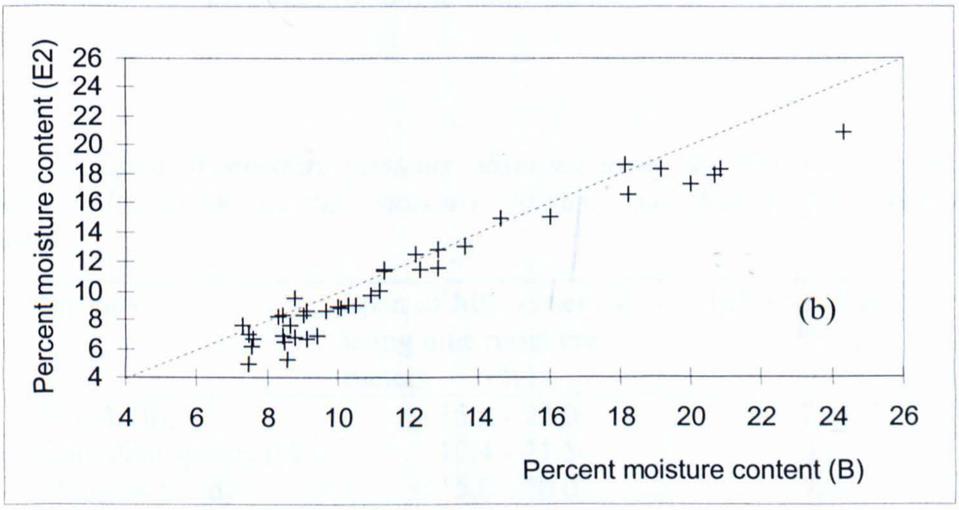


Figure 3-4 (a) and (b): Typical results showing corrected moisture contents where moisture meters from different manufacturers were compared at 20 °C.

Table 3-2 shows the summary of the range of readings obtained at 20 °C (meter calibration temperature) for set 4 (conditioned to RH = 85% at 20 °C). The moisture content (o.d. basis) is given for comparison; a pictorial representation of this information is also shown in Figure 3-5.

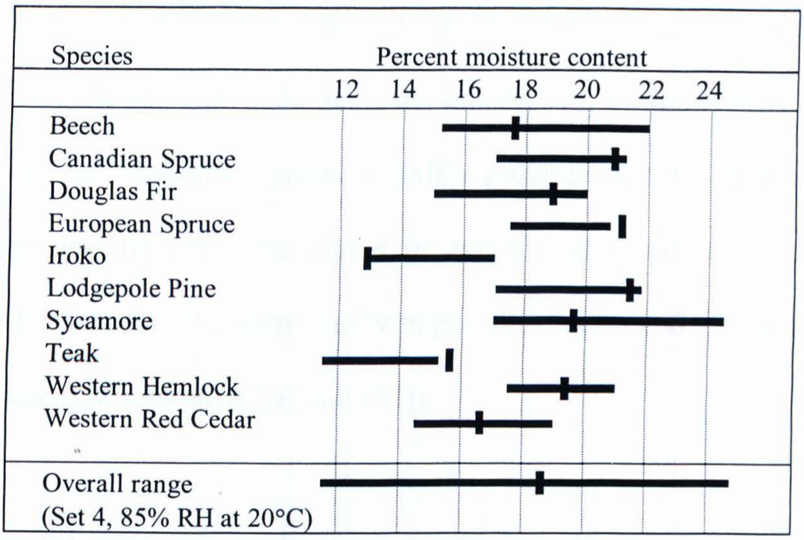


Figure 3-5: Summary of the results obtained at 20 °C for set 4 (conditioned to 85% RH, at 20 °C), the small rectangle indicates the moisture content (o.d. basis).

Table 3-2: Span of moisture contents observed using all nine meters for each species. Also given are the moisture content (o.d. basis)s for comparison purposes.

Species	Span of MC. observed using nine moisture meters (%)	MC (o.d. basis) (%)
Beech (b)	15.6 - 22.0	17.8
Canadian spruce (c)	17.4 - 21.5	20.8
Douglas fir (d)	15.0 - 20.0	19.0
European spruce (e)	17.7 - 20.7	21.6
Iroko (I)	12.8 - 17.1	12.8
Lodgepole pine (l)	16.9 - 21.8	21.0
Sycamore (s)	16.9 - 24.4	19.7
Teak (t)	11.7 - 14.6	15.8
Western Hemlock (wh)	17.8 - 21.0	19.4
Western red Cedar (wc)	14.6 - 18.9	16.5
Overall range	11.7 - 24.4	18.4 (mean)

It is often incorrectly assumed that all timber species reach approximately the same equilibrium moisture content (EMC). For set 4, the EMC values spanned

12.8% to 21.6%, with a mean value of 18.4%. Although, the relatively small sample population can not yield accurate statistic, the findings from this study clearly show the substantial range of EMCs possible, for the species selected. This finding was further consolidated in another study aimed at establishing detailed EMC data for 20 commercially important species and will not be further discussed here (see references [4] and [53]).

Returning to Table 3-2, the results show that for Douglas fir while one instrument gave a mean corrected moisture content of 15%, another gave a mean reading of 20% on the same sample. In this case, the worst deviation from the moisture content (o.d. basis) was 4% MC. Sycamore, as another example, showed even a larger worst deviation of 4.7% MC. It is important to stress again that these results were obtained under strictly controlled conditions at constant temperature and with moisture gradients minimized.

To follow, Table 3-3 summarizes the data from each instrument for each species at 20 °C. Each value shown is the difference between the meter reading and the moisture content (o.d. basis), rounded to the nearest integer. To further improve the clarity, all values of +1 and –1 have been entered as zero as it is conceivable that random errors could in these cases explain the deviations from zero. For example, referring to Table 3-3, a deviation of +2 indicates that the meter reading was 2% MC in excess of the moisture content (o.d. basis) while –4 shows that the instrument value is 4% MC below the moisture content (o.d. basis). In the last column, in order to provide a rough comparison between meters, the mean of the absolute deviations has been calculated. (This was done using the original data, not the simplified values shown in Table 3-3). Clearly, for a meter which gives moisture contents in perfect agreement with oven-dry values, the mean absolute deviation is zero.

Table 3-3: Percentage moisture content discrepancies between meter measurements and oven dry values at 20 °C, for samples conditioned to 85% RH. The last column was obtained using the original data. 'N' indicates that the species corrections was not available. (Full names of species have been given in Table 3-2.)

Instrument	Species										Mean absolute deviation
	b	c	d	e	i	l	s	t	wh	wc	
A	+2	−3	−2	−4	+4	−4	0	−2	0	0	2.4
B	0	0	0	0	+2	−2	+5	−2	0	0	1.5
C	0	0	−3	0	+3	−4	+5	0	+2	0	2.0
D2	0	0	−3	0	N	0	N	−3	0	0	1.5
E2	0	−2	−2	−4	+2	−3	0	−3	0	−2	2.0
F2	+4	0	−2	−3	0	−3	−2	−4	+2	+2	2.3

Continuing with a resume of the results, wood temperature is known to affect the correlation between resistance and moisture content. Ideally the application of temperature correction factors would enable the correct value of MC to be obtained at a given temperature. To observe the effectiveness of the temperature compensation factors over the span +20 °C to −10 °C, first the deviation of the corrected moisture content for each instrument (from the oven dry moisture content) was calculated, at the specified temperatures. Then, using d=(deviation at −10 °C) − (deviation at 20 °C) for all the species, the mean value of d ($\langle d \rangle$), and the uncertainty in the measurements ($\delta\langle d \rangle$) were calculated. These values are tabulated in Table 3-4. No values are given for instrument C as this device malfunctioned in the cold environments. A value of d=0 indicates a meter which is perfectly consistent in the readings over this temperature range (although the measured moisture content may not necessarily be correct).

Table 3-4: Mean value of changes in deviation in moisture content over the temperature interval 20 °C to –10 °C, and uncertainties in these measurements.

Instrument	‹*d*›/%MC	δ‹*d*›/%MC
A	+0.5	0.4
B	–0.4	0.4
C	-	-
D2	+0.5	0.3
E2	+2.7	0.3
F2	–1.8	0.4

A negative value indicates that insufficient compensation has been made for the reduction in electrical conductance resulting from the reduction in temperature. Likewise, a positive value shows over-compensation. The results in Table 3-4 show that while meters A, B and D2 have small values of ‹d›, E2 is seriously over-compensating, while F2 is under-compensating for this effect.

A general assessment was carried out by grouping together the difference between the corrected moisture content data and the corresponding oven dry values for individual species, at all temperatures for all the meters. Figure 3-6 show the resulting histograms.

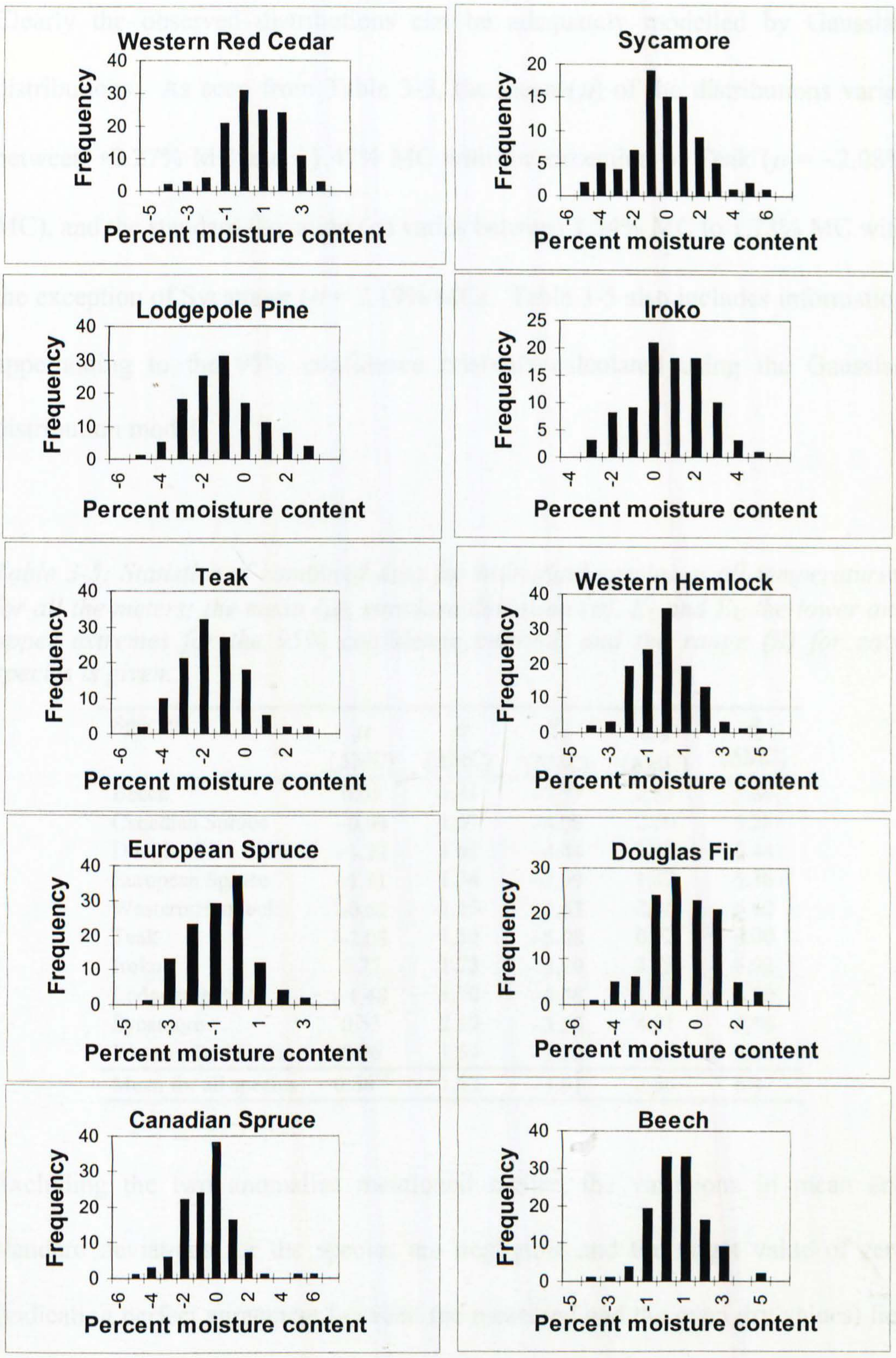


Figure 3-6: Histogram of the difference between the measured and moisture contents (o.d. basis), from all the meters at all temperatures. The data used are the corrected data in accordance with the manufacturers instructions for species and temperature corrections.

Clearly the observed distributions can be adequately modelled by Gaussian distributions. As seen from Table 3-5, the mean (μ) of the distributions varies between +0.27% MC and −1.47% MC with the exception of Teak (μ = −2.08% MC), and the standard deviation (σ) varies between 1.34% MC to 1.73% MC with the exception of Sycamore (σ = 2.19% MC). Table 3-5 also includes information appertaining to the 95% confidence intervals calculated using the Gaussian distribution model.

Table 3-5: Statistics of combined data for individual species at all temperatures, for all the meters; the mean (μ), standard deviation (σ), E_L and E_U the lower and upper extremes for the 95% confidence interval, and the range (R) for each species is given.

Species	μ (ΔMC)	σ (ΔMC)	E_L (ΔMC)	E_U (ΔMC)	R (ΔMC)
Beech	0.05	1.41	−2.77	2.87	5.64
Canadian Spruce	−0.94	1.57	−4.08	2.20	6.28
Douglas Fir	−1.22	1.61	−4.44	2.00	6.44
European Spruce	−1.31	1.34	−3.99	1.37	5.36
Western Hemlock	−0.61	1.53	−3.67	2.45	6.12
Teak	−2.08	1.50	−5.08	0.92	6.00
Iroko	0.27	1.73	−3.19	3.73	6.92
Lodgepole Pine	−1.48	1.70	−4.88	1.92	6.80
Sycamore	0.53	2.19	−3.85	4.91	8.76
Western Red Cedar	0.06	1.59	−3.12	3.24	6.36
Mean for all species	0.86[15]	1.62	−3.91	2.56	6.47

Excluding the two anomalies mentioned earlier, the variations in mean and standard deviations for the species are negligible and the target value of zero (indicating perfect agreement between the measured and the oven dry values) lies within the calculated confidence intervals, for all the species. However, the overall observed range has a mean value of 6.5% MC; the significance of such a

[15] mean of the absolute values

high value must not be underestimated: although this study was carried out under controlled laboratory conditions, the results from this analysis reveal the possibility of obtaining readings which can differ by 6.5% MC in situations when various conductance-type moisture meters are to be used and compared.

3.5 Discussion

The results presented above clearly and alarmingly show substantial variations in moisture content readings both between different instruments and when comparisons were made against moisture contents (o.d. basis). Do the observed discrepancies result from the inability of the instruments to accurately measure the d.c. resistance of the timber? The instantaneous d.c. resistance of timber when using typical electrodes is of the order of 10^6 to 10^7 ohm for moisture contents 20% and 15%, respectively. For this range of resistance there is clearly no problem in accurately measuring resistance with moderate circuitry, although it cannot be denied that better quality and higher accuracy electronics can be obtained at greater cost. See reference [33] for further discussion. Primarily, the observed discrepancies must be caused by the species corrections factors. More precisely, the observed variations result directly from the lack of common correction factors for any given species. The species correction factors, and those for compensating for the effects of wood temperature have been derived empirically at different times using different methodologies (see reference [31]). Also, species correction factors are not in the public domain but remain the commercial property of the meter manufacturers. Further, observations during the trials revealed that certain species are placed into *contradictory* groups for correction purposes by different manufacturers[16].

The large variations observed are clearly disturbing in that while one instrument may indicate a 'safe' moisture content, another one may be showing that fungal decay is possible! Similarly, it is quite possible that timber with a certain moisture content may be installed into an environment where the equilibrium moisture content is significantly different. This could result in the various problems of distortions and shrinkage (see reference [34]). It is well known that great care is necessary to obtain meaningful data from moisture meters. However, the results also show that when timber is inspected using hand-held moisture meters, the readings obtained are highly dependent on the particular instrument in use. As there are contractual obligations to supply timber within certain moisture content limits it should not be surprising if disputes occurred between two parties.

As already mentioned, the measured moisture content is a function of species, temperature, depth of measurement (where moisture gradients exist) and local inhomogeneities. Further, the d.c. resistance of wood is also affected by the presence of impurities, e.g. preservatives, due to the ionic nature of such chemicals. What is now very clear is that under highly controlled conditions severe disagreements can and do occur between different instruments. At present, the use of moisture meters by building professionals must be regarded as merely indicative. Manufacturers frequently quote reading accuracy of ±0.1% moisture

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[16] A commonly made comment by Dr Gavin Hall, Technical Director, TRADA

content. However, even the ±1% uncertainty limit (reference [32]) cannot be taken seriously unless some sort of international standardization is introduced. The various standards for timber stipulate that moisture meters should be accurate to within ±2% (see, for example, reference 35). Based on these observations, this accuracy is not generally achievable even when the species and temperature corrections have been correctly applied for the simple reason that there is no traceability to any internationally agreed standards. In section 3.6 an outline for the proposed methodology for global standardization of resistance-type moisture meters is given.

3.6 Proposals for standardization: outline of methodology

The results of the stringent meter comparison in section 3.4 (page 63) clearly show that standardization of moisture meters is essential if accurate forecasts are to be made regarding both the durability and behaviour of timber in service. The underlying problem is that the producers of these instruments do not use common data in the calibration of the meters: the species corrections and temperature corrections used have been obtained from a variety of sources. It is proposed to produce a standard calibration for eventual use world-wide. The aim is to produce data of d.c. resistance versus moisture content initially for all species of major commercial importance, and for this to be available in the public domain. The database produced would systematically be expanded and updated. In skeleton form, the methodology for the calibration procedure is as follows:

1. Electrode size and shape, configuration and applied voltage all have an effect on the instantaneous measured d.c. resistance; a standard method that can be readily applied must first be decided on.

2. (a) With (1) in effect, it is necessary to measure the instantaneous d.c. resistance of various species at 20 °C and various moisture contents. This should be carried out for representative samples, as recommended and verified by timber experts so as to ensure the suitability of the species for a wide variety of applications.

(b) Initially, the most commonly used species in the building industry are to be used, with the aim of producing species correction factors for approximately 120 species. It is envisaged that all samples are to be obtained in the green state with accurate knowledge of the origin, provenance, rate of growth, etc. documented. The samples will then be cut and conditioned in a stardartised manner in atmospheres of progressively lower relative humidity until various EMCs are reached.

(c) Resistance measurements to the agreed protocol should be made on these samples before moisture contents (o.d. basis) are determined. Thus, for each sample set of each species, the relationship between d.c. resistance and moisture content (o.d. basis) will be generated over the practical range of moisture content measurement. These relationships will be combined for each timber species or sub-species to give a mean relationship plus confidence estimates based upon the number of sample sets and the variability between them. It is important to emphasize that extreme care needs to be taken to ensure that the samples of the various species are representative of current commercial supplies of timber.

3. Temperature correction factors will also be derived as the tests in (2) above will be conducted at 20 °C. It is envisaged that the range of temperatures to be used will be –20 °C to +80 °C.

If the resulting data is utilized by instrument manufacturers world-wide, better agreement will be seen across the range of meters available in the market; this in turn will yield a structured framework by which the timber industry can monitor and improve and maintain the quality of timber and secondary products across the world.

3.7 Conclusion

The durability and performance of timber are strongly affected by its moisture content. Scientific investigations have shown that even under laboratory conditions severe discrepancies exist between a wide range of conductance-type instruments used to measure the moisture content of timber. It is quite clear, especially for the range of moisture content of concern, that it is not the inability of the electronics to accurately measure resistance and hence moisture content. The discrepancies (ignoring statistical deviations) are in fact being caused primarily by inconsistent corrections for species and also by non-standardized temperature corrections.

Chapter 4 discusses another electrical method of moisture content measurement where species corrections are not necessary.

Chapter 4

4 A Study of the Correlation Between Capacitance and Moisture Content at Various Frequencies

4.1 *Summary*

The characteristics of the dielectric properties of timber are summarized, these complement the definitions stated on page 16. To follow, the results from an early study into the correlation between capacitance and moisture content at various frequencies are presented for a two pole electrode-sample combination, with the vector of the electric field strength *E* oriented transverse ($E_{\perp}$) to the fibre direction.

The results from this study are compared with those from reference [36] in which the response of a similar electrode was reported with the vector of the electric field strength E oriented along the fibre direction ($E_{\parallel}$).

The frequency of measurement in this study spans 20Hz to 1MHz, one order of magnitude greater than that employed in reference [36]. The results show that although an increase in the frequency is followed by a decrease in the measured capacitance, beyond 10 kHz the decrease in the measured capacitance is reduced considerably. This observation is explained with reference to the complex polarization mechanism in timber. It is concluded that with careful selection of

frequency and electrode geometry, it is possible to design out the effects of temperature and grain direction on the measurements of dielectric properties.

4.2 Introduction

As already discussed in Chapter 1, dielectric moisture meters are frequently used as an alternative to resistance-type instrument. The principal quantities to which dielectric meters respond include the dielectric constant[17] and the loss factor see for example reference [37]. Several researchers have reported values for the dielectric parameters including loss tangent (already explained in section 1.5, page 15) of wood at various frequencies and moisture contents, and for a variety of samples with different specific gravity and grain orientation; a summary is given in the following sections.

Data sheets and representatives from leading brand moisture meter manufactures claim that some dielectric moisture meters are essentially unaffected by temperature, grain orientation or species [38] and [39]. An investigation into the theoretical possibility of this claim, with reference to existing literature, forms the initial part of this chapter.

It is advantageous at this point to summarize the polarization mechanisms which exist and their transitions in the frequency spectrum as this plays a fundamental

[17] However, due to the planar electrode configuration used by dielectric moisture meters, they do not actually measure the absolute value of dielectric constant, as this physical quantity is defined for a parallel plate capacitor with a uniform parallel electric field.

role in explaining the phenomenon of anomalous dispersion in timber (see section 4.2.2, page 85).

4.2.1 Polarization mechanisms in timber

At least four different types of polarization (depending on the frequency of measurement) can occur in timber namely interfacial, dipole, atomic and electronic polarization [40].

Figure 4-1 shows the effect of each type of polarization on dielectric constant and loss tangent: depending on the frequency of measurement the four types of polarization will contribute varying amounts to the dielectric properties.

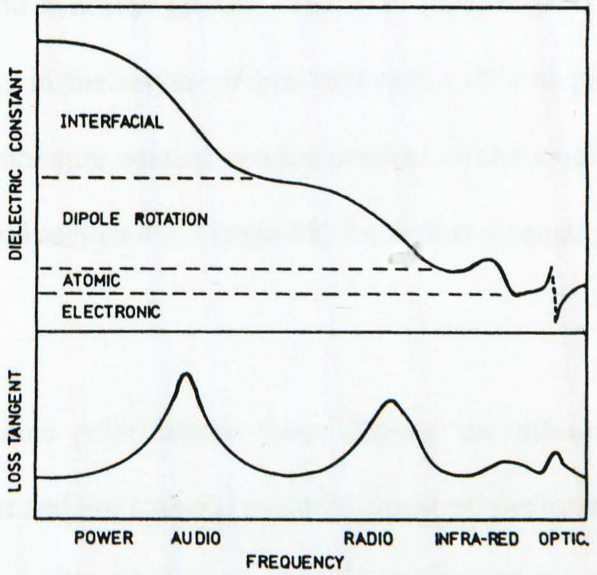

Figure 4-1: Dielectric constant and loss tangent as functions of applied frequency for a dielectric material; four kinds of polarization and their effects are shown, cited in reference [40].

The interfacial and dipole polarizations are of primary interest as they occur in the frequency range that is usually employed commercially for moisture content measurements or electrical heating of wood. The interfacial polarization is attributed to accumulation of charged ions at interfaces between different regions within the cell wall of wood. Interfacial polarization is also believed to be the cause of increase in the resistance of wood with time, when resistance-type moisture meters using DC measurements are used; a further factor here is the accumulation of charged particles at the electrode-wood contacts which in turn intensifies the observed effects.

The dipole polarization is due to rotation of permanent dipole molecules in timber, under the influence of an applied AC signal; these permanent dipoles include water molecules and hydroxyl groups. The time constant for the rotation of the dipole molecules is in the region of microseconds (10^{-6}) to picoseconds (10^{-12}) depending on the moisture content and temperature of the wood (refer to section 4.2.2.1 (page 85) and section 4.2.3 (page 88) for further discussions).

Electronic and atomic polarizations occur beyond the infra-red region of the frequency spectrum and are caused by displacement of electrons in the atom, and stretching or bending of bonds between the atoms of a molecule, respectively.

4.2.2 Anomalous dispersion

Anomalous dispersion refers to rapid changes observed in the dielectric properties with frequency. Essentially, anomalous dispersion is caused due to the accumulative contributions of various polarization mechanisms which exist at the frequency of measurement (see Figure 4-1).

At least two mechanisms contribute to anomalous dispersion in timber, the primary dispersion (or more descriptively known as the dipole rotation mechanism) and the secondary dispersion (interfacial polarization) [40]. A brief explanation of the two mechanisms follows.

4.2.2.1 Primary dispersion

Primary dispersion, caused by permanent dipole molecules, occurs in the radio frequency region of the spectrum, where the permanent dipole polarization is dominant (see Figure 4-1).

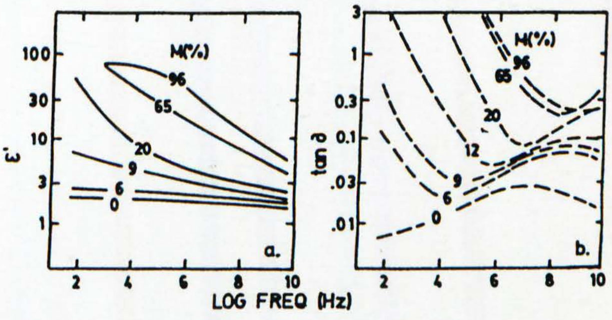

Figure 4-2: Dielectric constant (ε') and loss tangent (tanδ), of European Spruce (Picea abies) at 20 °C, as functions of frequency for a range of moisture contents, as cited in [40].

Figure 4-2 shows the primary dispersion observed in ε' and $\tan\delta$ for European Spruce at 20 °C. Two observation can made here: both ε' and tanδ generally increase with moisture content, and that the characteristic frequency at which tanδ peaks, tends to higher frequencies with increasing moisture content. The latter is consistent with individual peak frequencies for dipole rotation in liquid water and dry wood, 10^{10} Hz and 10^{7} Hz (at 20 °C), respectively. It is therefore deduced that water molecules in cell walls reduce the mean time constant for dipole rotation, and increase the magnitudes of ε'.

4.2.2.2 Secondary dispersion

Figure 4-3 shows the effect of interfacial polarization on ε' and tanδ for Douglas-fir, at 25 °C. This is pronounced at audio and sub-audio frequencies (6 to 7 orders of magnitude lower than the required frequency for primary dispersion), and is inconspicuous in dry wood.

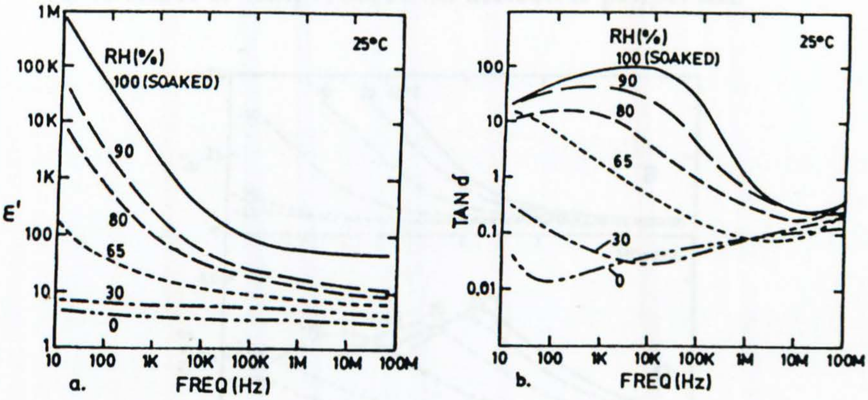

Figure 4-3: Dielectric constant (ε') and loss tangent (tanδ) of Douglas-fir (Pseudotsuga taxifolia), at 25 °C, as functions of frequency for a range of relative humidity; reproduced from reference [40].

For instance, it is evident from Figure 4-3 that the peak in tanδ for wood conditioned to 80% RH (approximately 16% MC), occurs at around 200 Hz. In comparison with Figure 4-2, this is about 7 orders of magnitude lower than the peak frequency of near 1 GHz, for the dipole mechanism. Interfacial polarization is more dominant in Douglas fir than in European Spruce; this is believed to be due to the differences in their cell wall structures. Douglas fir possesses cells in which an additional 'interface layer' is developed within the cell structure, viz. Spiral Thickening. The vessels in European Spruce are invariably devoid of spiral thickening [41].

4.2.3 The effect of temperature on dielectric properties

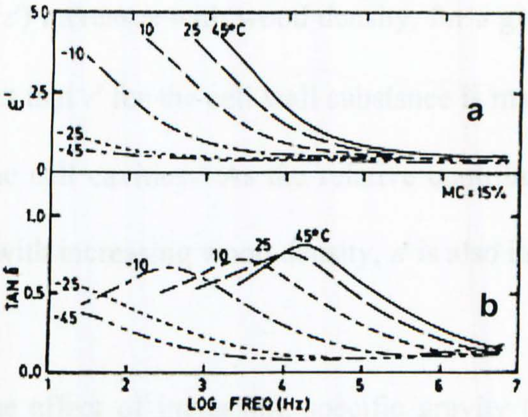

Figure 4-4: The effect of temperature on dielectric constant (ε') and loss tangent (tanδ) of wood of Tanagi (Salix jessoensis), conditioned to 15% MC, at various frequencies, from reference [42].

The effect of temperature on dispersion in timber is seen in Figure 4-4. It is evident from Figure 4-4 (a), that at frequencies below 100 kHz, that an increase in temperature, is followed by an increase in ε', with the exception that at temperatures below –25 °C the dependency of ε' and tanδ becomes negligible. This could be due to restricted movement of dipole molecules and the subsequent high activation energy required for polarization.

Figure 4-4 (b) shows that the peak frequency for tanδ moves toward higher frequencies as the temperature is increased. This trend is an indication that, similar to the effect of an increase in the MC (see page 85), an increase in temperature reduces the mean relaxation time for the dipole molecules, and hence dipole polarization becomes more dominant at higher frequencies.

4.2.4 The effect of density on dielectric constant

Dielectric constant (ε') increases with wood density, for a given moisture content. This is due to the fact that ε' for the cell wall substance is many times greater than that for air inside the cell cavities. As the relative contribution of the cell wall substance increases with increasing wood density, ε' is also increased.

Figure 4-5 shows the effect of increasing specific gravity (G) on ε', at various moisture contents. Specific gravity provides a useful measure of the dry mass of wood (m_d) per unit volume of moist wood (v_m) and is defined as in Equation 4-1.

$$G=(m_d/\ v_m)/\rho_m \qquad \textit{Equation 4-1}$$

where ρ_m is the density of water, in the same units as $m_d/\ v_m$.

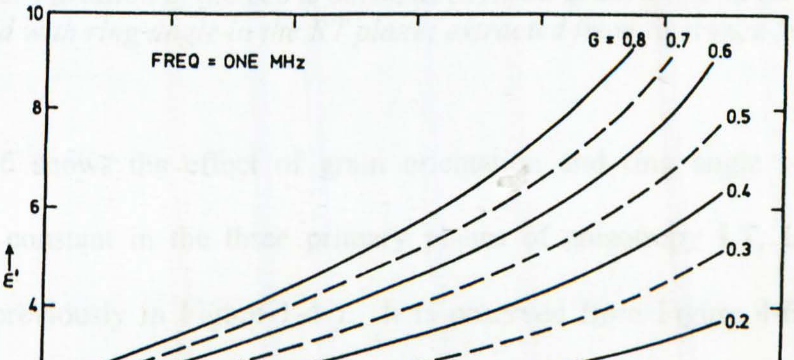

Figure 4-5: The effects of specific gravity (G) and moisture content on ε', from reference [43].

Figure 4-5 shows that at higher specific gravity, the variation of ε' with moisture content ($d\varepsilon'/dMC$) increases. For example, in the range of 5% to 20% MC, $d\varepsilon'/dMC$= 0.53 for *G*=0.8, while for *G*=0.2 $d\varepsilon'/dMC$=0.27 (decreased by a factor of 2, relative to *G*=0.8). This variation should be taken into account in density correction factors applied to dielectric moisture meters.

4.2.5 The effect of grain orientation on dielectric properties

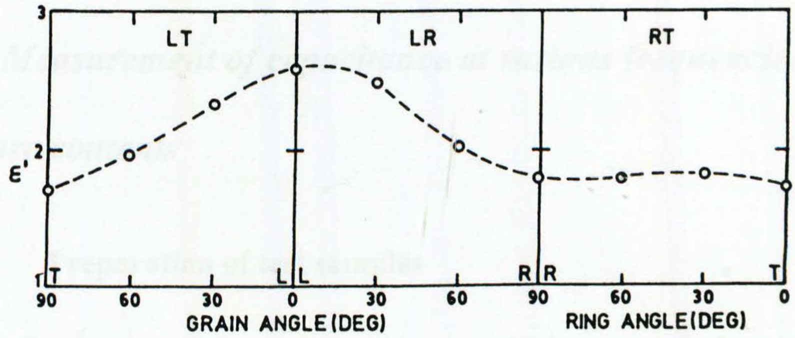

Figure 4-6: Variation of dielectric constant (ε') with grain angle in the LT and LR planes and with ring angle in the RT plane; extracted from reference [44].

Figure 4-6 shows the effect of grain orientation and ring angle variation on dielectric constant in the three primary planes of anisotropy LT, LR and RT (defined previously in Figure 1-4). It is observed from Figure 4-6 that grain orientation affects ε' considerably; measured values along the grain could be up to 50% higher than those across the grain (see LT and LR planes). In the RT plane however, the ring angle does not seem to make an appreciable difference to ε'.

The trends above show that for dielectric moisture meters to give a true estimate of moisture content, the instruments either have to be used in a prescribed angle of rotation with respect to the grain direction, or have electrode configurations which produce average values of ε' based on various grain angles.

In the following section an early study carried out by the author in measurement of capacitance at various frequencies and moisture contents is presented under various headings. The results are compared with the only published data in the field with a similar electrode-sample arrangement [36].

4.3 Measurement of capacitance at various frequencies and moisture contents

4.3.1 Preparation of test samples

Douglas-fir samples of dimensions 100 mm × 62.5 mm × 1.5 mm (along the grain, across the grain and in the radial direction, respectively) were obtained from four consecutive veneer leaves cut from the same tree[18]. Each sample was labelled with a unique code for identification purposes.

The samples were conditioned using saturated salt solutions in sealed bell-jar containers. Table 4-1 lists the salts used for conditioning the samples.

[18] Work carried out at TRADA Technology Ltd.

Table 4-1: Saturated salts solutions used in the study; the table shows the range of relative humidity provided by the salts in the temperature range between 20°C and 30°C [45].

Salt solution	Percent relative humidity		
	T °C		
	20	25	30
Magnesium chloride	33	33	33
Sodium nitrite	66	65	63
Ammonium sulphate	81	80	80
Potassium nitrate	93	92	91

The relative humidity and temperature inside each bell-jar container were monitored using pre-calibrated miniature data-loggers (TinyTalk models RS 216-845 and RS 213-436, respectively). Although the salts selected were relatively insensitive to variations in temperature (as seen from Table 4-1), the laboratory environment (also continuously monitored) provided a temperature range of 23 ±2°C.

Tests were carried out on stacks consisting of nine veneers conditioned to the four relative humidities listed in Table 4-1. The use of veneers speeded up conditioning time, ensured constant moisture content throughout the entire depth and enabled consistent measurements for a moisture gradient study (explained in Chapter 5).

4.3.2 Apparatus

The measuring device, a precision LCR meter[19], measures to a precision of ±0.05% in the range 0.01 fF to 9.9999 F, and is configurable for use with custom-made electrode configurations.

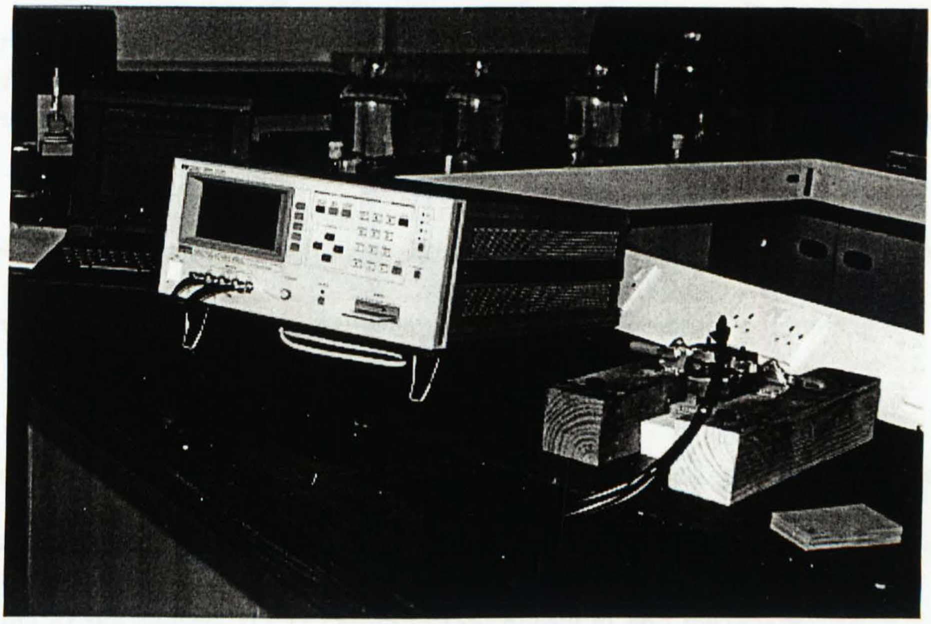

Figure 4-7: The measurement set-up, consisting of the precision LCR meter, test bench and custom made electrode. (Figure 4-9 shows the close up of the electrode arrangement).

The HP4284A LCR meter employs the four terminal pair (4TP) configuration shown in Figure 4-8 and can be programmed to perform automatic frequency sweeps. The latter feature proved to be an invaluable facility with which the time taken for each series of measurement was minimized to less than one minute, ensuring that the loss of moisture content form the samples during the tests was minimal.

[19] Model HP4284A, loaned by special arrangement with Hewlett Packard

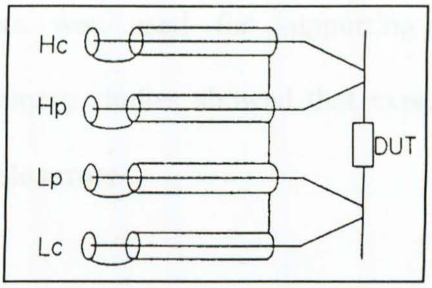

Figure 4-8: The four terminal pair configuration (4TP); where Hc and Hp are the high current and potential points, respectively, Lc and Lp are low current and potential points respectively. DUT (Device Under Test) refers to the sample.

The 4TP configuration minimizes the effects of stray capacitance which would otherwise affect the measurements especially at low moisture contents.

As seen in Figure 4-8 the 4TP configuration consisted of 4 shielded cables connecting the high current and potential terminals (H_c and H_p, respectively) to one side of the sample (DUT) and the low potential and current terminal (L_p and L_c, respectively) to the other. The shields of the connecting cables are connected together at a point close to the DUT. This ensured that the point of reference for the readings was at the DUT rather than the output terminals of the LCR meter, allowing the appropriate cable length correction to be used when performing the measurements.

The test bench, seen in Figure 4-9, was designed and assembled in order to facilitate a stable position for the electrode during the test, and comprised two toggle clamps fixed on to a platform on either side of the sample. The toggle clamps (model RS 542-655) served to apply consistent uniform pressure on either side of the electrode, thereby minimizing possible air gaps between veneers.

Expanded polystyrene was used for supporting the samples during the measurements; preliminary studies showed that expanded polystyrene does not introduce any detectable errors.

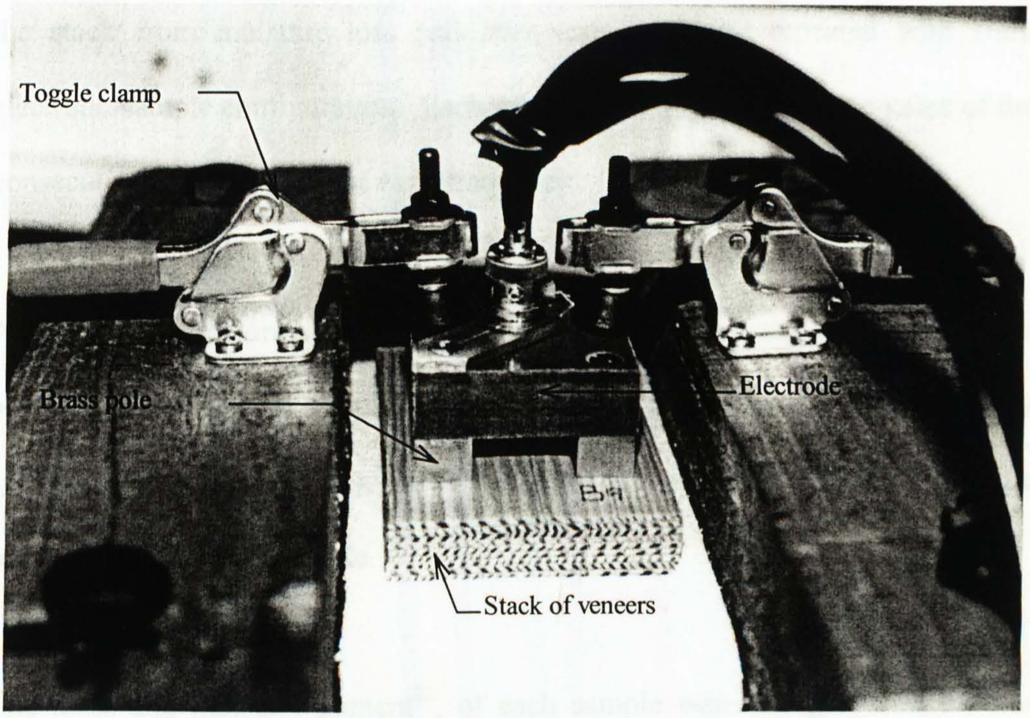

Figure 4-9: The final design of the test bench: toggle clamps and platforms on either side of the sample with the electrode held down (in the middle) on the sample. This design ensured constant uniform pressure on sample under test.

4.3.3 Methodology

The LCR meter was programmed to perform a frequency sweep in the range 20 Hz to 1 MHz yielding capacitance data at frequencies of 0.02, 0.1, 1, 10, 100 and 1000 kHz. The required settings (inter-sweep delay time and trigger settings) were configured in accordance with the manufacturers instructions so that the wide sweep of frequency required could be performed automatically and accurately. For each sample, data were taken at three different applied voltages of

1.0, 1.5 and 2.0 volts (this range was limited by the maximum applied voltage from the meter). The capacitance of each sample was measured twice, once with and once without one layer of thin PVC film around the stack of veneers. The purpose of this test was to investigate whether PVC film could be used to protect the stack from moisture loss and later tests could be repeated with similar electrode-sample configuration. Each reading taken was an average value of three consecutive measurements at each frequency.

According to [46] formation of a high resistance film between the contact surface of the electrode and the sample could cause variations in readings. For this reason special care was taken so as to avoid the build up of this layer, by frequent repositioning of the electrode.

The mass and moisture content[20], of each sample were measured once before, once during and once after each set of capacitance measurements.

4.3.4 Discussion of results

As in the previous chapters the results presented are a representative selection of the total data, based on moisture content calculated from the gravimetric method. Measurements of mass prior and subsequent to each set of readings showed negligible variations in the moisture content of the samples.

[20] An L606 WAGNER capacitance-type moisture meter was used to measure the moisture content. The results from the moisture meter measurements are discussed extensively in Chapter 5.

4.3.4.1 The effect of PVC film on measured capacitance

Figure 4-10 shows the correlation between capacitance and frequency for three different applied signal amplitudes of 1.0, 1.5 and 2.0 volts[21]. The graphs seen in Figure 4-10 are for samples conditioned at 92% relative humidity at 23 ± 2 °C. Each graph shows two sets of measurements, one set for the sample enclosed in one layer of PVC film, and another for the sample without the PVC film cover. It can be seen that the PVC film substantially increases the capacitance of the samples at the lower frequencies (≤10 kHz). This effect was found to be more pronounced with samples conditioned to higher moisture contents. It can further be deduced that the variation of the applied voltage from 1.0 to 2.0 volt, does not make a significant effect on the measured values.

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[21] The ac voltage figures used in the text are the effective (rms) values.

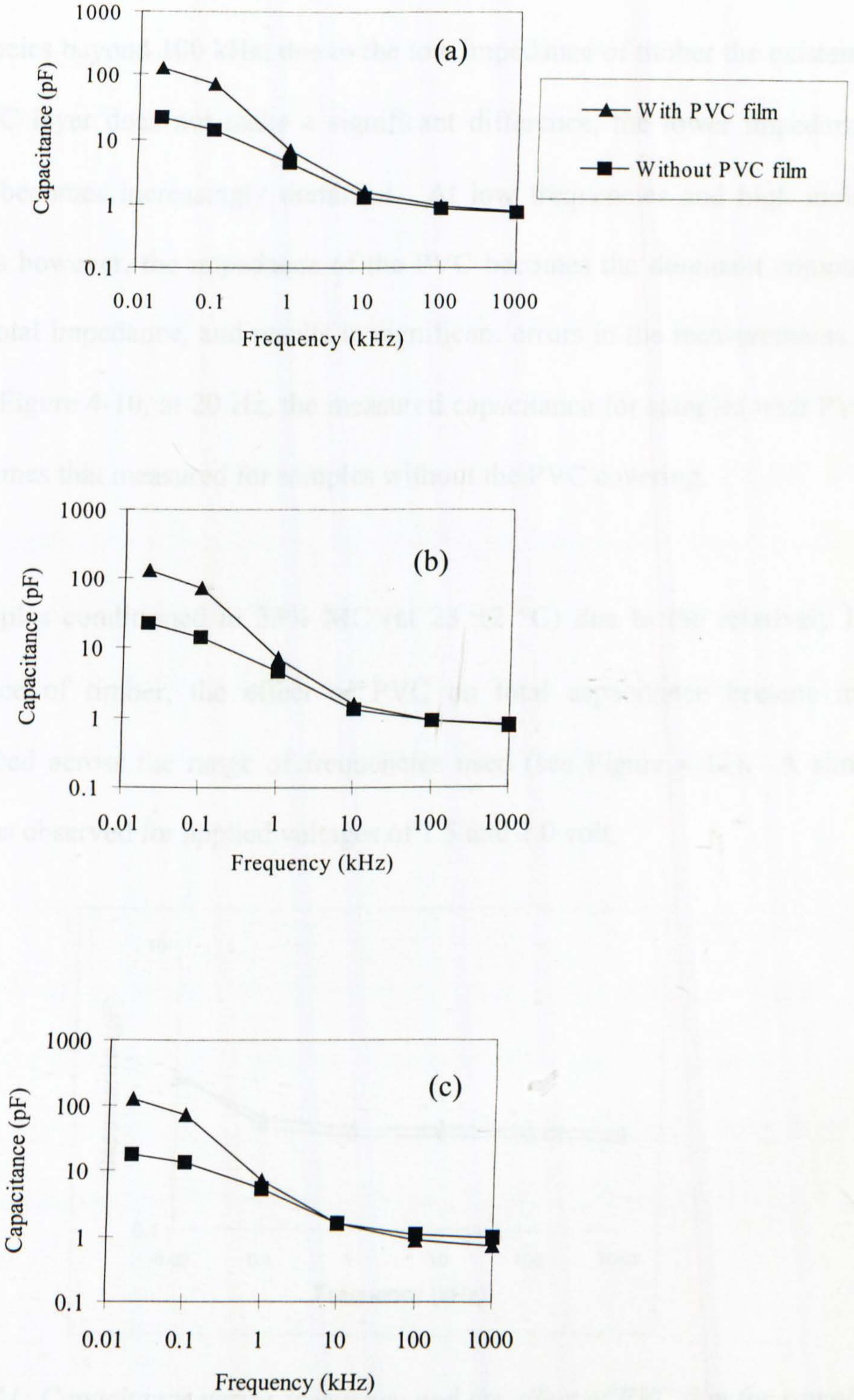

Figure 4-10: Capacitance versus frequency and the effect of PVC film at (a) 1.0, (b) 1.5 and (c) 2.0 volts.

The contribution of the PVC film to the total capacitance diminishes with increasing frequency (particularly for samples with high moisture content). At frequencies beyond 100 kHz, due to the low impedance of timber the existence of the PVC layer does not make a significant difference; the lower impedance of timber becomes increasingly dominant. At low frequencies and high moisture contents however, the impedance of the PVC becomes the dominant component of the total impedance, and results in significant errors in the measurements. As seen in Figure 4-10, at 20 Hz, the measured capacitance for samples with PVC is over 5 times that measured for samples without the PVC covering.

For samples conditioned to 33% MC (at 23 ±2 °C) due to the relatively high impedance of timber, the effect of PVC on total capacitance became more pronounced across the range of frequencies used (see Figure 4-11). A similar effect was observed for applied voltages of 1.5 and 2.0 volt.

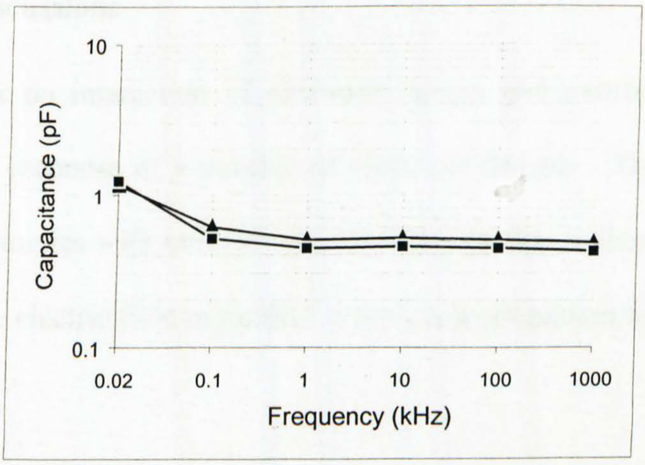

Figure 4-11: Capacitance versus frequency and the effect of PVC film for samples conditioned at 33% RH and at 23 ±2 °C.

Theses observations showed that although the choice of higher frequencies significantly reduces the contribution of PVC to measured capacitance, measurements of low moisture contents (around 8% or less) in the presence of PVC film could still be erroneous.

4.3.4.2 The effect of electric field orientation on measured capacitance

It was reported in section 4.2.5 (page 90) that the grain orientation plays an important role in measurements of dielectric properties. However, as the measurements are a function of the interaction between the electrode design (geometry) and the characteristics of the timber under test, it should be possible to implement an electrode design, which interacts with the structure of timber so as to minimize the effect of grain orientation on the measurements.

4.3.5 Discussions

Previous work on interaction of electrode design and moisture in timber [36] reports on the response of a number of electrode designs. The response of this electrode on samples with uniform moisture distribution is shown is Figure 4-12; direction of the electric field is parallel to the grain orientation for this data.

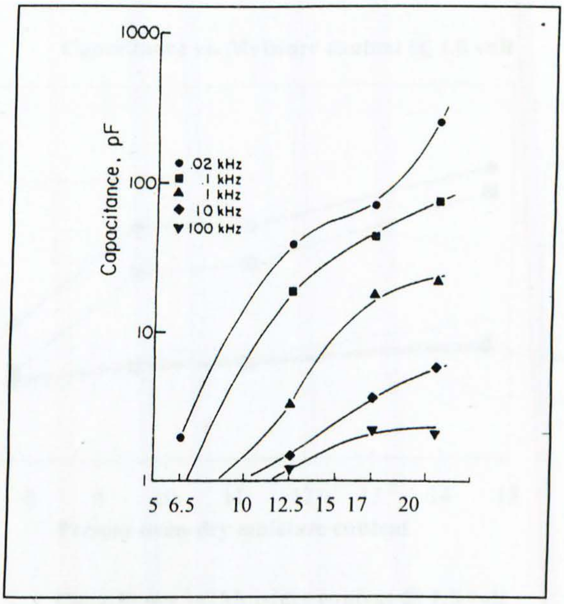

Figure 4-12:Correlation between capacitance and moisture content at various frequencies, as reported in reference [36]. The direction of the electric field was parallel to the grain direction.

Continuing, Figure 4-13 shows the correlation between capacitance and the moisture content (o.d. basis) at various frequencies for three signal amplitudes of 1.0, 1.5 and 2.0 volt. The trends observed in the graphs are consistent with that seen in Figure 4-12. An increase in the frequency of the applied signal is followed by a decrease in the value of the measured capacitance. However, the decrease in the capacitance values becomes negligible at frequencies beyond 100 kHz. It should be stated that the direction of the electric field for the measurements carried out in this study was perpendicular to the grain direction.

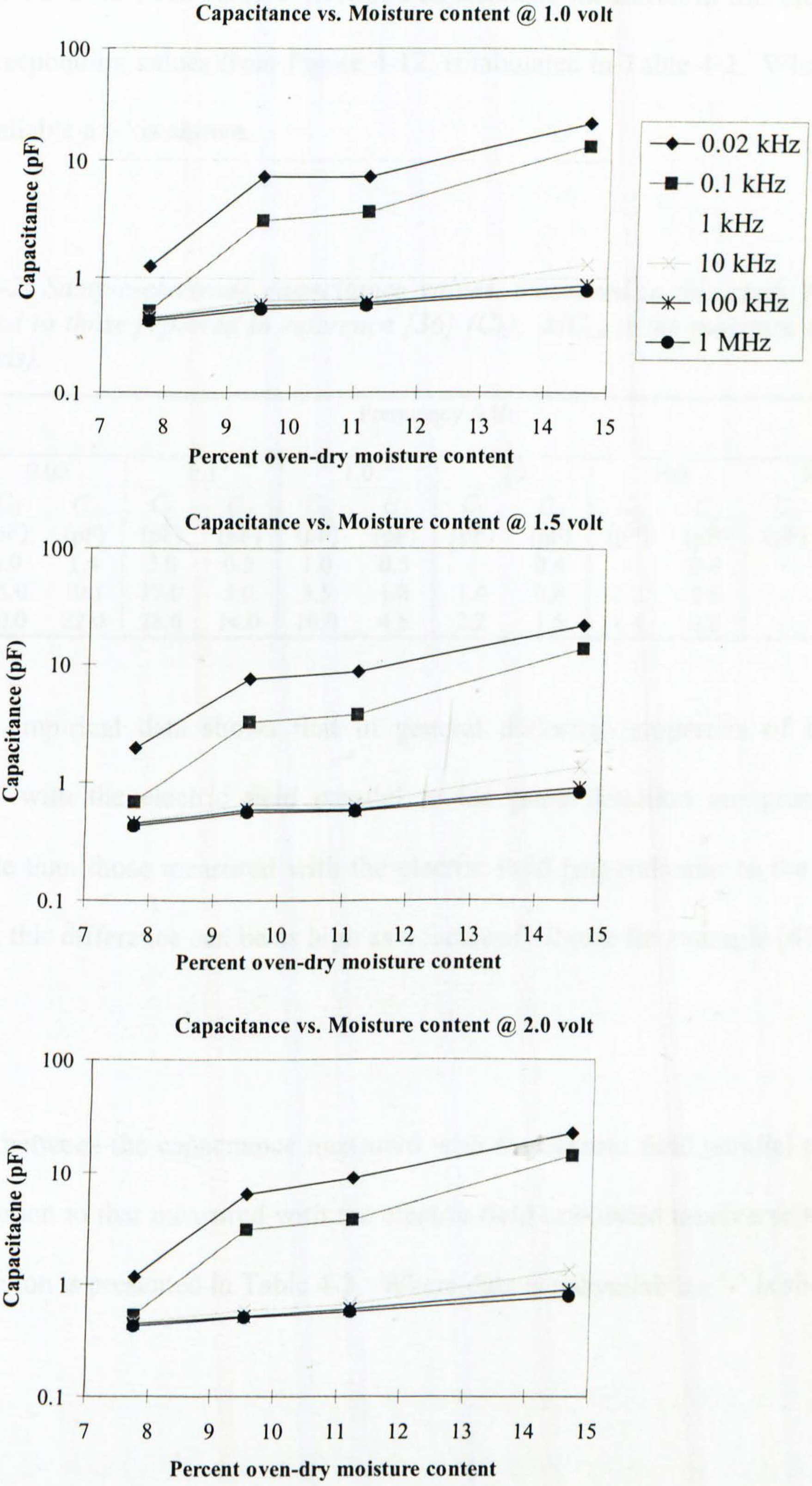

Figure 4-13: Capacitance versus moisture content (o.d. basis) at various frequencies with three applied ac. voltages of 1.0, 1.5 and 2.0 volts. Direction of the electric field was perpendicular to the grain direction.

A comparison between sample-electrode capacitance measured in this study and the corresponding values from Figure 4-12, is tabulated in Table 4-2. Where data is unavailable a '-' is shown.

Table 4-2: Sample-electrode capacitance values, measured in this study ($C_{\perp}$) as compared to those reported in reference [36] ($C_{\|}$). MC_{od} is the moisture content (o.d. basis).

	Frequency /kHz											
	0.02		0.1		1.0		10		100		1000	
MC_{od} (%)	$C_{\|}$ (pF)	$C_{\perp}$ (pF)	$C_{\|}$ (pF)	$C_{\perp}$ (pF)	$C_{\|}$ (pF)	$C_{\perp}$ (pF)	$C_{\|}$ (pF)	$C_{\perp}$ (pF)	$C_{\|}$ (pF)	$C_{\perp}$ (pF)	$C_{\|}$ (pF)	$C_{\perp}$ (pF)
7.8	6.0	1.4	3.0	0.5	1.0	0.5	-	0.4	-	0.4	-	0.4
12.5	35.0	10.1	17.0	5.0	3.5	1.8	1.4	0.8	1.2	0.6	-	0.6
14.8	60.0	22.0	28.0	14.0	10.0	4.5	2.2	1.5	1.8	0.8	-	0.8

Existing empirical data shows that in general dielectric properties of timber measured with the electric field parallel to the grain direction are greater in magnitude than those measured with the electric field perpendicular to the grain direction; this difference can be as high as a factor of 10 (see for example [47] and [48]).

The ratio between the capacitance measured with the electric field parallel to the grain direction to that measured with the electric field orientated transverse to the grain direction is presented in Table 4-3. Where data is unavailable a '-' is shown.

Table 4-3: Ratio between capacitance measured parallel to the grain direction ($C_{||}$) and that measured perpendicular to the grain direction ($C_{\perp}$) at various frequencies. M_{od} is the moisture content (o.d. basis).

MC_{od} (%)	Frequency (kHz)				
	0.02	0.1	1	10	100
	$C_{\|\|}/C_{\perp}$	$C_{\|\|}/C_{\perp}$	$C_{\|\|}/C_{\perp}$	$C_{\|\|}/C_{\perp}$	$C_{\|\|}/C_{\perp}$
7.8	4.3	6.0	2.0	-	-
12.5	3.5	3.4	1.9	1.8	2.0
14.8	2.7	2.0	2.2	1.5	2.3

Table 4-3 shows that in all cases the $C_{||}/C_{\perp}$ ratio is greater than 1, comparing reasonably with the findings of previous researchers (see [48] for example). This characteristic is attributed to the micro-structure of timber: the elongated wood cells (tracheids and fibres) forming the skeleton of the structure are mainly aligned in the longitudinal plane (along the stem), the microfibrils in the cell walls are also largely oriented in this direction. As the microfibrils are made of cellulose chains the contribution of the constituents of the cell walls are greater along the grain than across the grain. Further, water molecules join to the cellulose chains by breaking the chains which hold the cellulose molecules together [49], forming polar molecules which can move freely along the fibres and take part in the polarization process under the influence of an electric field.

4.4 Conclusion

The findings of this study show that an increase in frequency is followed by a decrease in the sensitivity of the measured capacitance to moisture content, for the electrode-sample configuration used.

The choice of frequency for the measurement of dielectric properties influences the variable which affect the correlation between moisture content and dielectric properties. At frequencies below 100 kHz, the effect of temperature on ε' becomes significant and needs to be taken into account. The variation of ε' with temperature decreases with decreasing frequency, with the exception of temperatures well below freezing (less than about –25 °C) in which case there is negligible correlation.

The voltage range employed does not produce a consistent measurable variation in the readings.

Analysis of the data obtained from this study and those reported in reference [36] yield results which correlate well with published data. Capacitance measurements made by simple two pole electrode arrangements (see Figure 4-9) have shown the measurements to be heavily dependant on the direction of the applied electric field (see for example Table 4-3).

To minimize these directional variations, the electric field produced by the geometry of the electrode should interact with both directions (i.e. along and across the grain). This geometry could be that of a rectangular live pole surrounded by a rectangular ground strip; the rectangular shape of the electrode would allow utilisation of optimum surface area during the measurements. This electrode and its response are discussed further in Chapter 6.

Chapter 5

5 Effects of Moisture Gradient on a Commercial Capacitance-type Moisture Meter

5.1 Summary

The sensitivity of a commercial capacitance-type moisture meter[22] to moisture content gradients was established. Three commonly occurring moisture gradients namely, moderate drying, steep drying and regain were designed and simulated in the study, with two projected *average* moisture contents of 12% and 17% were anticipated for the samples. The projected[23] EMC for the samples was based on industrially used and well established RH versus T charts [50]. The results from the study showed that although the penetration depth of the electric field is as specified (19 mm), the effective measuring depth of the field is much less (around 6 mm). Tests performed on samples with effectively zero moisture gradients showed that the meter reading suffered error of up to ±3% moisture content.

5.2 Introduction

As already discussed in Chapter 1, moisture meters are used world-wide by end users and suppliers as well as quality control agents for estimations of the moisture content in timber. In Europe, by far the most widely used type of

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[22] Model L606, on loan from WAGNER Europe Ltd.

[23] The actual achieved EMC values for the samples showed that due to the drying history of the samples, the actual moisture contents reached were somewhat different to those projected

moisture meter(s) is the resistance-type and existing standards tend to only refer to this type of moisture meter when setting out procedures for electrical methods of measuring moisture content. In contrast, one of the most effective on-line quality control systems in saw mills, both in the USA and also in Europe, is based on the same technology employed by the capacitance type moisture meters [51][24].

The study discussed in Chapter 3, identified magnitudes and sources of errors involved when using resistance-type moisture meters. This, along with the theory discussed in Chapter 4, clearly indicates that both types of instruments require compensation factors for accurate results. Considering that in practice, it is more cumbersome and time consuming to *use* the pin-type electrodes utilised by resistance-type meters than it is to use the planar electrode configuration utilised by the dielectric meters, the question that arises is one of accuracy and efficiency in measuring the *mean* moisture content.

The counteracting argument involves the actual "on-site" criteria for obtaining accurate results. It is clearly more sound to base the average moisture content of a batch of timber on a population size that is statistically representative of the batch of timber. More measurements can be performed in a given time with dielectric meters than with resistance-type of instruments, and therefore a better indication of the average moisture content may be obtained. However, it is important not

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[24] The accuracy of in-line moisture meters have been studied by various researchers; one such study concluded the accuracy of an in-line moisture meters to be ±2.9% MC, as compared to ±3.8% for resistance-type hand held moisture meters [51].

only to quantify the accuracy of dielectric moisture meters, but to identify the limitations of their applications.

It was explained in Chapter 1 that one of the most important causes of distortion is mismatch between the moisture content of timber components and the average seasonal EMC of the destination environment. A commonly undetected cause of this mismatch is the occurrence of moisture gradient in timber components. In this chapter the performance of a capacitance-type moisture meter is critically investigated in the presence of various practically occurring moisture gradients and for samples with effective moisture gradients of zero.

5.3 *Methodology*

5.3.1 Preparation of samples

Three moisture gradients, namely moderate drying, steep drying and regain were simulated by positioning pre-selected conditioned veneers symmetrically about the central veneer in each sample. The selection of the conditioned veneers was such that the measurements could be taken on samples with two projected *average* moisture contents of 12.5% and 17.0%. The projected values were based on existing relative humidity-equilibrium moisture content charts, also in agreement with the values used in reference [52]. It was found that the final EMC values reached by the individual veneers were somewhat different to those predicted. Table 5-1 below shows the comparison of achieved EMC in this study with those predicted.

Table 5-1: Comparison between projected and achieved EMC values for the range of relative humidity employed at 25 °C.

Projected EMC[25] from reference [52]		Actual EMC achieved	
RH (%)	EMC (%)	RH (%)	EMC (%)
30	6.50	33	6.88
65	12.50	65	10.29
80	17.00	80	12.46
90	22.50	92	17.14

The observed variation stems from the drying regime that is believed to have been used in the production of the veneers used in the study. The veneers were of known origin and cut to the required size by the supplier. The seasoning regime used for conditioning the veneers may have changed the response of the samples to changes in relative humidity (RH). Results from a recent study on determination of EMC for various species with known drying history, revealed that the final EMC for samples subjected to harsh drying prior to conditioning could be up to 3% MC lower that identical samples conditioned from the green state [53].

The projected moisture contents in this study were based on conditioning green timber[26] to the conditions tabulated in Table 5-1. Each sample consisted of 9 layers of Douglas-fir veneers with dimensions of 100 mm ×62.5 mm ×1.5 mm (along the grain, across the grain and in the radial direction, respectively).

[25] The stated figures refer to the oven dry values.

[26] Due to limitation of resources for cutting green timber to veneer dimensions the author was unable to pursue this route.

Figure 5-1 shows the stack arrangement and dimensions for each sample.

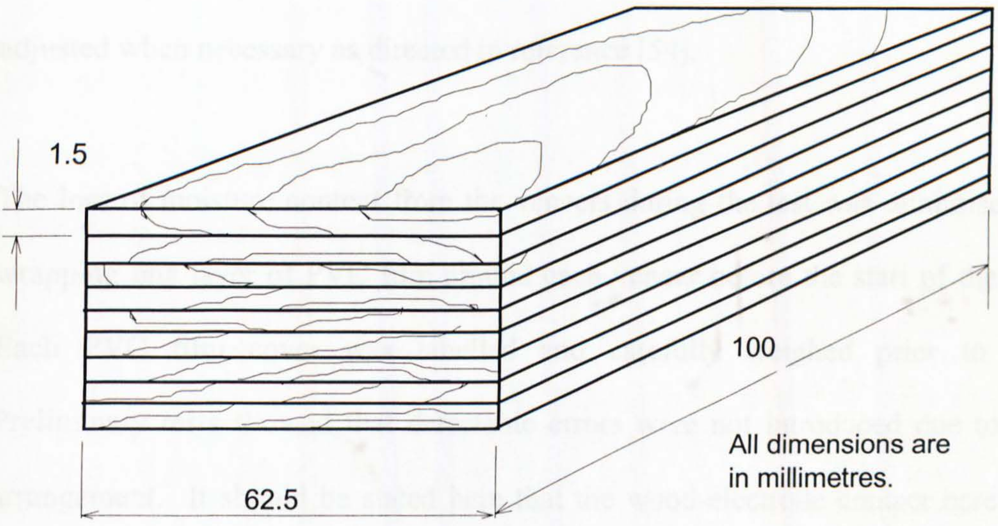

Figure 5-1: The stack configuration used and the dimensions of each veneer in the stack. Each veneer was conditioned to a known moisture content.

5.3.2 Moisture meter under test

The dielectric meter used in the study has a specified scanning depth of 19 mm [54], and operates at 1 MHz. With a typical rectangular surface electrode (see Figure 6-7, page 134), the meter has a scanning area of 37.5mm × 62.5mm. In order that the scanning electric field produced by the meter is not distorted due to any material other than the substance of the sample under test, it was critical to ensure that the sample was supported during the measurements with a material which does not affect the meter reading. Preliminary tests showed that a sheet of expanded polystyrene with thickness of about 23 mm could be used to support the samples without affecting the meter readings.

Regular checks during the course of the experiment ensured that the battery supplied correct inputs to the instrument; calibration and zero settings were adjusted when necessary as directed in reference [54].

The loss of moisture content from the veneers during the test was minimised by wrapping one layer of PVC film around each veneer before the start of the test. Each PVC film cover was labelled and carefully weighed prior to use. Preliminary tests showed that detectable errors were not introduced due to this arrangement. It should be stated here that the wood-electrode contact here is a non-metallic contact (unlike the electrode arrangement used in the study in Chapter 4): the back plane of the electrode which comes into contact with the sample is made of a non-metallic material.

To minimize the uncertainty due to inter-species variations and statistical fluctuations a systematic approach to averaging twelve readings for each sample was adopted. The two outermost veneers in each sample were rearranged or replaced systematically with other veneers seasoned to the same conditions and new readings taken. Thus a total of twelve readings was taken for each moisture gradient. In each case, the sample stack was weighed prior to the measurement and supported by expanded polystyrene during the measurement.

5.4 Discussion of results

The constructional details for each of the simulated gradients is tabulated Table 5-2. Also shown in Table 5-2 is the mean moisture content (o.d. basis) for each gradient. Clearly deviation of achieved EMC from those predicted (see Table 5-1) resulted in the observed variation in the mean moisture content values.

Table 5-2: Constructional details of the gradients; S, R and M refer to steep drying, regain and moderate drying gradients, respectively The Layer column specifies the position of veneers in the stack; e.g. layer 1 is the first veneer from the top, directly in contact with the electrodes during the tests, followed by layer 2 directly below it, and so on.

	Percentage moisture content					
Layers	**S1**	**R1**	**M1**	**S2**	**R2**	**M2**
1	6.88	17.14	6.88	6.88	17.14	10.29
2	6.88	17.14	10.29	17.14	17.14	10.29
3	12.46	6.88	10.29	17.14	12.46	17.14
4	12.46	6.88	12.46	17.14	10.29	17.14
5	12.46	6.88	12.46	17.14	10.29	17.14
6	12.46	6.88	12.46	17.14	10.29	17.14
7	12.46	6.88	10.29	17.14	12.46	17.14
8	6.88	17.14	10.29	17.14	17.14	10.29
9	6.88	17.14	6.88	6.88	17.14	10.29
Mean MC	9.98	11.44	10.26	14.86	13.82	14.10

Figure 5-2 shows the correlation between the meter reading and the moisture content (o.d. basis) obtained for the reference samples (with effective gradients of zero) from the samples described in Chapter 4 and additional data obtained from Poplar veneers. The appropriate density correction factors were applied in accordance with the manufacturer's instructions [54] for Poplar.

The solid diagonal in Figure 5-2 is the line of perfect fit while the dotted line shows the line of best fit for the stack constructed from the reference veneers. The two lines intercept one another at moisture content (o.d. basis) of 12.50%. The Pearson product moment correlation coefficient for the line of best fit is 1.00 ($R^2 = 0.97$) for the data points shown, a strikingly good correlation. However, due to the systematic shift, the magnitude of the error in the measured moisture content is increased with increasing moisture content. The slope of the line of best fit has a gradient of 1.31 and intercepts the y-axis at −3.87% MC; this signifies that deviations of up to about 4% MC are possible at moisture contents below 12.50% (the interception of the line of best fit and the line of best agreement). Beyond this point however, the readings tend to be greater than the moisture content (o.d. basis) and the error at 25% MC is around +4.00% MC[27].

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[27] Findings of this study were discussed extensively with the manufacturers; it was confirmed that the skew in the data had been reported by other independent bodies and that efforts were being made by their engineers to reduce them [38].

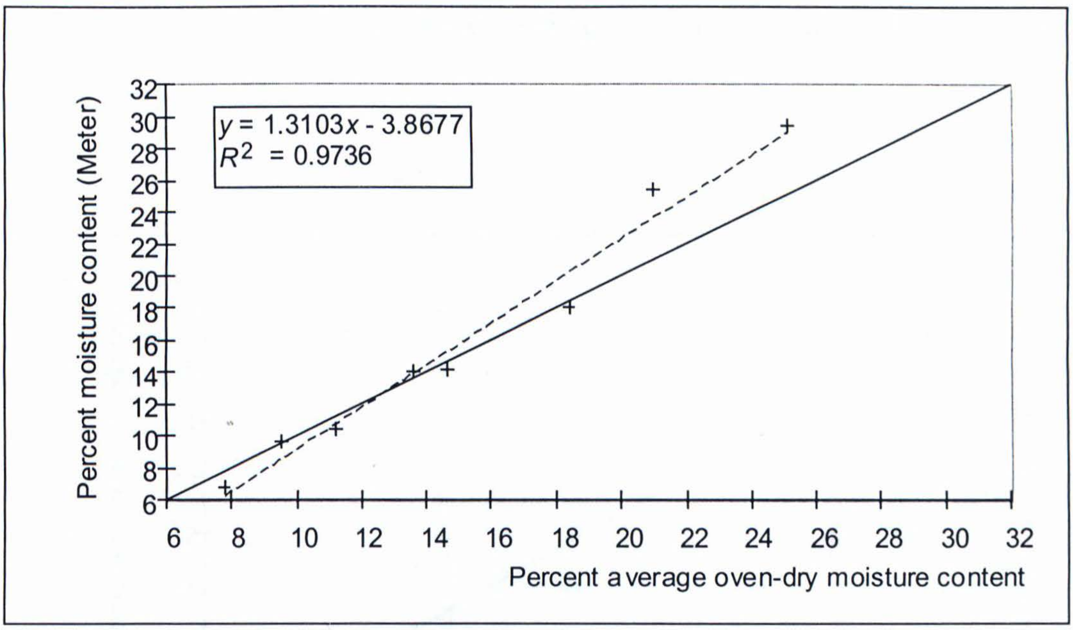

Figure 5-2: Meter reading for the reference samples, with effective moisture gradient of zero. The solid diagonal line shows the line of perfect fit, while the dotted line shows the line of best fit.

The increase in moisture content error beyond the point of interception was found to be 0.32%/M_{od}, where M_{od} is the moisture content (o.d. basis).

Figure 5-3 shows the moisture meter readings for samples with gradients, defined in Table 5-2.

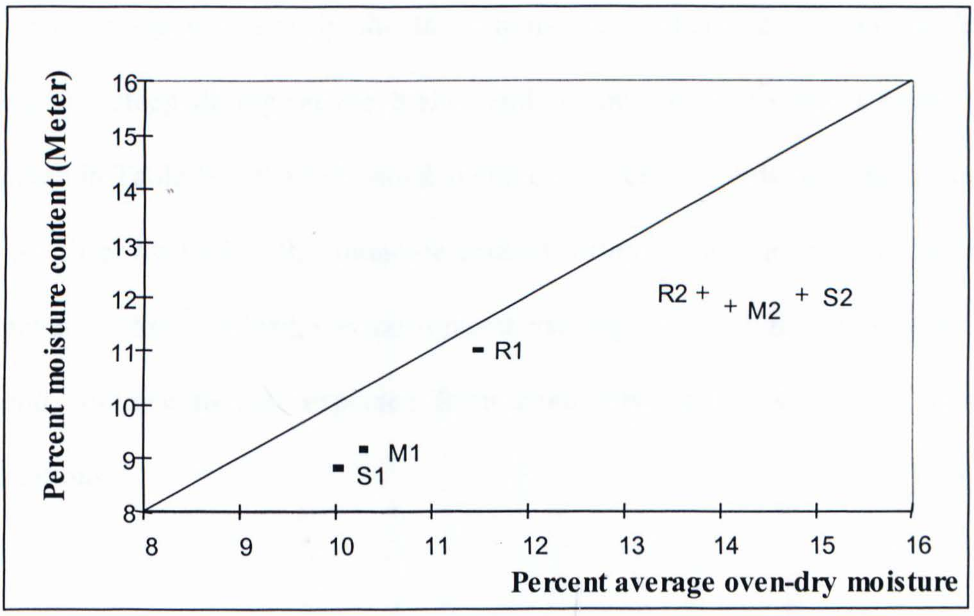

Figure 5-3: Readings from the capacitance-type moisture meter and the corresponding moisture contents (o.d. basis), for three moisture gradients of medium-dry (M), steep-dry (S) and regain (R). The diagonal line shows the line of perfect fit.

Each point in Figure 5-3 represents the mean of twelve meter readings. The moisture content (o.d. basis) was calculated from the cumulative oven-dry and wet masses of the nine veneers used in each sample, $\sum_1^9 M_o$ and $\sum_1^9 M_w$ respectively, using the following formula

$$MC = \frac{\sum_1^9 M_w - \sum_1^9 M_o}{\sum_1^9 M_o} \times 100$$

With reference to Figure 5-3, the following findings are revealed. The question of whether or not the systematic moisture gradients affect the meter reading can be answered by initially analysing the second set of data points namely R2, M2 and S2, representing respectively the three moisture gradients of regain, moderate drying and steep drying, at the higher end of the moisture content range. As tabulated in Table 5-3, the calculated average moisture contents (o.d. basis) for R2 and S2 differ by 1.04%; this moisture content difference has not been reflected in the meter reading. Indeed, the mean meter reading is very slightly higher for R2, a trend contrary to that expected from cumulative moisture content average calculations.

Table 5-3: Comparison between the average moisture content (o.d. basis) and the readings as indicated by the capacitance type moisture meter, for three moisture gradients of moderate drying (M2), steep drying (S2) and regain (R2).

	Percentage moisture content	
Gradient	**Average oven dry**	**Meter[28]**
M2	14.10	11.83
S2	14.86	12.04
R2	13.82	12.08

This indicates that the *effective* penetration depth of the meter is somewhat less that the actual specified depth of 19 mm (each veneer is 1.5 mm), and that the meter reading does not give a true indication of the total average moisture content. Findings reported in [20] consolidate the observed trends in this study.

[28] The meter readings show the mean value for 12 readings.

Preliminary tests on this meter showed that for samples with uniform moisture profile (moisture gradient of zero) the specified penetration depth of the meter is in fact correct[29]. However the facts revealed in this moisture gradient study indicate that the presence of moisture gradients in the test samples affect the meter readings considerably, by causing the *specified* penetration depth to be *not* the actual *effective* scanning depth which determines the moisture content.

To determine the effective scanning depth in the presence of moisture gradients, the average moisture contents (o.d. basis) to various depths (starting with layer 1) for S2, R2 and M2 combinations were calculated. For example for the number of layers n = 5, this means that the moisture content was calculated by averaging the moisture contents (o.d. basis) for the first 5 layers. These are tabulated in Table 5-4.

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[29] An aluminum plate (1.5mm × 62.5mm × 100mm) was used to support the samples during the measurements. The number of veneers in the stack (see Figure 5-1) was increased gradually, and measurements taken with and without the aluminum plate. The increase in the measured value due to conductance of the aluminum plate became negligible after 13 layers of veneers.

Table 5-4: The average (for number of layers identified) moisture content (o.d. basis) calculated for the corresponding construction used in each of the three moisture gradients of Steep drying (S2), Regain (R2) and Moderate drying (M2); the last column shows the difference between the average moisture contents (o.d. basis) for S2 and R2.

No of Layers	Percent average moisture content (o.d. basis) over specified layers			
	S2	**R2**	**M2**	**R_2 - S_2**
1	6.88	17.14	10.29	10.26
2	12.01	17.14	10.29	5.13
3	13.72	15.58	12.57	1.86
4	14.58	14.26	13.72	-0.32
5	15.09	13.46	14.40	-1.62
6	15.43	12.94	14.86	-2.50
7	15.67	12.87	15.18	-2.81
8	15.86	13.40	14.57	-2.46
9	14.86	13.82	14.10	-1.04

The discrepancy between the average moisture contents (o.d. basis) for S2 and R2 (see R_2 - S_2 column in Table 5-4) reaches a minimum for 4 layers; as the meter readings for S2 and R2 are almost identical (see Table 5-3) it is deduced that the effective scanning depth of the meter is around 6 mm (4 layers of 1.5 mm veneer). This finding was evaluated for the moisture gradients S1, R1 and M1. With reference to Figure 5-3, the expected trend for the average moisture contents for S1, R1 and M1 at a depth of 4 layers should be $M_{R1}>M_{M1}>M_{S1}$, where M_x is the average moisture content (o.d. basis) to a depth of 4 layers. The results shown in Table 5-5 confirm that the readings indicated by the meter fall into the expected trend at a depth of 4 layers.

Table 5-5: The average (for number of layers identified) moisture content (o.d. basis) calculated for the corresponding construction used in each of the three moisture gradients Steep drying (S1), Regain (R1) and Moderate drying (M1).

No of Layers	Percent average moisture content (o.d. basis) for specified layers		
	S1	**R1**	**M1**
1	6.88	17.14	6.88
2	6.88	17.14	8.59
3	8.74	13.72	9.15
4	9.67	12.01	9.98
5	10.23	10.98	10.48
6	10.60	10.30	10.81
7	10.87	9.81	10.73
8	10.37	10.73	10.68
9	9.98	11.44	10.26

The indicated 2% moisture content difference between R1 and M1 (see Figure 5-3) by the meter is a reflection of the difference between the average oven-dry moisture contents of the two gradients at a depth of 4 layers (as seen in Table 5-5). Similarly, the meter produced a difference of about 0.4% MC for S1 and M1, again an indication of the difference between the average moisture contents (o.d. basis) at a depth of 4 layers. It is therefore observed that the meter consistently produces reading which correlate with the average moisture contents (o.d. basis) at a depth of around 6mm.

5.5 Conclusion

Reference samples with uniform moisture distribution showed the meter to be underestimating for moisture contents (o.d. basis) below 12.5%, while overestimating for moisture contents greater than 12.5%. The worst case scenarios in the range on moisture contents employed resulted in errors of ±4% MC. A clear skew is observed in the response of the meter in relation to the line of perfect fit.

It was further found that the presence of moisture gradients reduces the effective measuring depth of the meter; for the meter used in this study the *effective* measuring depth was reduced by more than 60%, when samples had systematically induced moisture gradients.

The reduction in the effective measuring depth is attributed to the measurement strategy used. Instrument calibration and electrode response characterisation are carried out using samples with *uniform* moisture distributions only, and with the assumption that the meter would only be used for applications in which any non-uniformity in the moisture profile would be minimal.

However, the extent of the potential errors highlighted in this study shows that the existence of moisture gradients at the time of measurement could severely distort the measured moisture content (it was reported in reference [55] that the accuracy of a power loss moisture meter was limited to a depth of 2.5 mm, in presence of moisture gradients).

Given that dielectric moisture meters currently available have no means of indicating the existence of moisture gradients, the use of such instruments should be limited only to applications in which existence of moisture gradients is known to be negligible.

In Chapter 6, design and development of a computer controlled measurement system is discussed. Results are presented for two electrode configurations used with this system. The concluding part of the chapter discusses a measurement protocol for evaluating moisture gradients to a depth of at least 10mm.

Chapter 6

6 Moisture Gradient Studies in Timber by Measurement of Dielectric Parameters

6.1 Summary

Following on from the findings reported in chapter 5, a detailed analysis of the effects of moisture gradients on dielectric measurements were carried out. In this chapter the methodology for investigation of several systematic moisture gradients over a depth of 20 mm is discussed.

Studies were carried out by the penetration of a 0.90 MHz electromagnetic field making precision dielectric measurements using a technique developed by the author, involving a computer controlled resonance circuit. The base measurement system (see Figure 6-3) was used in conjunction with two electrode configurations (shown in Figure 6-7 and Figure 6-8) to investigate and develop techniques for detection of transverse moisture gradients.

Results show that with constant mean moisture content, both the capacitance and loss tangent, which are frequently used correlation parameters for measuring the moisture content, are severely affected by the gradients. The findings of the study

further revealed that detection of moisture profiles up to a depth of about 10 mm can be achieved with the use of a multiple-plate surface electrode[30].

6.2 Introduction

Early detection and knowledge of the causes of moisture gradient in timber are vital in establishing the final EMC; assessment of moisture gradient is not only an important factor in controlling the seasoning environment for the timber (as discussed in Chapter 1) and hence as a cost saving measure during the seasoning period, but ultimately serves to ensure the durability of timber. If measures are not taken into account in the seasoning process to counterbalance the effects of moisture gradient during the seasoning period, then distorted measurements could cause premature termination of the seasoning cycle and result in batches of seasoned timber with specified MC which could potentially be far from the final EMC for the batch. The time taken for dispersion of moisture in such causes depends on several factors including the severity of the gradient and the permeability of the species. Nevertheless, although the MC of the batch at the time of shipment may be as specified by the customer requirements, the transit time may well have caused the MC to vary by unacceptable amounts, even if packaging requirements had been met. In such cases a knowledge of moisture gradients at the time of shipment could prove an invaluable remedy for insurance claims.

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[30] Preliminary results from this study were disseminated in April 1996 at the Third International Symposium on Humidity and Moisture, National Physical Laboratory, London (see reference [59]); dissemination of the final results was carried out in April 1999 at the Third Workshop on Electromagnetic Wave Interaction with Water and Moist Substances, Georgia, USA [60].

The study which follows elucidates a methodology for detection of moisture gradients.

6.3 *Methodology*

6.3.1 Material preparation

The samples were cut from green Poplar[31] (*Populus tacamahaca*) and conditioned using saturated[32] salt solutions in purpose-built environmental chambers. The development of the latter are discussed in [53]. Saturated salt solutions are widely used for providing constant RH at a given temperature (see for example [56]). Chambers were equipped with miniature fans for forced convection and micro-dataloggers monitoring relative humidity and temperature. The final dimensions of the veneers were 100 mm × 60 mm × 2 mm (along the grain, across the grain and in the radial direction), where the tolerance in the latter dimension was ±0.1 mm. Sets were conditioned to various moisture contents, at 20±2 °C in temperature cabinets discussed in [53]; Table 6-1 shows the resulting moisture contents for the sets of veneers.

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[31] Veneers used in the experiment were supplied by ASTON TIMBER PRODUCTS LIMITED, Sedge Fen, Lakenheath, Suffolk, IP27 9LQ, where Green Poplar was sliced using a rotary blade, and cut into size and wrapped with PVC film prior to transportation to the research laboratories. The author wishes to thank Mr Martin Axman, the general manager, who coordinated the supply and preparation of the samples.

[32] The solutions were made at 20±2 °C using distilled water and the relevant salt according to reference [45].

Table 6-1: Relative humidity and the resulting moisture content (o.d. basis) for four representative conditions

Relative humidity (%)	Moisture content (%)
33	7.53
66	13.64
81	18.42
93	25.14

For all subsequent measurements, test stacks were assembled from nine veneers, Figure 6-1; a similar test bench to that shown in Figure 4-9 was used during the measurements to ensure that the veneers were stacked flat, and uniform and constant pressure was applied to the samples throughout the measurements.

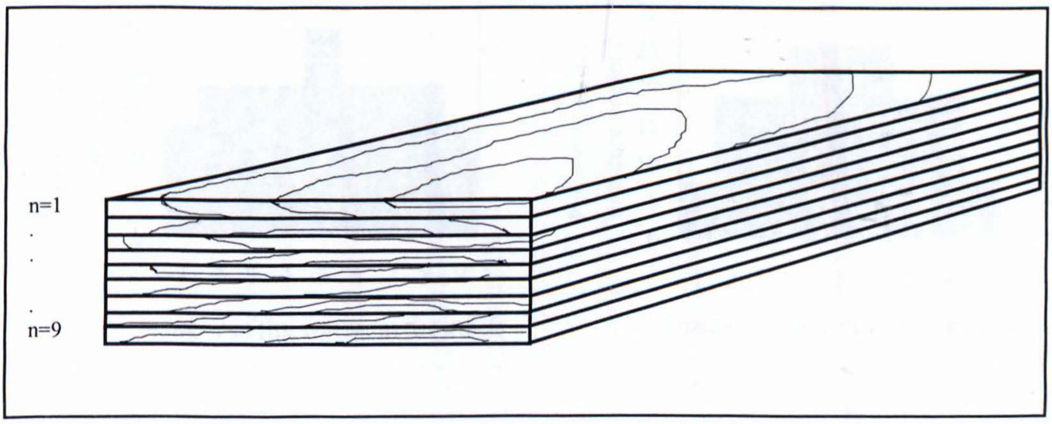

Figure 6-1: The sample under test, comprising a stack of 9 veneers. The planar electrodes discussed in section 6.3.2.3 (page 134) was in contact with the top veneer (n=1) under constant pressure during the measurements.

This arrangement allowed systematically defined moisture gradients to be built into the samples. Figure 6-2 shows the moisture content profiles for four particular sets used in the investigations. Moisture profiles were designed to minimize the deviation in mean moisture content of each stack from the zero gradient situations (i.e. samples with uniform moisture content); the worst deviation was a mere ±0.35% moisture content. The mean moisture content for the four gradients of the set whose profiles are displayed in Figure 6-2 is 18.42%.

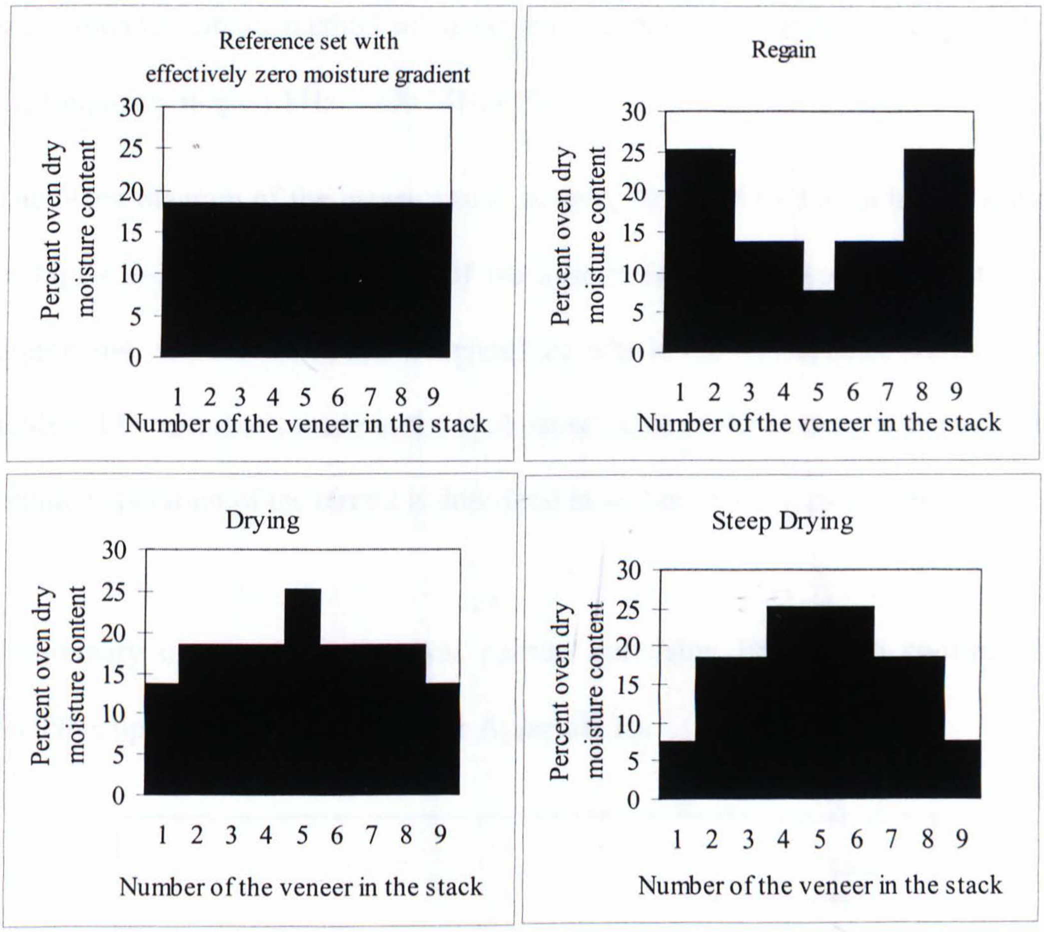

Figure 6-2: Moisture distribution in a representative sets of samples.

These systematically introduced moisture gradients were investigated using the measurement system discussed in section 6.3.2.

6.3.2 Measurement system

6.3.2.1 System hardware

The method used for the measurement of the dielectric parameters in the study is the resonance circuit method of susceptance variation; a method widely used in the frequency range 1 kHz – 200 MHz [13].

The block diagram of the measurement system, designed by the author, is shown in Figure 6-3. The heart of the of the system is an LC resonant circuit (see Figure 6-4 for the schematic diagram) in which the susceptance variation is achieved by variations made to the total capacitance of the resonance circuit. The detailed operation of the circuit is described in section 6.3.2.4, page 136.

Preliminary circuit simulation was carried out using PSPICE to confirm the principle operation of the circuit (see Appendix E).

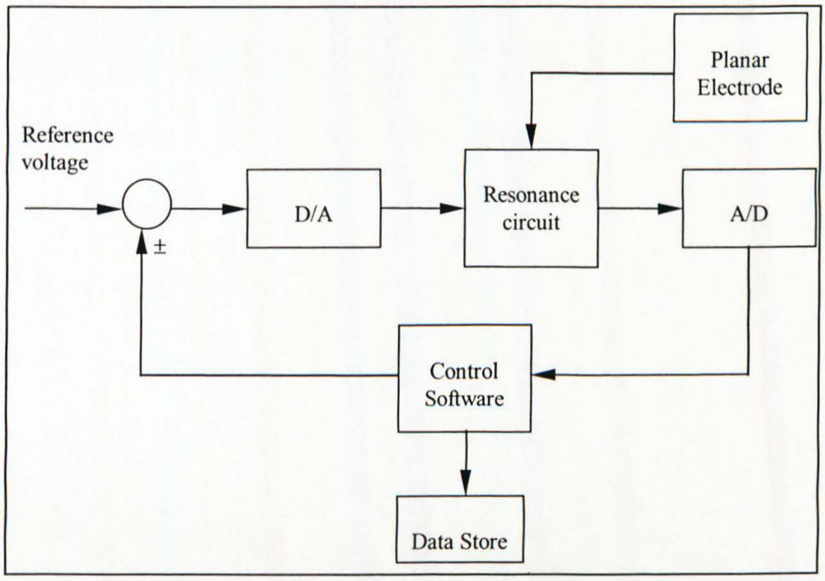

Figure 6-3: The block diagram of the measurement system

The operation of the measurement system is based on the sweep of capacitance, and real time auto-detection of the corresponding resonance and half-power points. High precision was achieved using a 14 bit ADC-DAC plug-in card[33], which controlled the sweep of capacitance and sampled the output of the resonance circuit under software control. Every measurement was initiated by a calibration cycle, during which resonance was achieved without the sample. After the calibration cycle, the sample was placed in contact with the planar electrode under constant pressure (the meter and the sample were clamped together), and the measurement cycle repeated. Every measurement was repeated five times to ensure repeatability and the mean value calculated for the analysis. All veneers were weighed before and after each test (to ±0.01 g) for gravimetric reference, and covered with polythene film[34] to minimize moisture migration between veneers.

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[33]MPS CS23A

[34] Preliminary tests which involved measurement on samples with and without PVC film, showed that the addition of the PVC film does not affect the measurements.

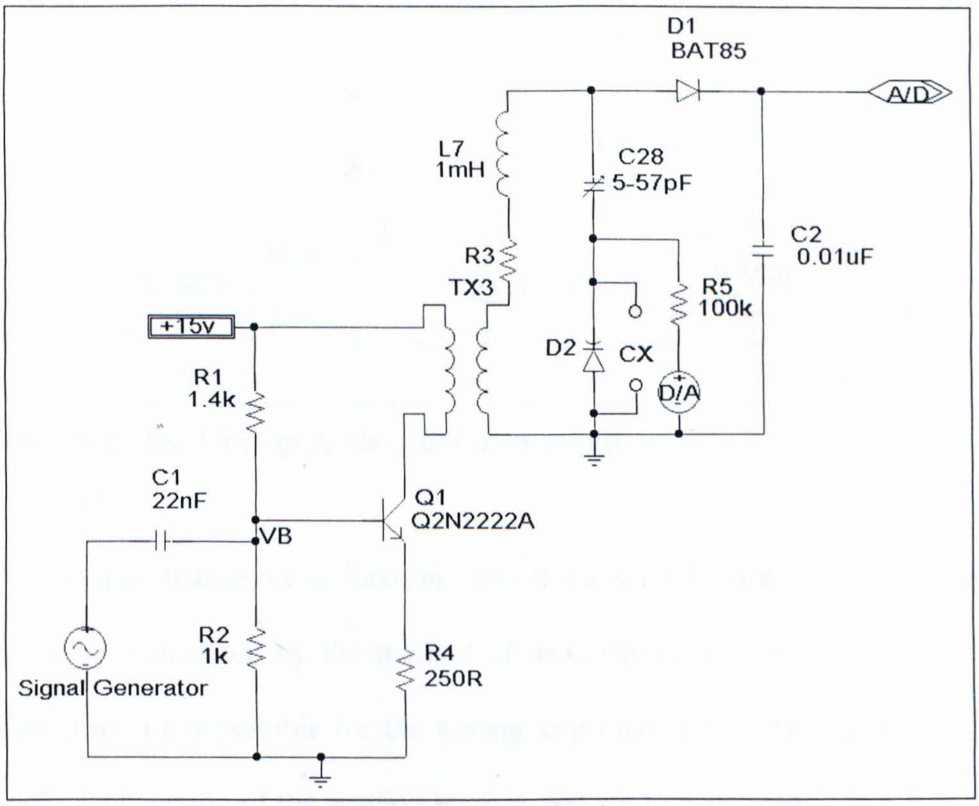


Figure 6-4: Schematic diagram of the resonance circuit

6.3.2.2 *Varicap calibration*

The capacitance-voltage relationship of the Varicap diode D2 (see Figure 6-4) is of utmost importance to the accuracy of measurements and therefore although a general chart had been supplied through the data sheets, it was considered vital to calibrate the Varicap diode before assembly. Figure 6-6 shows the calibration set-up used. The Q-meter was set to the frequency of measurement (0.90 MHz) and the applied d.c. voltage increased in increments of 0.3 V, in the range of zero to 10 V, the maximum available voltage from the DAC.

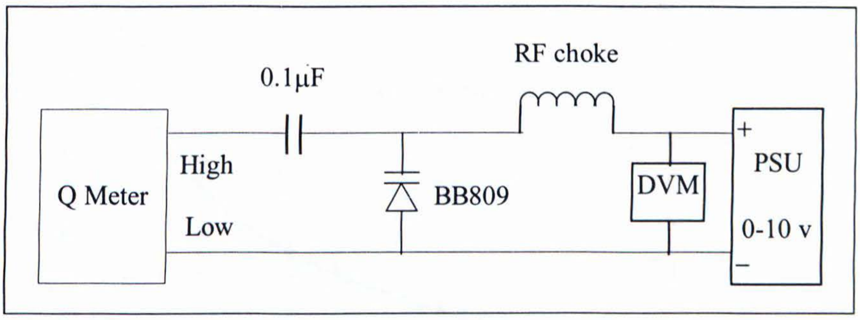
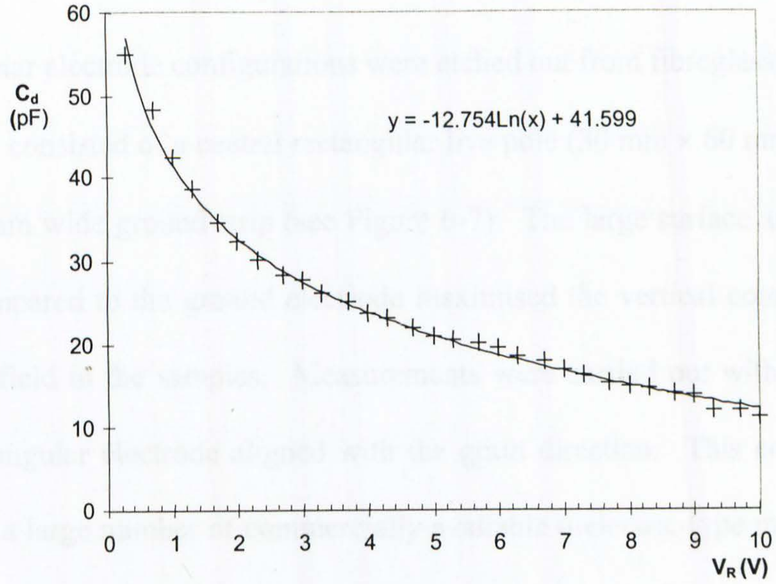
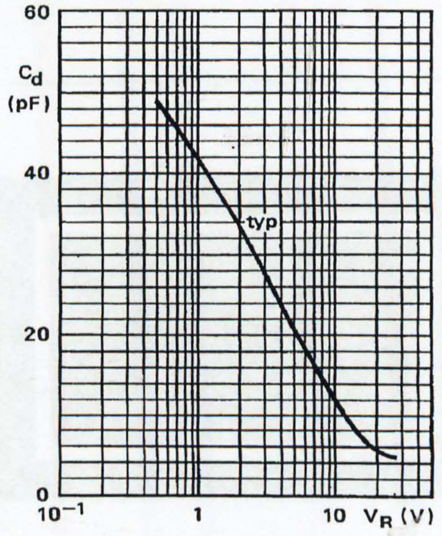


Figure 6-6: The Varicap diode calibration set-up

The voltage-capacitance calibration curve is shown in Figure 6-7. The equation of the curve (calculated by the method of least squares) reveals that an excellent logarithmic fit is possible for the voltage-capacitance relationship of the varicap diode. Conversion of the applied varicap voltage to capacitance data was carried out based on equations derived from the calibration data in the region of interest (3 to 6 volt).



(a)



(b)

igure 6-7: Voltage-capacitance relationship for the calibrated varicap diode (a) rom calibration data and (b) from data sheet[35] where V_R is the reverse bias oltage across the varicap diode.

BB809 data sheet, Silicon Planar variable capacitance diode, Philips international

6.3.2.3 Electrode configurations

Two planar electrode configurations were etched out from fibreglass circuit board. The first consisted of a central rectangular live pole (30 mm × 60 mm) surrounded by a 2 mm wide ground strip (see Figure 6-7). The large surface area of the live pole compared to the ground electrode maximised the vertical component of the electric field in the samples. Measurements were carried out with the length of the rectangular electrode aligned with the grain direction. This configuration is used by a large number of commercially available dielectric-type moisture meters and was therefore chosen in order to replicate the existing shortcomings of the this type of moisture meters, when measurements are performed in the presence of moisture gradients.

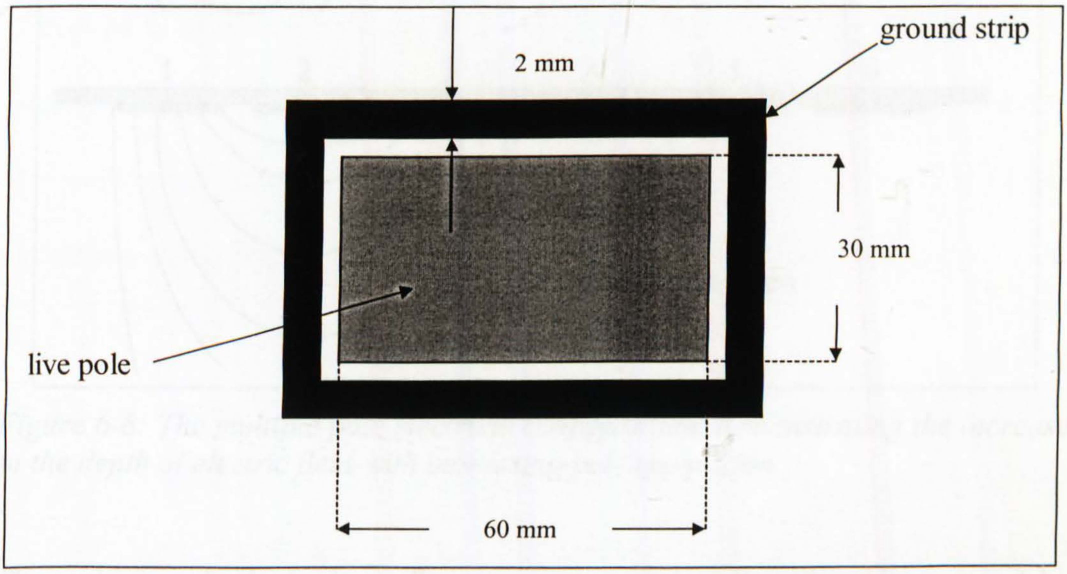


Figure 6-7: Concentric rectangular planar electrode with central live pole, and a surrounding ground strip. The large surface area of the live pole in the electrode arrangement maximises the vertical component of the electric filed.

The second electrode configuration consisted of six equidistant rectangular poles (20 mm × 5 mm) with centre to centre separation of 6 mm. The aim was to investigate the effect of electrode pole separation on the effective penetration of the electric field into the samples. A similar electrode was reported in [57] in a different application (measurement the moisture content of roof surfaces). Insights into the operation of such electrode would determine if a profile scan into the depth of the sample could be obtained.

This electrode configuration is shown in Figure 6-8.

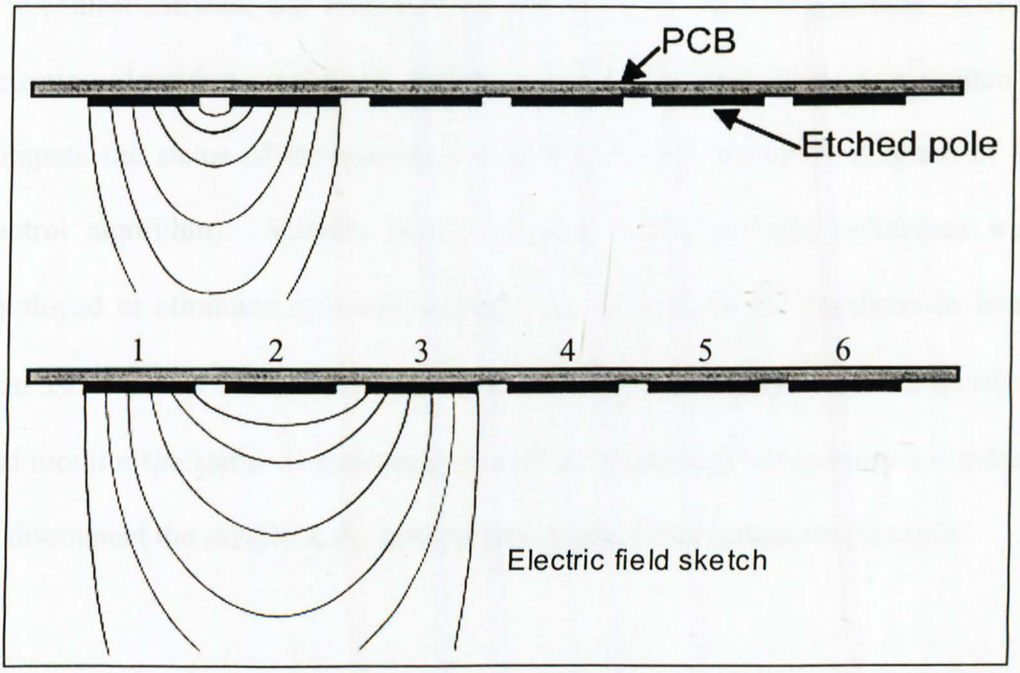


Figure 6-8: The multiple pole electrode configuration, demonstrating the increase in the depth of electric field with increasing pole separation.

The multiple pole electrode configuration was substantially utilized in a procedure involving a sequence of measurements cycles. During the first measurement cycle pole 1 was used in conjunction with pole 2 (see Figure 6-8). Having completed the measurements on all samples, pole 2 was disconnected, and pole 3 connected up for the next measurement cycle. Similarly, measurement cycles 3 to 6 utilized pole1 in conjunctions with poles 4 to 6, respectively. This procedure was used in order to determine its effectiveness as a moisture gradient detection technique. Although all six plates were used during the study, it was found that data collected from pole 6 was not repeatable to within the required tolerance of ±0.05 pF; this is probably due to the weakening of the electric field strength with electrode separation.

6.3.2.4 The control software

The control software was written using Borland C++, on a PC platform. A slope detection algorithm employing present and past sampled values was written to compute the status of the resonance (see Figure 6-10 for block diagram of the control algorithm). Various noise reduction algorithms and techniques were employed to eliminate spurious readings and to increase the precision to better than ±0.05 pF. The control software, a real-time state machine, served to adjust and monitor the status of resonance as well as prompting the operator to connect or disconnect the sample at the appropriate stages of the measurement cycle.

Each measurement was preceded by a calibration cycle during which the circuit was set to resonance without the sample. This was achieved through a precision d.c. voltage sweep which in turn changed the capacitance of the calibrated Varicap diode D2 (see Figure 6-4). The capacitance C_1 of the Varicap diode D2 and the corresponding output voltage (V_1) from the circuit were automatically recorded. C_1 was then incremented and V_1 monitored, until ΔC_1, the change required for a reduction of V_1 to $V_1/\sqrt{2}$, was achieved. This procedure was repeated with the sample (CX) connected to the circuit, at the indicated points in

Figure 6-4. The values of C_2 and the corresponding V_2, and ΔC_2 corresponding to the reduction of V_2 to $V_2/\sqrt{2}$ were then determined.

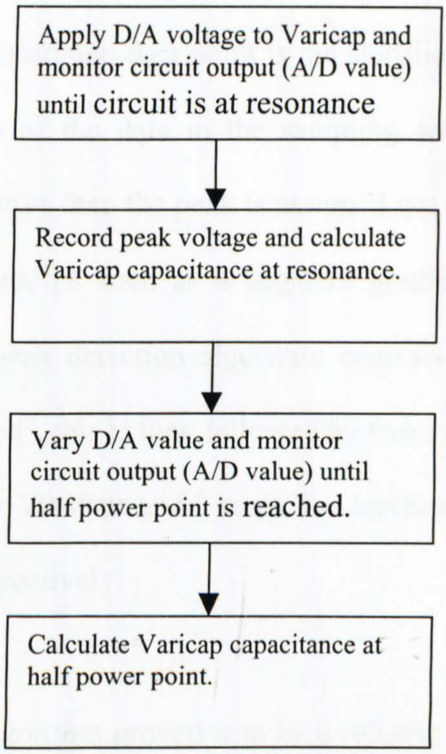


Figure 6-10: Block diagram of the control algorithm; this algorithm was executed once without the samples (to calibrate the system) and once with the samples connected to the measurement system (in order to perform the actual measurement)

The control software consisted of two main algorithms; one for detecting the resonance voltage (peak of the output voltage), and the other for detecting the half-power point (see Appendix D for flow charts). Three different tuning states are employed in the algorithm in order to increase the resolution of the control output and optimise the search without any loss of accuracy. Initially, step sizes of 50 (increments of approximately 30.5 mV) are sent out to the varicap diode D2 (see Figure 6-4). The increments are added to an initial offset voltage near the point of resonance for the circuit, in the stand-alone mode. The algorithm employs a sampling window of size 20 (data points). The detection of the peak is based on comparison of the sampled data in the window, at each stage. Each sampled data is compared with the next 19 and only when the first sampled data in the window is greater than the next successive 19, it is taken to be the peak. It should be noted that each sampled data point is the statistical mean of 50 filtered data points. Comparison of the data in the sampling window determines the nature of the slope; if positive then the peak is assumed not to have been reached. The tuning state is changed as soon as a negative gradient is detected in the sampling window. The peak detection algorithm controls the output such that initially, the peak is "missed", this is then followed by two increases in the control output resolution namely to 20 steps and 3 steps, i.e. increments of approximately 12.2 mV and 1.83 mV, respectively.

Thorough testing of this algorithm proved it to be a reliable and efficient method for ensuring that the detected peak is not due to spurious readings while improving and optimising the response time of the measurement system. Minimization of the response time was an important factor, as this ensured the minimization of the migration of moisture between veneers during the measurement cycle.

On entry to the half-power point algorithm (see Appendix D for further details and flow charts) the voltage of the peak of resonance (vpeak) is calculated, and then recorded along with the varicap voltage (vcap) at which resonance occurred. At half-power point, the magnitude is $vpeak/\sqrt{2}$; this is calculated and recorded as the target voltage. The DAC output is then appropriately controlled and the error signal, the difference between the target and the circuit output voltage, monitored. To improve the response time of the system, this algorithm caters for adjustments to the step size, in real time, depending on the magnitude of the error signal. Initially, the change in the DAC output is in steps of approximately 0.12 V, decreasing in two further stages to steps of 12.2 mV and 610 μV. The error signal therefore decreases sharply until its magnitude is less than 1.5 V, when the step size is changed to approximately 12.2 mV. Similarly, once the magnitude of the error signal has reduced to less than 0.1 V, the step size changes to approximately 610 μV. The search for the target voltage stops when the target ± 0.01 V is reached.

The a.c. signal was supplied to the circuit by an external signal generator set to 0.90 MHz, also connected to a frequency counter; the frequency was therefore monitored during the experiment, and was steady to better than ±1% over time scales of hours. The a.c signal was also monitored to ensure that the variations of amplitude stay well within the tolerance limit of ±3%, the requirement for the procedure used [58].

At constant frequency, the circuit resonance state at the second tuning occurs when $C_2 + C_x = C_1$, enabling the change in capacitance due to the sample, C_x, to be determined.

The tuned circuit Q-factor and the loss tangent can be calculated using Equation 6-1 and Equation 6-2 (from reference [58], page 46).

$$\frac{1}{Q_1} = \frac{\Delta C_1}{C_1}$$ *Equation 6-1*

$$\tan\delta = \frac{C_1\left(Q_2^{-1} - Q_1^{-1}\right)}{C_x}$$ *Equation 6-2*

where subscript 1 denotes measurements carried out without samples

and subscript 2 denotes measurements carried out with samples

6.4 *Discussion of results*

6.4.1 Studies with the concentric rectangular planar electrode configuration (single pole)

As in the previous chapter the data presented here are typical of various tests carried out with a range of mean moisture contents. For correlation purposes, moisture contents were determined by the gravimetric method. The first set of data presented in Figure 6-12 shows the measurements performed on the reference samples with effectively zero moisture gradient, using the concentric rectangle electrode configuration (see Figure 6-7). A clear correlation exists, enabling an accurate relationship between moisture content and capacitance to be established for this electrode configuration

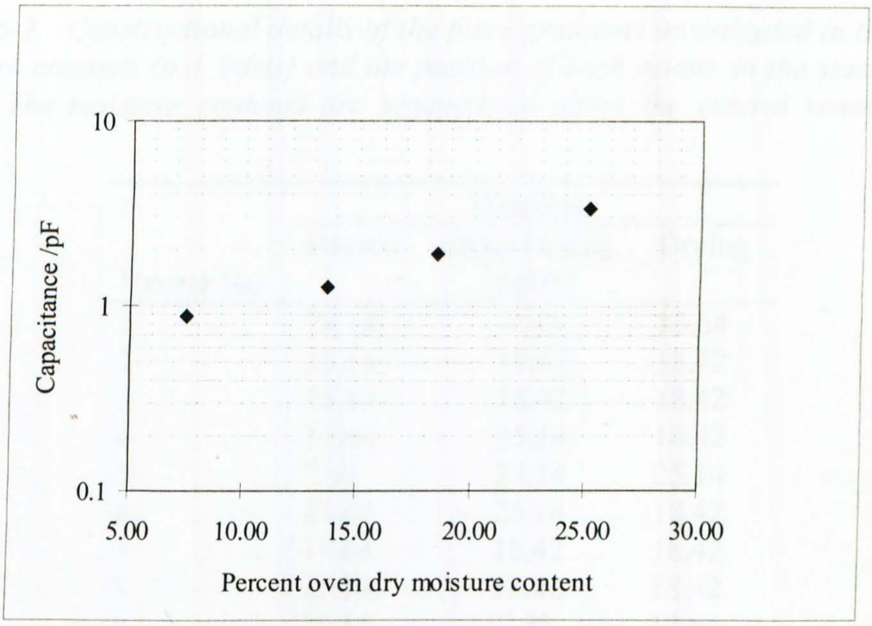


Figure 6-12: Variation of capacitance with moisture content (o.d. basis) for reference samples with effectively zero moisture gradient.

Over the moisture content range employed the change in the measured capacitance per %MC is 0.1 pF. Clearly, the set-up can be used for measurement of moisture content over a wide range, when the moisture distribution of the sample is uniform.

To follow, tests were carried out on stacks with systematic moisture gradients depicted in Figure 6-2 and defined in Table 6-2.

Table 6-2 : Constructional details of the three gradients investigated in the study; moisture contents (o.d. basis) and the position of each veneer in the stack can be seen. The moisture contents are symmetrical about the central veneer in all cases.

	Gradients		
	Regain	Steep Drying	Drying
Veneer No		%MC	
1	25.14	7.53	13.64
2	25.14	18.42	18.42
3	13.64	18.42	18.42
4	13.64	25.14	18.42
5	7.53	25.14	25.14
6	13.64	25.14	18.42
7	13.64	18.42	18.42
8	25.14	18.42	18.42
9	25.14	7.53	13.64

Table 6-3 tabulates the mean moisture content at various depths in samples with moisture gradients. The average moisture contents were calculated based on the moisture contents (o.d. basis) for the specified number of layer.

Table 6-3: Average moisture content (o.d. basis), where MC is obtained by averaging from the first to the n^{th} veneer; moisture gradient for individual veneers have been defined in Table 6-2. The is analogous to the drilling method, whereby specimens of wood dust taken by penetrating the sample to a specified depth are oven-dried, and the moisture content calculated by the gravimetric method.

	$\overline{MC}$ (%)		
	Regain	Steep Drying	Drying
Veneer No			
1	25.14	7.53	13.64
2	25.14	12.98	16.03
3	21.31	14.79	16.83
4	19.39	17.38	17.23
5	17.02	18.93	18.81
6	16.46	19.97	18.74
7	16.05	19.74	18.70
8	17.19	19.58	18.66
9	18.07	18.24	18.10

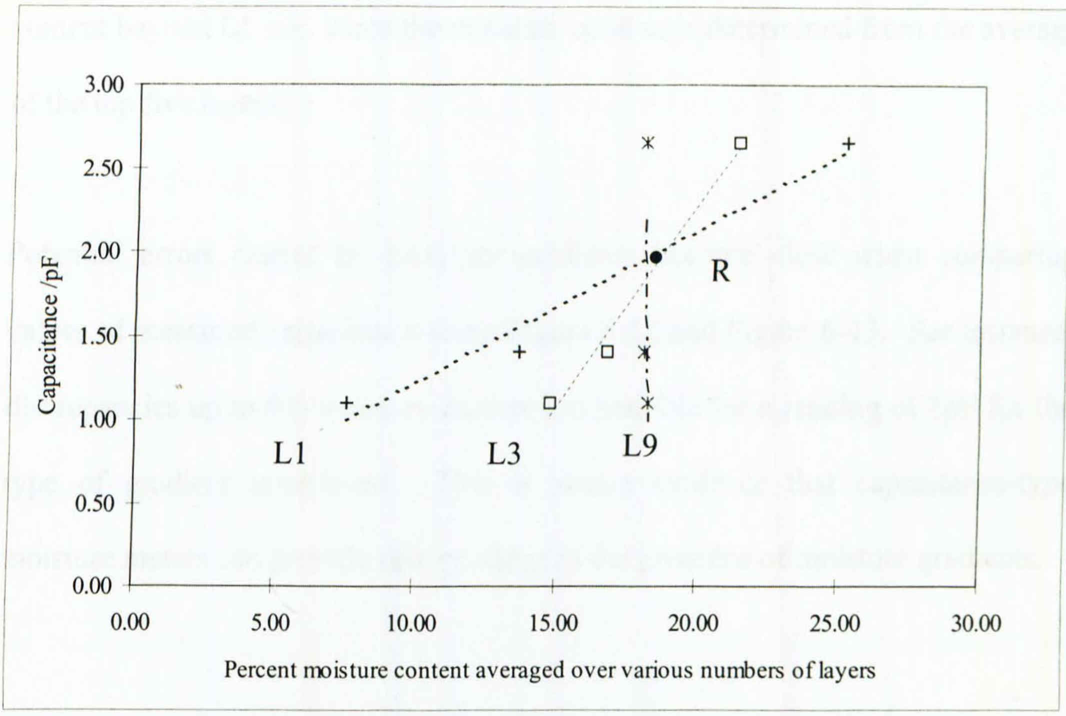


Figure 6-13: Capacitance versus the average moisture content for the three simulated moisture gradients for various numbers of layers of veneers in each stack. Moisture contents were calculated by averaging the oven dry values for the top layer (L1), the top three layers (L3) and all nine layers (L9) in each stack. Point 'R' represents the measurement obtained from the reference stack, with effective zero moisture gradient. Trends for other depths L2, L4 ... L8 have been omitted for clarity.

Figure 6-13 shows the correlation between the measured capacitance and the average moisture content for three depths in each stack. The trendlines indicate good correlation between capacitance and the average moisture content at small depths (L1 and L3). However, as the number of layers increases, moving from L1 to L9, the correlation gradually ceases to exist. The inverse gradient for L1 is 11.1 %MC per pF change in capacitance while for L3 the value is 4.0 and virtually zero for L9. These observations strangely indicate that the electric field strongly interacts only with the top few layers (down to no more than 10 mm) as there is practically no relationship between capacitance and mean moisture content beyond L5 (i.e. when the moisture content is determined from the average of the top five layers).

Potential errors caused by moisture gradients become clear when comparing values of measured capacitance using Figure 6-12 and Figure 6-13. For instance, discrepancies up to 9% moisture content are possible for a reading of 1pF for the type of gradient introduced. This is strong evidence that capacitance-type moisture meters can provide fake readings in the presence of moisture gradients.

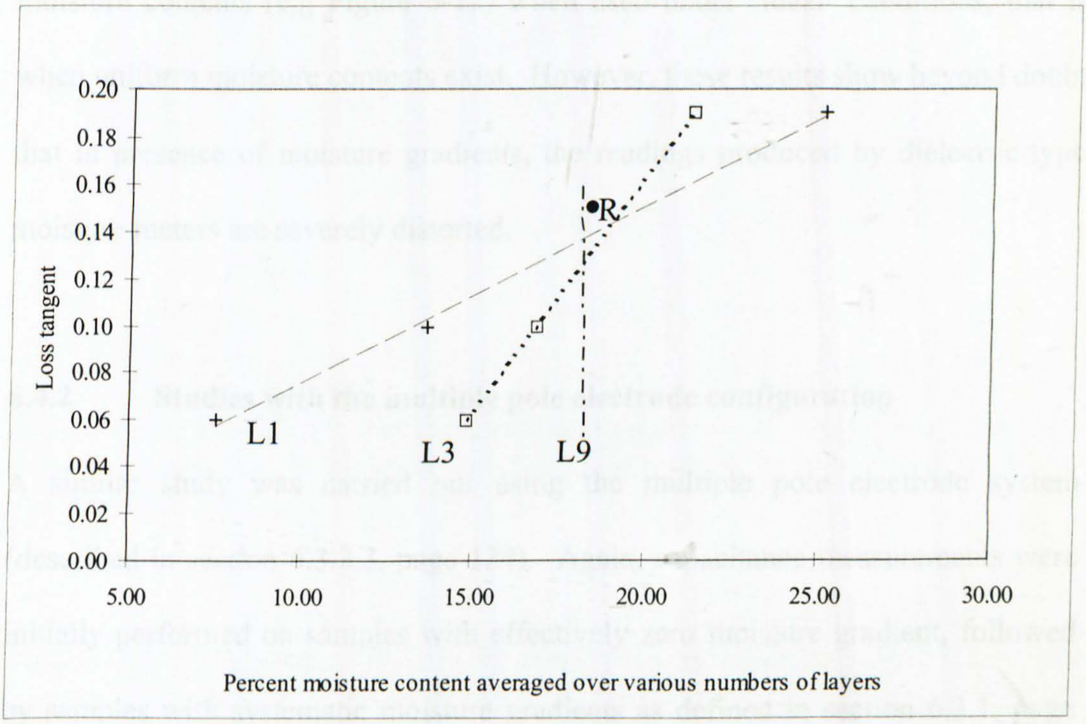


Figure 6-14: Correlation between the loss tangent and the average moisture content for various layers of veneers in each stack Moisture contents were calculated by averaging the oven dry values for the top layer (L1), the top three layers (L3) and all nine layers (L9) in each stack. Point 'R' represents the measurement obtained from the reference stack, with effective zero moisture gradient. Trends for other depths L2, L4 ... L8 have been omitted for clarity.

Analogous to the above sample plot, Figure 6-14 shows tanδ versus mean moisture content. Incidentally the data points on trend-line L1 are in good agreement with other published values of tanδ for density 0.45 g/cm^3 (refer to [58] for comparison of trends). Beyond L5 there is very little correlation remaining, similar with the findings with the capacitance data. Again, the implication is that where loss tangent is to be used for instrument calibration the existence of moisture gradients even over depths of a few millimetre severely distorts readings.

In conclusion, capacitance-type moisture meters can provide reproducible moisture contents (e.g Figure 6-12) when used under 'ideal' conditions, that is when uniform moisture contents exist. However, these results show beyond doubt that in presence of moisture gradients, the readings produced by dielectric-type moisture meters are severely distorted.

6.4.2 Studies with the multiple pole electrode configuration

A similar study was carried out using the multiple pole electrode system (described in section 6.3.2.3, page 134). Again, capacitance measurements were initially performed on samples with effectively zero moisture gradient, followed by samples with systematic moisture gradients as defined in section 6.3.1, page 126.

Similar to Figure 6-12, Figure 6-15 shows one of the correlations between the moisture content (o.d. basis) and electrode-sample capacitance for the multiple pole electrode configuration (see Figure 6-8). The exponential equation of best fit is also shown. Initial tests revealed that the required accuracy and repeatability could be obtained with maximum pole separation of about 24 mm (poles 1 and 5). The first and fifth plates of the electrode were thus used for the presented measurements. Emphasizing, every point in Figure 6-4 is the statistical mean of five measurements taken during the course of each measurement and were repeatable to an accuracy of ±0.05pF.

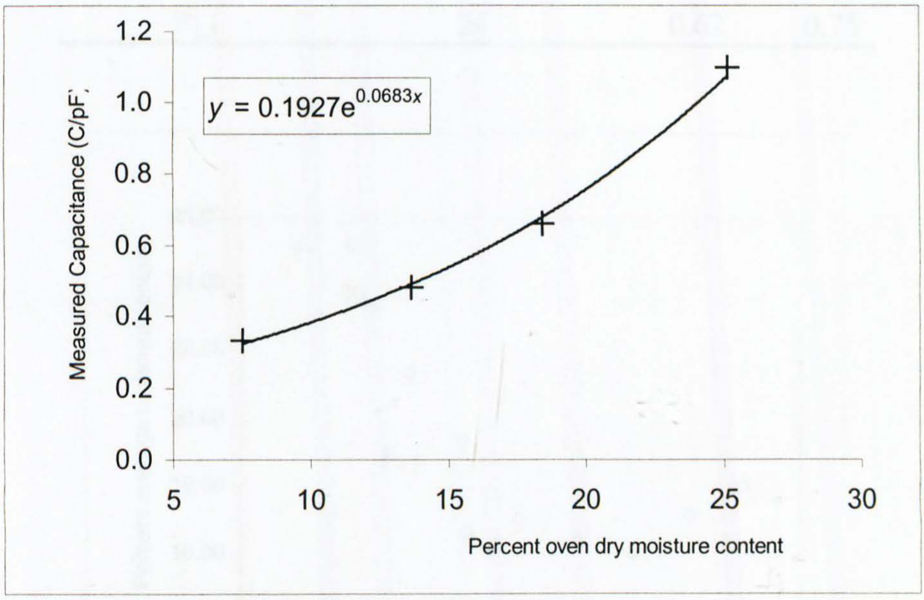


Figure 6-15: Correlation between moisture content (o.d. basis) and electrode-sample capacitance for electrode configuration two (see Figure 6-8) when plates 1 and 5 were used.

Similar to the situation reported for the single pole set up, a clear correlation exists enabling an accurate and repeatable relationship between moisture content and capacitance to be established for this electrode configuration.

Next, the effectiveness of the moisture gradient detection technique (described in section 6.3.2.3, page 134) was investigated by plotting average moisture contents for various depths in the samples (see Table 6-3) versus measured moisture content for four pole-pole combinations (see Table 6-4).

Table 6-4: Measured electrode-sample capacitance for the regain (C_r) and steep drying (C_d) gradients for four pole to pole separations.

Pole Combination	Centre-Centre separation (mm)	ΔC_r (pF)	ΔC_d (pF)
$P_{1,2}$	6	0.98	0.33
$P_{1,3}$	12	0.71	0.53
$P_{1,4}$	18	0.60	0.68
$P_{1,5}$	24	0.62	0.75

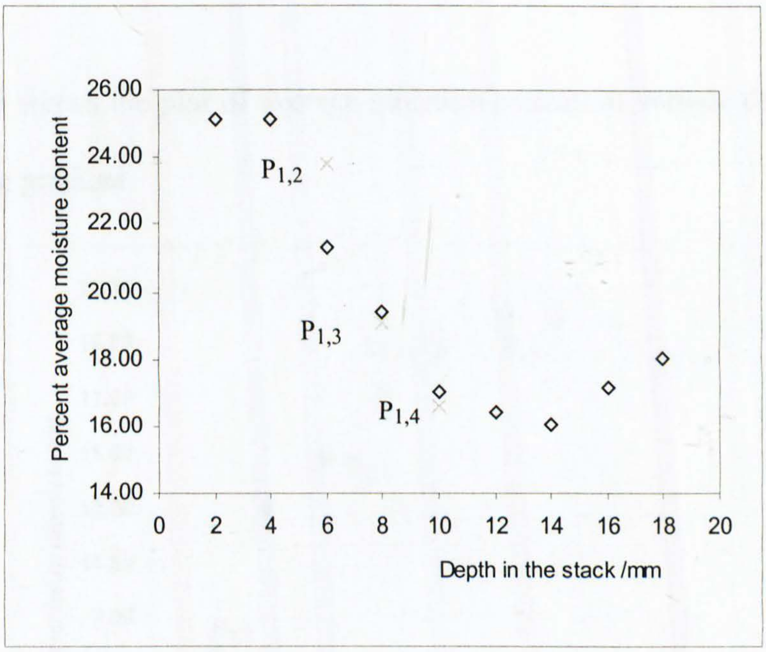


Figure 6-16: Average moisture contents at depths of one to nine veneers, and measured values. Data presented are for samples with the Regain gradient. The cross symbols mark the data points obtained using pole1 in conjunction with poles 2 to 4.

Figure 6-16 shows the superposition of measured values on average moisture content at various depths, where the average moisture contents as tabulated in Table 6-3, were calculated based the moisture contents (o.d. basis) for the number of layers specified. Each measured value (labelled as $P_{1,n}$ and based on calibrations performed for each pole separation) has been plotted at the nearest possible quantised depth with nearest matching moisture content. The observed trend in the measured values reflects the nature of the profile to a depth of around 10 mm. Data collected from the combination of poles 1 and 5 proved to be not repeatable to within the working tolerance of ±0.05 pF; this observation is considered to be due to a combination of a decrease in the electric field strength and a decrease in the average moisture content in the profile.

Figure 6-17 shows the plot of average moisture content at various depths for the *steep drying* gradient.

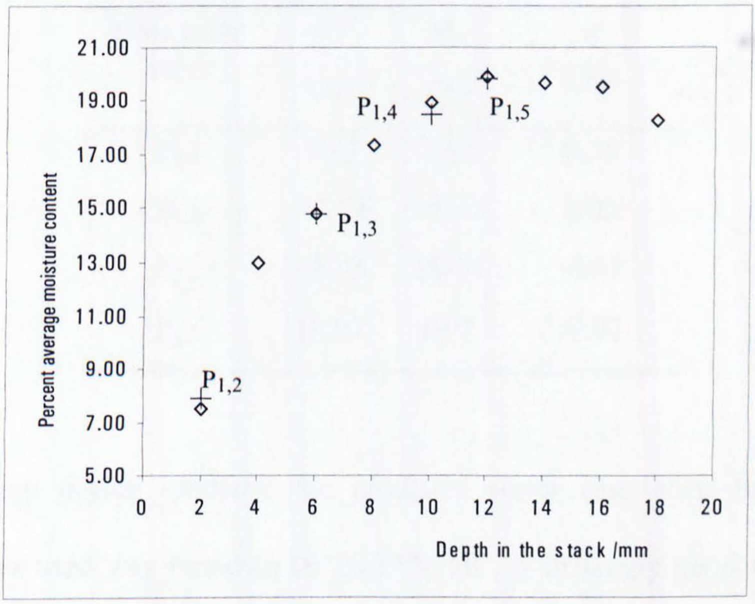


Figure 6-17: Average moisture contents at depths of one to nine veneers. Data presented are for samples with the steep drying gradient. The "+" symbols mark the data points obtained using pole 1 in conjunction with poles 2 to 5, from left to right respectively. Capacitance data was converted to moisture content using the relationship defined from Figure 6-15.

The superposition of points $P_{1,2}$, $P_{1,3}$, $P_{1,4}$ and $P_{1,5}$ onto the graph impressively shows that measured values reflect the variation in the calculated average moisture contents (o.d. basis) to a depth of 12 mm.

The superimposed data points in Figure 6-17, are tabulated in Table 6-5; in addition to the average moisture content (o.d. basis) and the corresponding *measured* value, the produced error *d*, defined as $M_m - \overline{MC}$ has also been tabulated.

Table 6-5 :Average moisture content (o.d. basis) MC, the corresponding measured value M_m (for $P_{1,2}$ to $P_{1,4}$) and the error in the measured value, d = $M_m - MC$, *for data presented in Figure 6-17*

Data point label	$\overline{MC}$ (%)	M_m (%)	*d* (%)
$P_{1,2}$	7.53	7.88	0.35
$P_{1,3}$	14.79	14.81	0.02
$P_{1,4}$	18.93	18.46	-0.47
$P_{1,5}$	19.97	19.9	-0.07

For the steep drying gradient, the produced worst case error for the pole combinations used was found to be ±0.35% MC, a strikingly good result. The decrease in the electric field strength for the steep drying gradient is considered to be partially compensated by the increase in the moisture content in the profile.

Generally, during the development of moisture gradients (e.g. section 1.7, page 20) the hygroscopic nature of timber causes gradients which are symmetrical about the centre of the sample; it is therefore considered that the multiple electrode arrangement is suitable for samples with thickness of around 20 mm.

6.5 *Discussion*

Dielectric-type moisture meters are frequently employed to measure moisture content. Precision measurements with a planar electrode system have shown that although the measured change in capacitance is a strong function of moisture content for *uniform* gradients, measurements on *systematic* gradients show effectively no correlation of *mean* moisture content with the dielectric parameters for modest depths, for the typical surface electrode (see Figure 6-7) used in dielectric moisture meters. The results show that caution must be taken in the use of dielectric-type moisture meters to avoid discrepancies between the measured and the mean moisture content (o.d. basis) [59][36]. This is especially the case as it is rare with dynamic environments to encounter zero moisture gradients.

Further, the results from the second part of the study show that a new multiple electrode arrangement can be used for unambiguous detection of two moisture gradients of regain and steep drying, to depths of about 10 mm [60]. The electrode system employed in the study utilizes a multi-electrode configuration in which several measurement points are considered for each measured value, enabling the measurement system to perform a more realistic and accurate scan of

[36] Following a presentation at National Physical Laboratory, discussions with various researchers revealed substantial support for cost effective techniques such as that employed in this study. It was also identified that such techniques could be developed for other application areas such as agriculture, where moisture content of various types of grain is of great interest.

the sample under test. This feature is considered to be a valuable element in the measurement system which provides improved insight into the distribution of moisture.

Although, a greater scanning depth is desirable, various studies carried out on the effects of drying stress and check development showed that the moisture gradient developed during the drying process (from the green state) concentrated in the outer 4 mm of the wood [see for example 61][37].

Typical commercial dielectric moisture meters currently in use are not only not capable of assessing moisture gradients (or even indicating them), but also depend only on just one pair of electrodes for their measurements and are therefore considered to be less reliable and accurate and could potentially indicate erroneous readings when subject to samples with moisture gradients. This was shown clearly in Chapter 5 and also in the first part of the study discussed in this chapter.

6.6 Further work

The measurement system employed during the moisture gradient study was intended as a prototype system, and as such can be improved for optimal response and variable depths into the sample. Although, the prototype system performed extremely well and reliably produced repeatable measurements, the results show

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[37] Confirmed by Dr G Hall, Technical Director at TRADA Technology Ltd.

that the response of the system may be limited by the moisture content of the sample under test as the control loop is essentially an open loop system (i.e. there is no feedback element). Modifications to the system could include the addition of a feedback path such that the voltage applied to the sample is proportional to the electrode separation. It is anticipated that a decrease in the average moisture content toward the core would then be counterbalanced by the higher applied voltage, creating a stronger electric field in the area of measurement.

As explained in section 6.3.2.3 (page 134), the measurement procedure utilised a sequence of measurements for which 2 of the 6 poles were employed at a time. This means that 4 electrodes were disconnected and 'redundant' during each measurement. Investigations into the effect of the redundant electrodes on the electric field could yield insight into further possible improvements in the electrode arrangement. This is discussed in [60].

6.7 Conclusion

Results from the moisture gradient study confirm the disruptive effects of moisture gradients on the correlation between capacitance/loss tangent and moisture content using typical surface electrode arrangements. Findings clearly indicate that in order to produce reliable moisture content measurements using dielectric-type moisture meters, an indication of the moisture profile in the sample is essential. The facility to indicate the existence of transverse moisture gradient is not currently available; this could at least partially explain lack of *reliability in -situ* use.

A new multiple electrode arrangement however can be used to detect moisture gradients easily to depths of 10 mm (approximate for timber). Repeatable results from measurements of capacitance using this electrode system show a consistent correlation between the measured capacitance and mean moisture content, under simulated moisture gradient conditions. This electrode system could be utilised in a handheld moisture meter, as a facility for indicating the existence of transverse moisture gradients, thus enabling the operator to take appropriate action.

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Appendix A

Spreadsheet containing demographic data for samples used in the EMC project discussed in Chapter 2.

Appendix B

Typical graphical data obtained from TinyTalk™ miniature data-loggers for monitoring temperature and relative humidity in the EMC project, discussed in Chapter 2.

Appendix C

List and details of the resistance type moisture meters used in the study discussed in Chapter 3.

Appendix D

The control software source code and diagrams

1 The main function
1.1 Peak detection algorithm : part 1
1.2 Peak detection algorithm : part 2
1.3 The Qfactor detection algoritm : part 1
1.4 The Qfactor detection algoritm : part 2
1.5 The Qfactor detection function
1.6 The D/A driver function
1.7 The A/D driver function
1.8 Data storage function
1.9 The histogram function
2 General purpose functions
2.1 The audio functions flow chart
2.1.1 The sound function source code
2.1.1.1 The bleep function source code
2.1.1.2 The beep function source code
2.2 The circuit response plot function
2.2.1 The EPSON LQ570+ printer driver function source code
2.3 The power supply function

Appendix E

SPICE simulation results for the measurement system used in Chapter 6.

Appendix F

Publications which include the author

Appendix A

Spreadsheet containing demographic data for samples used in the EMC project discussed in Chapter 2.

Batch number	Installation date	Location	Type of building	Class of purpose group	Approx number of persons using facility	Number of storeys	Description of environment	Level (floor)	Height above floor level (m)	Type of heating	Approx no of hours heating in winter (per day)	Air-conditioned	Approx age (at end of Sept 1995) (years)	Mean MC (%)	Lowest MC (%)	Highest MC (%)	Standard Deviation
1	24-Nov-93	Sundon Park	Office Block	3	15	1	Finance Office (1)	Ground	1.6	C/H	24	no	35	**9.3**	8.3	10.3	0.7
2	24-Nov-93	Sundon Park	Office Block	3	6	1	Finance Office (2)	Ground	1.6	C/H	24	no	35	**8.6**	7.7	9.5	0.6
3	24-Nov-93	Sundon Park	Office Block	3	0	1	Computer room (1)	Ground	1.2	Ducted Air	24	yes	35	**9.6**	8.3	10.0	0.3
4	24-Nov-93	Sundon Park	Office Block	3	0	1	Computer room (2)	Ground	1.2	Ducted Air	24	yes	35	**10.0**	9.0	10.9	0.4
5	24-Nov-93	Sundon Park	Industrial	6	4	1	Standards room (1)	Ground	1.2	Ducted Air	24	yes	45	**8.7**	6.8	10.8	0.7
6	24-Nov-93	Sundon Park	Industrial	6	4	1	Standards room (2)	Ground	2	Ducted Air	24	yes	45	**8.6**	7.2	9.8	0.7
7	24-Nov-93	Sundon Park	Industrial	6	10	2	Above offices	2nd	3	Ducted Air	24	no	45	**8.4**	6.7	10.0	1.0
8	24-Nov-93	Sundon Park	Industrial	6	8	1	Machine Shop	Ground	2.2	Ducted Air	24	no	45	**9.8**	8.6	11.7	0.9
9	24-Nov-93	Sundon Park	Industrial	6	30	1	Grinding Factory	Ground	2.1	Ducted Air	24	no	45	**9.0**	7.8	10.2	0.8
10	24-Nov-93	Sundon Park	Industrial	6	4	1	Measuring Room	Ground	2	Ducted Air	24	yes	45	**8.3**	6.8	9.9	1.1
11	24-Nov-93	Sundon Park	Industrial	6	1	2	Tool Store	2nd	2.2	Ducted Air	24	no	45	**7.8**	6.5	9.3	0.8

Batch number	Installation date	Location	Type of building	Class of purpose group	Approx number of persons using facility	Number of storeys	Description of environment	Level (floor)	Height above floor level (m)	Type of heating	Approx no of hours heating in winter (per day)	Air-conditioned	Approx age (at end of Sept 1995) (years)	Mean MC (%)	Lowest MC (%)	Highest MC (%)	Standard Deviation
12	24-Nov-93	Sundon Park	Industrial	6	2	2	Measuring Room	Ground	2.2	Ducted Air	24	yes	45	**8.3**	7.1	10.2	0.8
13	24-Nov-93	Sundon Park	Industrial	6	1	1	Heat Treatment room	Ground	1.3	Ducted Air	24	no	45	**8.5**	7.3	9.8	0.8
14	24-Nov-93	Sundon Park	Industrial	6	8	1	Workshop	Ground	2	Ducted Air	24	no	45	**9.3**	7.8	11.4	1.1
15	24-Nov-93	Sundon Park	Industrial	6	4	1	Engineers Office	1st	3.2	C/H	24	no	45	**9.0**	7.4	10.4	0.9
16	24-Nov-93	Sundon Park	Industrial	6	6	2	Design Offices	1st	2	C/H	24	no	45	**8.2**	6.9	9.4	0.7
17	09-Dec-93	Luton	2-bedroom semi-bungalow	1(c)	2	1	Kitchen	Ground	2.5	Gas C/H	10	no	45	**10.4**	9.5	11.4	0.5
18	24-Nov-93	Dunstable	3-bedroom det	1(c)	2	3	Bedroom	1st	1.8	Gas C/H	24	no	120	**11.4**	10.5	12.9	0.7
19	10-Jan-94	Luton	University Block	5	1	4	Office (control batch)	2	1.8	Gas C/H	10	no	40	**9.8**	9.5	11.2	0.2
20	10-Jan-94	Studham	4-bedroom det	1(c)	5	2	Master Bedroom	1st	2	Oil C/H	7.5	no	57	**11.2**	10.2	12.4	0.8
21	09-Dec-93	Stevenage	3-bedroom det	1(c)	5	2	Lounge	Ground	1.5	Gas C/H	8	no	32	**11.2**	10.1	12.6	0.7
23	04-Feb-94	Harlington	Swimming pool	5	N/A	1	Pool area	Ground	1.8	From Pool (33°C)	24	no	6	**12.5**	11.1	15.1	1.0

Batch number	Installation date	Location	Type of building	Class of purpose group	Approx number of persons using facility	Number of storeys	Description of environment	Level (floor)	Height above floor level (m)	Type of heating	Approx no of hours heating in winter (per day)	Air-conditioned	Approx age (at end of Sept 1995) (years)	Mean MC (%)	Lowest MC (%)	Highest MC (%)	Standard Deviation
24	02-Feb-94	Harlington	2-bedroom semi	1(c)	2	2	Conservatory	Ground	2	none	0	no	7	**12.8**	9.9	15.3	2.0
25	24-Jan-94	Luton	3-bedroom det	1(c)	2	2	Kitchen	Ground	2.2	Gas C/H	6	no	10	**10.5**	9.1	11.6	0.8
27	24-Jan-94	St Albans	3-bedroom terraced	1(c)	2	2	Bedroom	1st	1	Gas C/H	6	no	100	**10.0**	9.0	11.9	0.9
28	24-Jan-94	Luton	Flat	1(a)	1	1	Kitchen	Ground	2	Storage	24	no	1	**11.9**	9.8	13.2	1.1
29[a]	04-Feb-94	Dunstable	Church	5	10	2	Worship Centre	1st	2.5	Gas central	7	No	21	**14.0**	13.0	14.8	0.7
30	25-Jan-94	Dunstable	3-bedroom semi	1(c)	3	2	Master bedroom	1st	2	Gas C/H	18	no	31	**10.7**	9.5	12.0	0.8
31[b]	26-Jan-94	Milton Keynes	3-bedroom det	1(b)	2	3	Study	2nd	2	Gas C/H	18	no	6	**9.4**	8.4	11.2	0.7
32	26-Jan-94	Irthlingborough	4-bedroom det	1(c)	2	2	Bedroom	1st	1	Gas C/H	12	no	8	**10.9**	9.6	11.7	0.5
33	26-Jan-94	Buntingford	19th Cent Timber Frame	1(b)	3	3	Lounge	Ground	2.2	Storage	24	no	165	**9.7**	7.9	13.0	1.5
34	04-Feb-94	Luton	University Block	5	1	4	Office	2nd	2.2	Gas C/H	12	no	2	**7.8**	6.4	9.1	0.9
35[c]	19-Jan-94	Luton	Underground Car Park	7(b)	N/A	3	Car park	Ground	2	Warm Air	6	no	7	**8.1**	6.9	9.1	0.6

Batch number	Installation date	Location	Type of building	Class of purpose group	Approx number of persons using facility	Number of storeys	Description of environment	Level (floor)	Height above floor level (m)	Type of heating	Approx no of hours heating in winter (per day)	Air-conditioned	Approx age (at end of Sept 1995) (years)	Mean MC (%)	Lowest MC (%)	Highest MC (%)	Standard Deviation
36[d]	19-Jan-94	Luton	Research Facility	6	1	3	Building Services Lab	Ground	2	None (Test conds)	24	yes	7	**9.6**	8.8	10.7	0.4
37	19-Jan-94	Luton	Research Facility	6	4	3	Analytical Services Lab	1st	2	convection heating	24	yes	7	**7.9**	6.9	8.9	0.5
38	19-Jan-94	Luton	Research Facility	6	2	3	Food Science Office	1st	2.2	convection heating	24	yes	7	**7.9**	6.8	9.3	0.8
39	19-Jan-94	Luton	Research Facility	6	1	3	Food Science Kitchen	1st	1.2	convection heating	24	no	7	**10.9**	8.6	12.6	1.3
40	19-Jan-94	Luton	Research Facility	6	4	3	Brewery	Ground	4	Warm Air	24	no	7	**8.7**	7.1	11.5	1.2
41	19-Jan-94	Luton	Research Facility	6	2	3	Dispense Workshop	2nd	2.2	Warm Air	24	yes	7	**8.4**	7.1	9.7	0.8
42	19-Jan-94	Luton	Research Facility	6	1	3	Demo Bar	2nd	3	Warm Air	24	yes	7	**8.6**	6.4	11.1	1.6
43	19-Jan-94	Luton	Research Facility	6	4	3	Gas Chromatography Lab	2nd	2	Warm Air	24	yes	7	**7.4**	6.7	8.3	0.5
44	19-Jan-94	Luton	Research Facility	6	2	3	CAD Room	2nd	2.2	Warm Air	24	yes	7	**7.6**	6.4	8.8	0.9
45	19-Jan-94	Luton	Research Facility	6	10	3	Retail Property Office	2nd	2	convection heating	24	no	7	**7.2**	5.9	9.0	1.0

Batch number	Installation date	Location	Type of building	Class of purpose group	Approx number of persons using facility	Number of storeys	Description of environment	Level (floor)	Height above floor level (m)	Type of heating	Approx no of hours heating in winter (per day)	Air-conditioned	Approx age (at end of Sept 1995) (years)	Mean MC (%)	Lowest MC (%)	Highest MC (%)	Standard Deviation
46[e]	17-Feb-94	Brighton	Research Lab	6	0	1	Jungle box	Ground	1.5	N/A	N/A	yes	8	**11.3**	7.8	12.1	2.0
47	17-Feb-94	Cheam	3-bedroom det	1(c)	2	2	Lounge	Ground	2	Gas C/H & Gas fire	5	no	35	**10.9**	9.7	12.0	0.7
48	17-Feb-94	Brighton	University Block	5	3	4	Office	1st	2	Ceiling	10	no	30	**9.2**	8.4	11.8	0.7
49	17-Feb-94	Brighton	University Block	5	1	4	Office	1st	1	Ceiling	10	no	30	**9.8**	8.7	12.0	0.8
51	17-Feb-94	Brighton	University Block	5	30	4	Library	1st	2	Ceiling	10	no	30	**6.3**	5.3	9.0	0.6
52	17-Feb-94	Brighton	Public House	4	50	2	Bar	Ground	2	Gas C/H	N/A	no	50	**10.0**	9.2	13.0	0.7
53	17-Feb-94	Brighton	Church	5	70	1	Church	Ground	1.5	Gas air	N/A	no	6	**10.9**	10.0	11.9	0.7
55	18-Apr-94	Luton	University Block	5	1	4	Office	2nd	1.5	Gas C/H	14	no	40	**8.6**	6.9	10.6	1.1
56	18-Apr-94	Luton	University Block	5	1	4	Office (control batch)	2nd	1.5	Gas C/H	14	no	40	**9.0**	8.7	9.3	0.2
57	18-Apr-94	Luton	Flat	1(a)	1	5	Lounge	2nd	2	Storage	24	no	23	**11.3**	8.9	12.6	0.9

Batch number	Installation date	Location	Type of building	Class of purpose group	Approx number of persons using facility	Number of storeys	Description of environment	Level (floor)	Height above floor level (m)	Type of heating	Approx no of hours heating in winter (per day)	Air-conditioned	Approx age (at end of Sept 1995) (years)	Mean MC (%)	Lowest MC (%)	Highest MC (%)	Standard Deviation
58	18-Apr-94	Luton	Flat	1(a)	1	5	Bedroom	2nd	1.2	Storage	0	no	23	**12.0**	9.5	13.0	0.9
59	20-Apr-94	Houghton Regis	4-bedroom det	1(c)	3	2	Study	1st	1.5	Gas C/H	8	no	20	**9.8**	9.0	10.6	0.5
60	19-Apr-94	Harpenden	4-bedroom det	1(c)	2	2	Studio	Ground	2	Gas C/H	0	no	18	**11.9**	9.7	13.1	0.7
61	18-Apr-94	Harlington	3-bedroom det	1(c)	3	2	Bedroom	1st	2	Gas C/H	10	no	30	**11.2**	9.2	13.1	1.1
62	21-Apr-94	Bedford	3-bedroom semi	1(c)	2	2	Lounge	Ground	2	Gas C/H	8	no	30	**9.1**	8.1	10.3	0.7
63	19-Apr-94	Luton	6-bedroom det	1(b)	3	3	Lounge	Ground	2	Gas C/H	8	no	22	**10.8**	9.1	11.4	0.4
64	21-Apr-94	Cambridge	4-bedroom det	1(b)	4	3	Lounge	Ground	1.8	Gas C/H	8	no	100	**10.8**	9.8	11.2	0.4
65	18-Apr-94	Luton	University Block	5	0	4	Store room	2nd	2.3	Gas C/H	14	no	40	**9.0**	8.1	10.0	0.5
66	19-Apr-94	Luton	University Block	5	4	4	Kitchen	Ground	2.2	From ovens	8	no	2	**10.2**	9.2	11.7	0.8
67	19-Apr-94	Luton	University Block	5	8	4	Kitchen	Ground	2.2	From ovens	8	no	40	**9.2**	7.3	11.6	1.1
68	21-Apr-94	Luton	University Block	5	10	1	Repro graphics	Ground	3	Fan heaters	10	no	30	**7.9**	6.4	9.8	1.0

Batch number	Installation date	Location	Type of building	Class of purpose group	Approx number of persons using facility	Number of storeys	Description of environment	Level (floor)	Height above floor level (m)	Type of heating	Approx no of hours heating in winter (per day)	Air-conditioned	Approx age (at end of Sept 1995) (years)	Mean MC (%)	Lowest MC (%)	Highest MC (%)	Standard Deviation
69	26-May-94	Luton	2-bedroom terraced	1(c)	1	2	Dining Room	Ground	2	Gas fire	24	no	85	**11.5**	9.4	12.5	0.5
70	21-Apr-94	Luton	University Block	5	1	4	Office	2nd	1.8	Gas C/H	10	no	40	**9.1**	7.8	10.4	0.7
71	22-Apr-94	Luton	Research centre	5	1	2	Entrance hall	Ground	1.8	Gas C/H	12	no	130	**8.8**	7.6	10.3	0.8
72	22-Apr-94	Luton	Research centre	5	1	2	D&T Workroom	1st	1.2	Gas C/H	12	no	130	**10.2**	8.6	11.2	0.8
73	22-Apr-94	Luton	Research centre	5	2	2	Healthcare room	1st	2	Gas C/H	12	no	130	**10.3**	9.0	11.4	0.7
74	22-Apr-94	Luton	Research centre	5	2	2	Office	Ground	2.2	Gas C/H	12	no	130	**9.5**	8.6	10.4	0.6
75	22-Apr-94	Luton	Research centre	5	2	2	Computing Room	Ground	0.4	Gas C/H	12	no	130	**9.6**	8.6	11.1	0.7
76	22-Apr-94	Luton	Research centre	5	1	2	Office	1st	1.8	Gas C/H	12	no	130	**10.3**	8.9	11.6	0.7
77	22-Apr-94	Luton	Research centre	5	1	2	Ecotoxicology Lab	Ground	2	Gas C/H	12	no	130	**8.8**	7.6	10.0	0.6
78	22-Apr-94	Luton	Research centre	5	0	2	Basement	Below Ground	2	Gas C/H	12	no	130	**8.7**	7.5	11.4	1.0
79[f]	23-Apr-94	Stevenage	Garage	1(c)	0	1	Garage	Ground	2	None	0	no	32	**15.7**	9.3	20.0	3.0

Batch number	Installation date	Location	Type of building	Class of purpose group	Approx number of persons using facility	Number of storeys	Description of environment	Level (floor)	Height above floor level (m)	Type of heating	Approx no of hours heating in winter (per day)	Air-conditioned	Approx age (at end of Sept 1995) (years)	Mean MC (%)	Lowest MC (%)	Highest MC (%)	Standard Deviation
80	23-Apr-94	Stevenage	3-bedroom det	1(c)	5	2	Bedroom	1st	2	Gas C/H	8	no	32	**11.3**	9.0	12.4	0.7
81	27-May-94	Stevenage	School	5	3	2	Office	Ground	1.5	Gas C/H	9	no	35	**9.6**	8.3	10.9	0.8
82	18-Jul-94	Milton Keynes	Garage	1(c)	N/A	1	Garage	Ground	3	N/A	N/A	no	6	**14.1**	9.4	17.6	2.6
83[g]	08-Jun-94	Stevenage	Home for old people	2(a)	0	2	Storage space	1st	1	Gas C/H	24	no	30	**4.0**	3.2	9.8	0.7
84	08-Jun-94	Stevenage	Home for the handicapped	2(a)	1	1	Guest Room	Ground	1	Gas C/H	24	no	35	**11.3**	9.4	12.4	1.2
85	27-May-94	Stevenage	School	5	30	2	Classroom	1st	1.5	Hot Air	9	no	35	**10.8**	9.2	12.6	1.0
88	10-May-94	Luton	University Block	5	50	1	Library	Ground	2.5	Gas C/H	16	no	3	**8.0**	6.8	9.4	0.8
89	27-May-94	Stevenage	School	5	3	1	Office	Ground	1	Gas C/H	9	no	35	**10.0**	8.7	11.5	1.0
90	08-Jun-94	Stevenage	Home for old people	2(a)	6	2	Guest Room	Ground	1.5	Gas C/H	12	no	30	**9.8**	9.4	10.3	0.3
92	08-Jun-94	Stevenage	Home for the handicapped	2(a)	4	1	Bedroom	Ground	1.5	Gas C/H	24	no	35	**10.9**	8.9	11.7	0.6
94	15-Jun-94	Stevenage	Hospital	2(a)	1	10	Endoscopy	10	1.5	Gas C/H	24	no	24	**7.8**	6.3	10.3	1.0

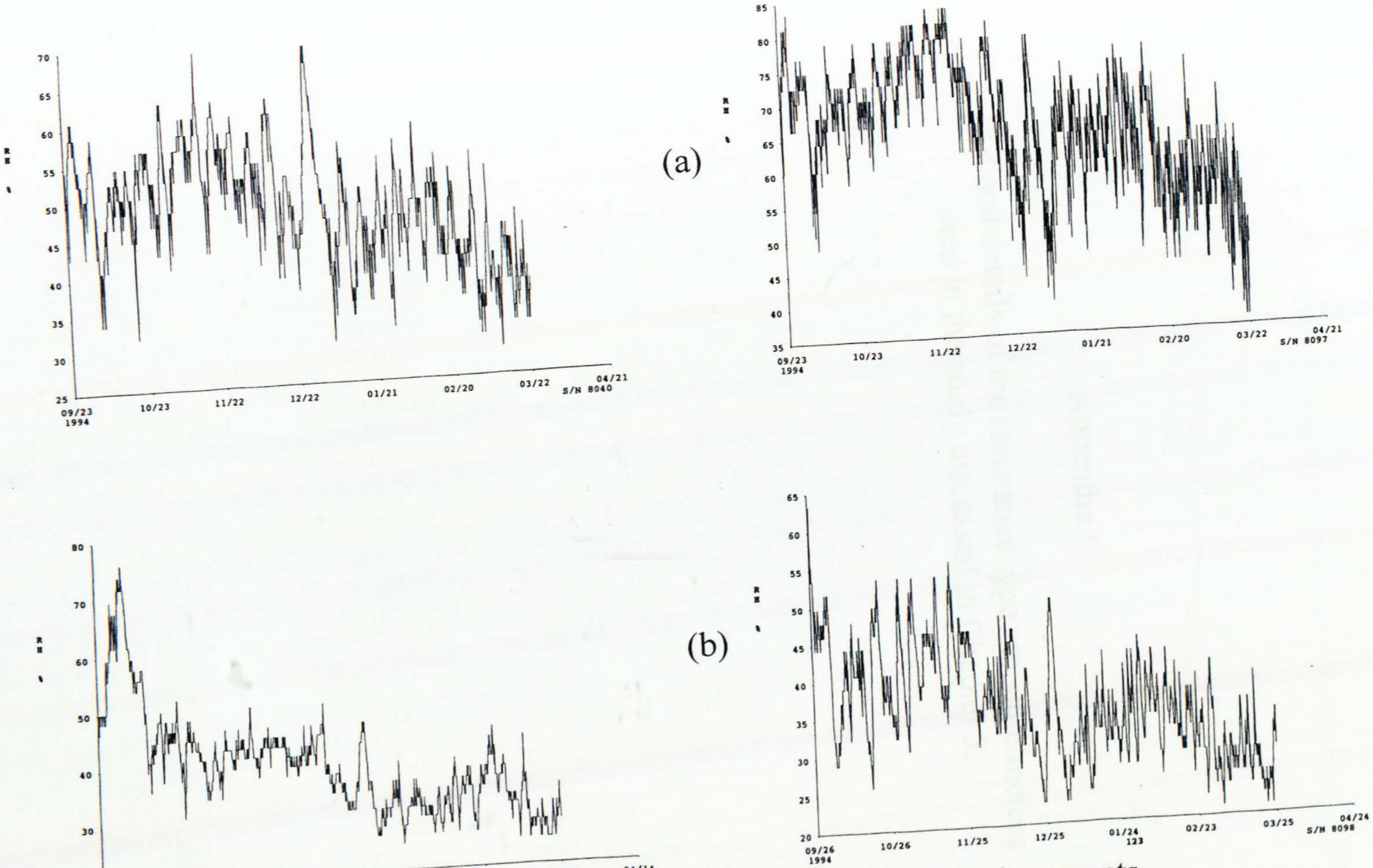
Batch number	Installation date	Location	Type of building	Class of purpose group	Approx number of persons using facility	Number of storeys	Description of environment	Level (floor)	Height above floor level (m)	Type of heating	Approx no of hours heating in winter (per day)	Air-conditioned	Approx age (at end of Sept 1995) (years)	Mean MC (%)	Lowest MC (%)	Highest MC (%)	Standard Deviation
95	15-Jun-94	Stevenage	Hospital	2(a)	20	10	Ward 8B South	8	1.5	Gas C/H & Hot Air	24	no	24	**7.7**	6.4	9.4	0.8
97	15-Jun-94	Stevenage	Hospital	2(a)	20	10	Ward 5B South	5	1.5	Gas C/H & Hot Air	24	no	24	**8.3**	7.8	10.7	0.8
98	15-Jun-94	Stevenage	Hospital	2(a)	1	10	Utility room	Ground	1.5	Hot Air	24	no	24	**8.4**	7.4	9.4	0.6
100	06-May-94	Luton	University Block	4	10	4	Bookshop	Ground	1.4	Portable heaters	10	no	40	**10.0**	8.4	10.9	0.7
101	09-May-94	Luton	Educational	5	3	1	Plaster Workshop	Ground	3	Gas C/H	8	no	120	**10.7**	9.9	11.5	0.4
102	09-May-94	Luton	Educational	5	3	1	Plaster Workshop	Ground	3	Gas C/H	8	no	120	**10.4**	9.2	11.4	0.5
104	10-May-94	London E4	Hairdressers	4	2	2	Shop	Ground	1.5	Gas C/H	4	no	80	**11.3**	9.0	12.7	1.1
109	08-Jun-94	Stevenage	Home for old people	2(a)	3	2	Common Room	Ground	2	Gas C/H	24	no	30	**7.9**	6.7	9.6	0.5
113	30-Jun-94	Stevenage	Video shop	4	2	2	Shop	Ground	2	Convectio n heaters	12	no	30	**8.9**	8.0	10.1	0.7
114	30-Jun-94	Stevenage	Chemist Shop	4	2	2	Shop	Ground	3	Convectio n heaters	0	no	40	**12.6**	9.2	15.2	1.7
115	30-Jun-94	Stevenage	Bakers shop	4	2	3	Shop	Ground	2.5	Hot Air	10	no	50	**10.0**	9.6	10.7	0.4

Batch number	Installation date	Location	Type of building	Class of purpose group	Approx number of persons using facility	Number of storeys	Description of environment	Level (floor)	Height above floor level (m)	Type of heating	Approx no of hours heating in winter (per day)	Air-conditioned	Approx age (at end of Sept 1995) (years)	Mean MC (%)	Lowest MC (%)	Highest MC (%)	Standard Deviation
118	01-Jul-94	Stevenage	Co-op Supermarket	4	4	3	Store	Ground	2	N/A	N/A	no	20	**10.3**	8.8	11.9	1.0

a Heating on certain days of the week only
b Energy efficient house. Built well beyond the demands of current Building Regulations
c Warm air discharged into underground car park from building
d Environmental parameters varied according to test being carried out in the laboratory
e Relative humidity and temperature varied on a regular basis
f Damp environment due to lack of damp proof membrane within walls below ground level
g Constantly heated enclosed environment

Appendix B

Typical graphical data obtained from TinyTalk™ miniature data-loggers for monitoring temperature and relative humidity in the EMC project, discussed in Chapter 2.



Tinytalk data from typical (a) domestic and (b) office-type environments

Appendix C

List and details of the resistance type moisture meters used in the study discussed in Chapter 3.

Table c1: lists the details of the nine resistance type moisture meters used in the study fully discussed in Chapter 3..

Table c1: Details of the moisture meters used in the moisture meter comparison study of Chapter 3.

Model[1]	**Manufacturer**	**Technology**
Timbermaster	Protimeter	Analogue
Timbermaster	Protimeter	Digital
FMD	Brookhius	Digital
HM T	Aquaboy	Analogue
HT 60	Lignometer	Digital
J3	Delmhurst Instrument CO.	Analogue
R 2000	Delmhurst Instrument CO.	digital
HT 85	Gann	Analogue
HT 85 T	Gann	Digital

[1] There is no correlation between the order used in Table c1 and the labelling used in the body of the thesis.

Appendix D

The control software source code and diagrams

1 The main function

```
/*
Function name: main: serves as the top level of the hierarchy in the design; a state machine
which controls the flow of data and control parameters, and sequences the events.

Arguments type: void

Returned value type: void

Functions called:      find_peak, find_Qfactor, save_data, get_graph, sound
*/

#include"header.h"

#define BLEEP 1
#define BEEP 2

float find_peak(int*, int*, unsigned*,int ,unsigned, float*); // finds max voltage at resonance.
float find_Qfactor(unsigned, float, int*, int*, float*); // finds vcap corresponding to 0.707*vpeak
fpos_t save_data(float,float,float,float,float,float,float,float,unsigned char,char *);
void get_graph();
void sounds(int);

void main()
{
    float vcap1=0.0,vpeak1=0.0,vcap2=0.0,vpeak2=0.0,qfactor1=0.0,qfactor2=0.0;
    float vcap=0.0, peakvoltage=0.0, vatq=0.0,vq1=0.0,vq2=0.0;
    static unsigned d2a_atpeak=0;
    unsigned char a2d_channel='1'; // pin 23;
    int ch=0, measure=0;

    // define state machine
    enum states {TUNE, DETECTQ, SAVEDATA, NEXT, STOP, COMMAND};
    // state variable
    states state=TUNE;
    // file postion indicating the start of data
    fpos_t datastart;
    static char file_name[13];
    int keypressed=0, comm=0;

    clrscr();
    printf("save to file: ");
    scanf("%s",file_name);
    printf("Disconnect the sample and press return");
    getch();
    clrscr();
```

```
while(state!=STOP)
{
    switch(state)
    {
        case TUNE:
            vcap=find_peak(&comm,&keypressed,&d2a_atpeak,measure,
                                                    d2a_atpeak,&peakvoltage);
            if(keypressed)
                state=COMMAND;
            else
                state=DETECTQ;
            break;

        case DETECTQ:
            clrscr();
            if(measure==0)      // if sample not connected
            {
                vpeak1=peakvoltage;
                vcap1=vcap;
                qfactor1=find_Qfactor(d2a_atpeak,vpeak1,&comm,&keypressed,&vatq);
                vq1=vatq; // voltage at Q_factor1

                if(keypressed)
                {
                    keypressed=0;
                    state=COMMAND;
                    break;
                }
                sounds(BEEP);
                window(1,1,80,25);
                clrscr();
                printf("Put the sample in place and press return\n\n");
                getch();
                measure=1;
                state=TUNE;
                break;
            }
            if(measure==1)                  // if sample connected
            {
                vpeak2=peakvoltage;
                vcap2=vcap;
                qfactor2=find_Qfactor(d2a_atpeak,vpeak2,&comm,&keypressed,&vatq);
                vq2=vatq;  //volatage at Q_factor2

                if(keypressed)
                {
                    keypressed=0;
                    state=COMMAND;
                    break;
                }
                measure=0;
                state=SAVEDATA;
                break;
            }
```

```
case SAVEDATA:
    if(kbhit()) // chech for request from user
    {
        comm=getch();
        printf("Data for this round was not saved, press return to continue\n");
        getch();
        state=COMMAND;
        break;
    }
    datastart=save_data(vcap1,vpeak1,vq1,qfactor1,vcap2,vpeak2,vq2,qfactor2,
                                        a2d_channel,file_name);
    window(1,1,80,25);
    clrscr();
    printf("Vpeak1=%.4f at Vcap1=%.4f\tVpeak2=%.4f at Vcap2=%.4f\n"
           "qf1=%.4f at Vq1=%.4f\tqf2=%.4f atVq2=%.4f\n",
                vpeak1,vcap1,vpeak2,vcap2,qfactor1,vq1,qfactor2,vq2);
    state=NEXT;
    break;

case NEXT:
    sounds(BLEEP);
    printf("Press ""Q"" or ""q"" to quit"
    " or any other key to continue\n\n");
    ch=getch();
    window(1,1,80,25);
    clrscr();

    if(ch=='Q'||ch=='q')
    {
        state=STOP;
        break;
    }
    else
    {
        sounds(BLEEP);
        window(1,1,80,25);
        clrscr();
        printf("Disconnect the sample and press return");
        getch();
        window(1,1,80,25);
        clrscr();
        state=TUNE;
        break;
    }
```

```
            case COMMAND:
                switch(comm)
                    {
                        case 'Q':
                        case 'q':
                            window(1,1,80,25);
                            clrscr();
                            printf("Press return to QUIT\n");
                            getch();
                            clrscr();
                            state=STOP;
                            comm=0;
                            break;

                        case 'R':
                        case 'r':
                            window(1,1,80,25);
                            clrscr();
                            printf("Press enter to RESET\n");
                            getch();
                            clrscr();
                            state=TUNE;
                            comm=0;
                            break;

                        case 'G':
                        case 'g':
                            get_graph();
                            state=TUNE;
                            comm=0;
                            break;

                        default :
                                comm=0;
                                break;
                    }
                break;

            case STOP:
                window(1,1,80,25);
                clrscr();
                printf("This state ""STOP"" is unreachable !\n");
                break;

            default:
                exit(0);
                break;
        }
    }
}
```

1.1 Peak detection algorithm : part 1

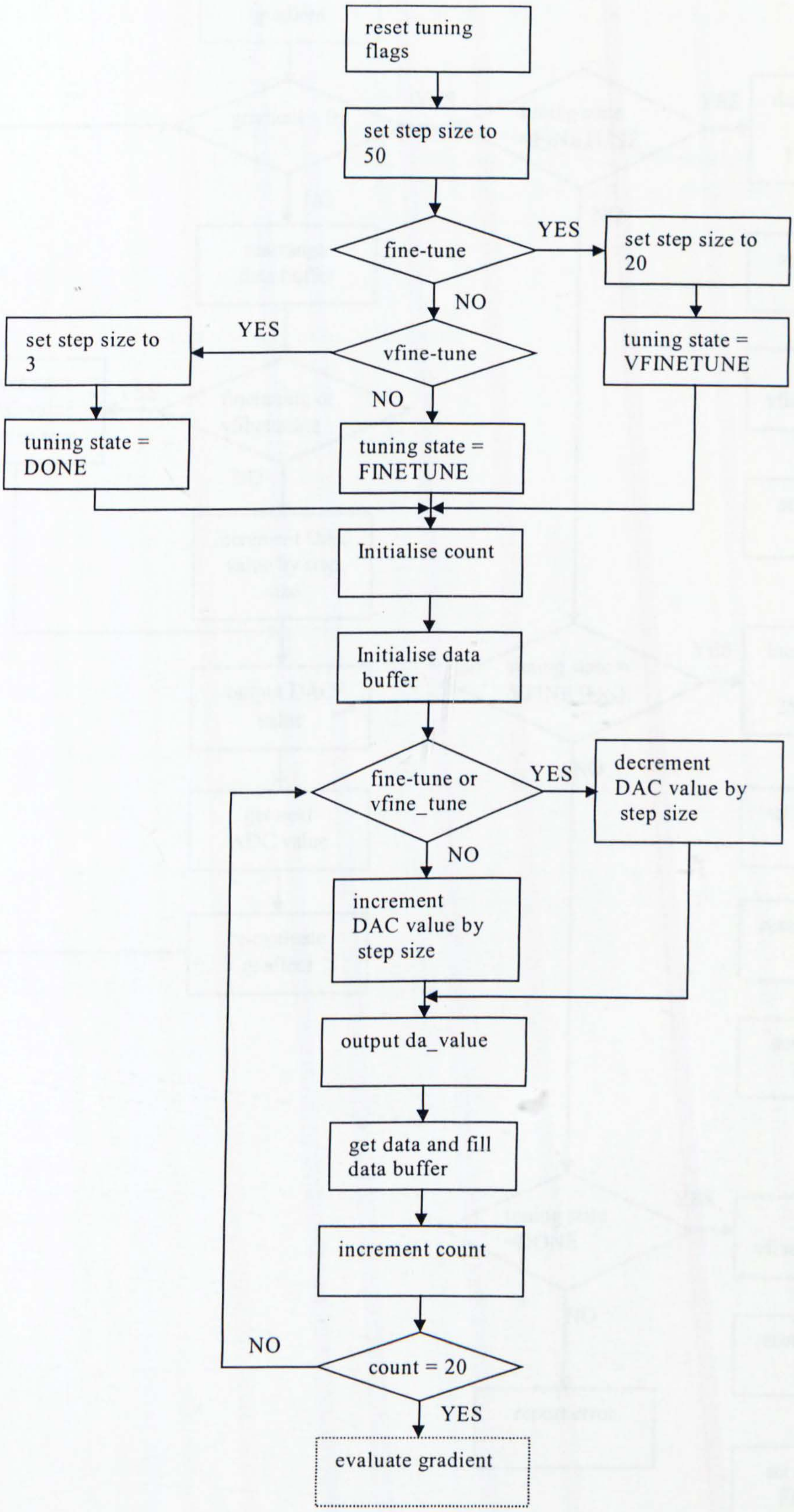


Figure D1: Peak detection algorithm: Data collection and stepwise refinement of increments in the applied DAC value (as discussed in detail in Chapter 6)

1.2 Peak detection algorithm : part 2

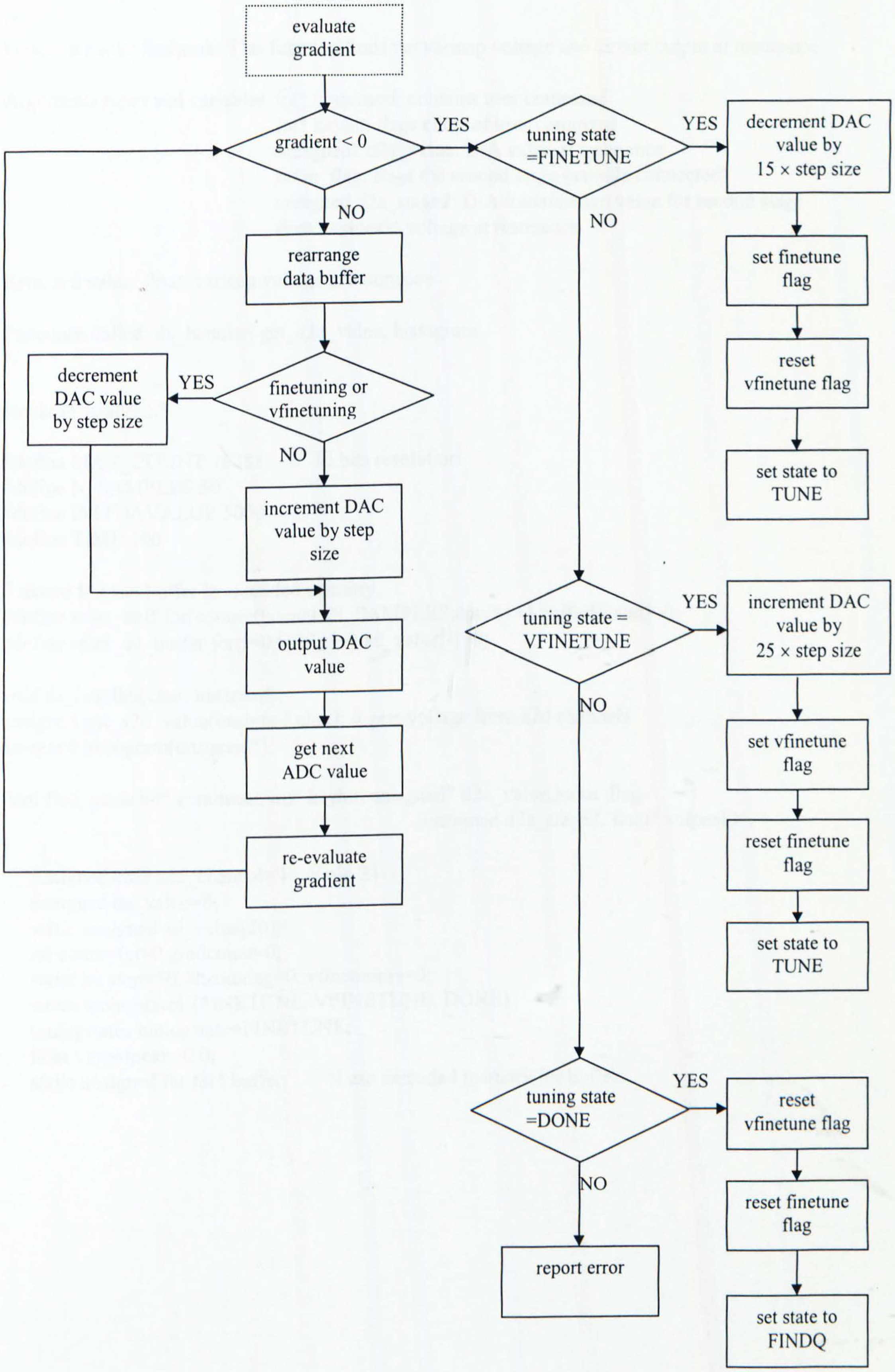


Figure D2:Peak detection algorithm: Gradient detection and control of the tuning state variable

The peak detection function

```
/*
Function name: findpeak: This function finds the varicap voltage and circuit output at resonance

Arguments types and variables: int* command: contains user command
                               int* keyhit: flags entry of user command
                               unsigned* d2a_value: D/A value at resonance
                               int m_flag: flags the second stage (sample connected)
                               unsigned d2a_stage2: D/A initialisation value for second stage
                               float* vatpeak: voltage at resonance

Returned value: float: varicap voltage at resonance

Functions called: da_handler, get_a2d_value, histogram
*/

#include"header.h"

#define MAX_COUNT 16383    // 14 bits resolution
#define N_SAMPLES 50
#define INITDAVALUE 5000
#define TIME 100

// macro to reset buffer in extended memory
#define reset_buff for(count=0;count<N_SAMPLES;count++) buffer[count]=0;
#define reset_ad_buffer for(i=0;i<20;i++) ad_value[i]=0;

void da_handler(char, unsigned);
unsigned get_a2d_value(unsigned char); // gets voltage from a2d channels
unsigned histogram(unsigned*);

float find_peak(int* command, int* keyhit, unsigned* d2a_value,int m_flag,
                                        unsigned d2a_stage2, float* vatpeak)
{
    unsigned char a2d_channel='1'; // pin 23
    unsigned da_value=0;
    static unsigned ad_value[20];
    int count=0,i=0,gradcount=0;
    static int step=50, finetuning=0, vfinetuning=0;
    enum tuningstates {FINETUNE, VFINETUNE, DONE};
    tuningstates tuningstate=FINETUNE;
    float vcapatpeak=0.0;
    static unsigned far far* buffer;       // use extended memory for buffer
```

```
if(!m_flag) // if sample not connected
    da_value=INITDAVALUE;          // initialise da
else
    da_value=d2a_stage2; // if sample connected

if (!(buffer = new unsigned[N_SAMPLES])) // allocate memory block to buffer
    {
        printf("Insufficient memory for buffer");
        exit (1);
    }
reset_buff; //macro for resetting the buffer
reset_ad_buffer;
clrscr();

do
{
    if(finetuning)
    {
        step=20;
        puts("finetuning ...");
        tuningstate=VFINETUNE;
    }
    else
        if(vfinetuning)
        {
            step=3;
            puts("extra fine tuninig ...");
            tuningstate=DONE;
        }
        else
            if(!finetuning&&!vfinetuning)
            {
                puts("State=TUNE");
                tuningstate=FINETUNE;
            }
```

```
for(i=0;i<20;i++)
{
    if(kbhit())
    {
        *command=getch();
        *keyhit=1;
        return(0);
    }
    if(finetuning||vfinetuning)
        da_value-=step;
    else
        da_value+=step;
    da_handler('2', da_value);
    delay(TIME);
    reset_buff;
    for(count=0;count<N_SAMPLES;count++)
    {
        buffer[count]=get_a2d_value(a2d_channel);
        //  printf("%d\t",buffer[count]);
    }
    ad_value[i]=histogram(buffer);
    clrscr();
    window(30,1,80,5);
    printf("%d",ad_value[i]);
}
gradcount=0;
for(i=1;i<20;i++)
    if(ad_value[0]>ad_value[i]) //if -ve gradient
        gradcount++;
```

```
while(gradcount<19)
{
    if(kbhit())
    {
        *command=getch();
        *keyhit=1;
        return(0);
    }
    for(i=0;i<19;i++)              //then rearrange data
        ad_value[i]=ad_value[i+1]; // for next comparison
    ad_value[19]=0;

    if(finetuning||vfinetuning)
        da_value-=step;
    else
        da_value+=step;

    window(30,1,40,10);
    da_handler('2', da_value);
    delay(TIME);
    clrscr();
    reset_buff;
    for(count=0;count<N_SAMPLES;count++)
        buffer[count]=get_a2d_value(a2d_channel);

    ad_value[19]=histogram(buffer);
        printf("%d",ad_value[19]);

    gradcount=0;
    for(i=1;i<20;i++)              // recalculate gradient
        if(ad_value[0]>ad_value[i]) //if -ve gradient
            gradcount++;
}
```

```
    switch(tuningstate)
    {
        case FINETUNE:
            da_value=da_value-15*step;
            finetuning=1;
            vfinetuning=0;
            window(1,1,80,25);
            clrscr();
            break;

        case VFINETUNE:
            da_value=da_value+25*step;
            vfinetuning=1;
            finetuning=0;
            window(1,1,80,25);
            clrscr();
            break;

        case DONE:
            finetuning=0;
            vfinetuning=0;
            break;

        default:
            exit(1);
            break;
    }
  }while(tuningstate!=DONE);

  *vatpeak=(float)ad_value[0]*10000/MAX_COUNT;
  *vatpeak=(float)ceil((double)*vatpeak)/1000;

  da_value=da_value+19*step; //find vcap at peak
  *d2a_value=da_value;
  vcapatpeak=(float)da_value*10000/MAX_COUNT; //round up to 3rd dp.
  vcapatpeak=(float)ceil((double)vcapatpeak)/1000;

  delete[] buffer;
  da_handler('2', da_value);        // set D/A to resonance voltage
  delay(TIME);
  return(vcapatpeak);
}
```

1.3 The Qfactor detection algoritm : part 1

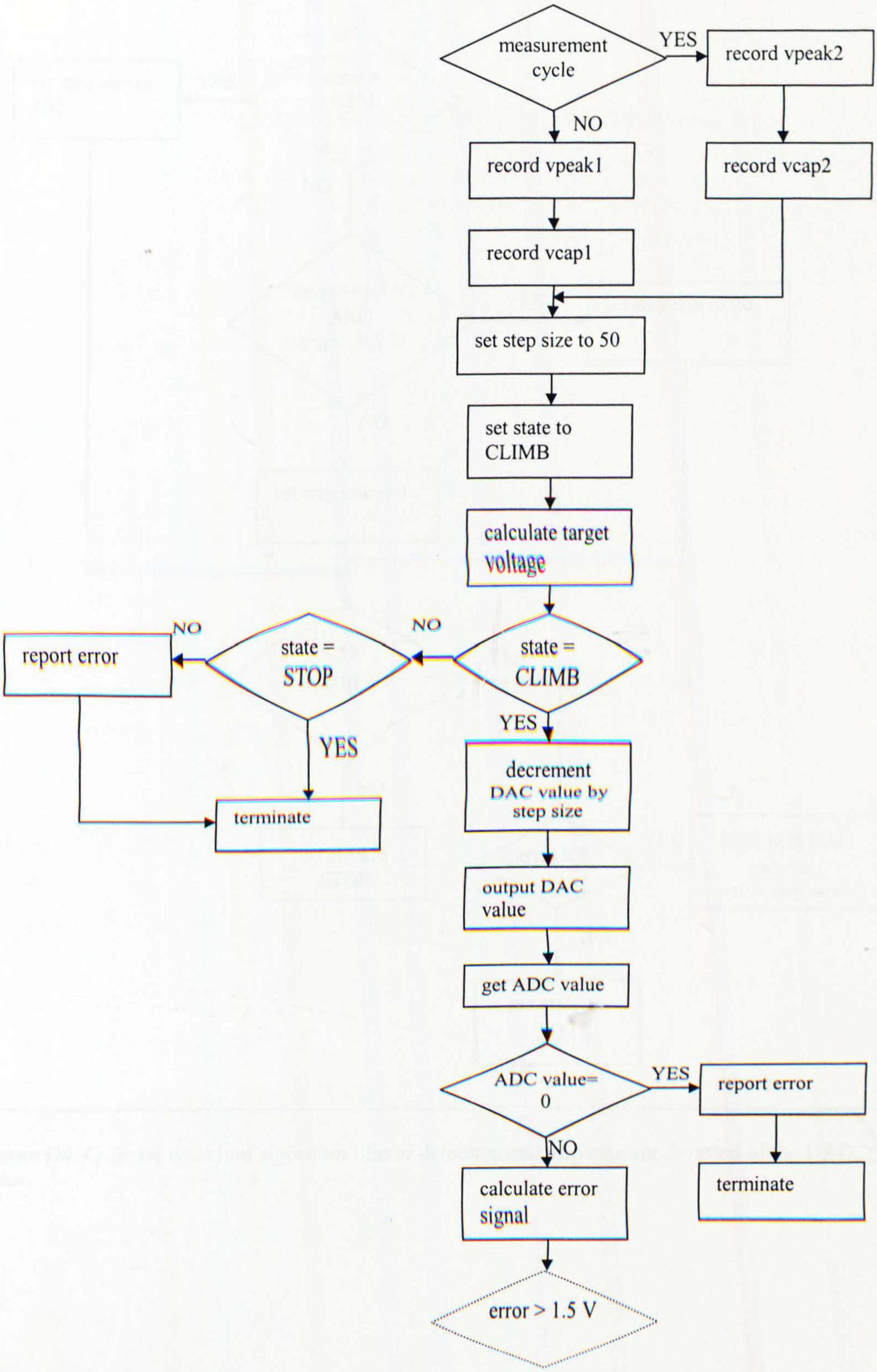


Figure D3: Q-factor detection algorithm : stepwise refinement of DAC output, and search for the half-power point (as discussed in detail in Chapter 6)

1.4 The Qfactor detection algoritm : part 2

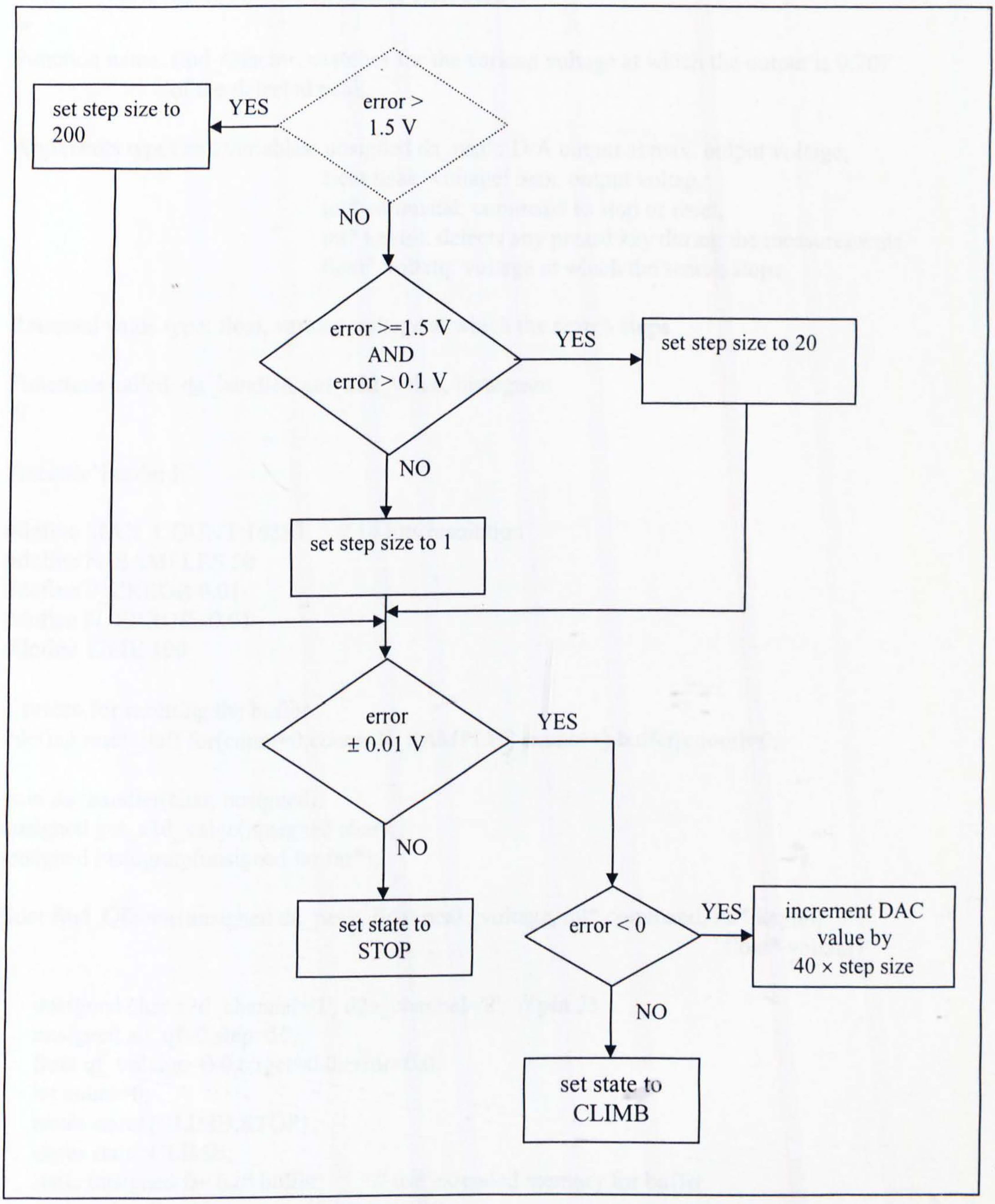


Figure D4: Q-factor detection algorithm : Error detection and stepwise acceleration of the DAC value.

1.5 The Qfactor detection function

```
/*
Function name: find_Qfactor, searches for the varicap voltage at which the output is 0.707
        of the detected peak.

Arguments types and variables: unsigned da_peak: D/A output at max. output voltage,
                               float peak_voltage: max. output voltag,
                               int* command: command to stop or reset,
                               int* keyhit: detects any pressd key during the measurements,
                               float* voltatq: voltage at which the search stops

Returned value type: float, varicap voltage at which the search stops

Functions called: da_handler, get_a2d_value, histogram
*/

#include"header.h"

#define MAX_COUNT 16383    // 14 bits resolution
#define N_SAMPLES 50
#define P_ERROR 0.01
#define N_ERROR -0.01
#define TIME 100

// macro for resetting the buffer
#define reset_buff for(count=0;count<N_SAMPLES;count++) buffer[count]=0;

void da_handler(char, unsigned);
unsigned get_a2d_value(unsigned char);
unsigned histogram(unsigned far far*);

float find_Qfactor(unsigned da_peak, float peak_voltage, int* command, int* keyhit,
                                                                float* voltatq)
{
   unsigned char a2d_channel='1', d2a_channel='2'; // pin 23
   unsigned ad_qf=0,step=50;
   float qf_voltage=0.0,target=0.0,error=0.0;
   int count=0;
   enum states{CLIMB,STOP};
   states state=CLIMB;
   static unsigned far far* buffer;     // use extended memory for buffer
   unsigned x=0, y=0, max_x=40, max_y=20;

   if (!(buffer = new unsigned[N_SAMPLES]))
   {
      printf("Insufficient memory for buffer");
      exit (1);
   }
      target=0.707*peak_voltage;

  //set output for peak voltage
  da_handler('2', da_peak);
  delay(TIME);

  // display progress report
  window(1,1,40,25);
```

```
clrscr();
puts("finding the Q factor ...");
printf("\ntarget voltage = %.4f\n",target);
do
{
    switch(state)
    {
        case CLIMB:
            da_peak-=step;      //climb up the peak
            da_handler('2', da_peak); // output reduced value
            delay(TIME);
            reset_buff;
            for(count=0;count<N_SAMPLES;count++)
            {
                if(kbhit())      //check for request from user
                {
                    *command=getch();
                    *keyhit=1;
                    return(0);
                }
                buffer[count]=get_a2d_value(a2d_channel); // get reduced peak
            }
            //for(count=0;count<N_SAMPLES;count++)
                //printf("buffer[%d]=%d\t",count,buffer[count]); test statement
            ad_qf=histogram(buffer);   // find the histogram of data and eliminate random noise

            if(ad_qf!=0)
            {
                qf_voltage=(float)ad_qf*10000/MAX_COUNT;
                qf_voltage=(float)ceil((double)qf_voltage)/1000;
                window(max_x/2,max_y/2,max_x/2+30,max_y/2+2);
                clrscr();
                error=qf_voltage-target;
                cprintf("Error= %.3f",error);
            }
            else
            {
                window(1,1,80,25);
                printf("Error:ad_qf=0\n");
                exit(1);
            }

            // determination of the step size
            if(error>1.5)
                step=200;
            else
                if(error<=1.5&&error>0.1)
                step=20;
            else
                step=1;

            // start of the search algorithm
            if(error<N_ERROR||error>P_ERROR)
            {
                if(error>0)
                {
                    state=CLIMB;
                    break;
                }
```

```
                    if(error<0)
                    {
                        da_peak=da_peak+40*step;
                        state=CLIMB;
                        break;
                    }
                }
                else
                {
                    state=STOP;
                    break;
                }

            case STOP:
                break;

            default:
                window(1,1,80,25);
                clrscr();
                puts("default state: error in FIND_Qfactor\n");
                getch();
                exit(1);
        }
    }while(state!=STOP);
    delete[] buffer;
    clrscr();

// convert D/A output at half power point to voltage
*voltatq=(float)da_peak*10000/MAX_COUNT;
*voltatq=(float)ceil((double)*voltatq)/1000;

    return(qf_voltage);
}
```

1.6 The D/A driver function

```
/*
Function name: da_handler, handles the output of the D/A

Arguments types and variables: char da_channel: D/A channel used, unsigned da_value: D/A value

Returned value types: void

Functions called: none
*/

#include"header.h"

#define PORT 368

void da_handler(char da_channel,unsigned da_value)
{
    unsigned char hi,lo; // outportb sends unsigned char data type.

    // mask off the low 8 bits to reveal the hi 6 bits
    hi=(da_value&0x3F00)>>8;

    // mask off the hi 6 bits to reveal the low 8 bits
    lo=da_value&0x00FF;

    switch(da_channel)
    {
        case '1':           //channel 1 D/A
            outportb(PORT+5,hi);  delay(1);
            outportb(PORT+4,lo);  delay(1);
            break;

        case '2':           // channel 2 D/A
            outportb(PORT+7,hi);  delay(1);
            outportb(PORT+6,lo);  delay(1);
            break;

        default:
            break;
    }
    //printf("DA_VALUE: %x\t",da_value);  // test statement used during debugging
}
```

1.7 The A/D driver function

```
/*
Function name: get_a2d_value, gets the value of the requested A/D channel

Argument type and variable: unsigned char ad_channel: A/D channel to be read

Returned value type: unsigned int: 0 ≤ A/D value ≤ 16384

Functions called: none
*/

#include"header.h"
#define PORT 368  // base address

unsigned get_a2d_value(unsigned char ad_channel)
{
    int i=0;
    unsigned char hi='0',lo='0',loop='0';
    unsigned hi_shift=0;
    unsigned a2d_value=0;

// output channel number to port 0
    outportb(PORT, ad_channel);
    delay(1);

// clear A/D register port 1
    outportb(PORT+1, '0');
    delay(1);

// start conversions
    for(i=0;i<8;i++)
    {
        loop=inportb(PORT+12);
        delay(1);
    }
    for(i=0;i<8;i++)
    {
        loop=inportb(PORT+10);
        delay(1);
    }

// read hi byte (6 bits)
    hi=inportb(PORT+3);
    delay(1);

// read low byte (8 bits)
    lo=inportb(PORT+2);
    delay(1);

// shift bits to form 14 bit Number.
    hi_shift=hi<<8;
    a2d_value=hi_shift+lo;

    return(a2d_value);
}
/*
```

1.8 Data storage function

Function Name: save_data

Argument types and variables: float vc1: varicap voltage at resonance without the sample
float vp1: voltage at the output at resonance without the sample
float vqf1: varicap voltage at half power point without the sample
float qf1: output voltage at half-power point without the sample
float vc2: varicap voltage l at resonance with the sample
float vp2: voltage at the output at resonance with the sample
float vqf2: varicap voltage at half power point with the sample
float qf2: output voltage at half-power point with the sample
unsigned char channel: A/D channel used
char *filename: data store file name

Returned value type: pos_t: a file position type, returning the start postion of the saved data, excluding the header information

Functions called: none
*/

```
#include"header.h"

fpos_t save_data(float vc1,float vp1,float vqf1,float qf1,float vc2,float vp2,float vqf2,float qf2,
                 unsigned char channel,char *filename)
{
   FILE *stream;
   static fpos_t filepos;
   struct time t;

   gettime(&t);      // gets the time, at which the data was recorded

   if ((stream = fopen(filename, "rt+")) == NULL)      // if file does not exist
   {
      stream=fopen(filename,"wt+");      // open a new file with the given name

      // start of the header information
      fputs(filename,stream);
      fprintf(stream,"\nTime: %2d:%02d\n",t.ti_hour, t.ti_min);
      fprintf(stream,"\nADChannel used: %c\n",channel);
      fputs("\n\n------------------------------------------------------\n",stream);
      fputs("Vcap1\tVpeak1\tVq1\tQfact1\tVcap2\tVpeak2\tVq2\tQfact2\n",stream);
      fputs("------------------------------------------------------\n\n",stream);
      // end of the header information

      fgetpos(stream,&filepos);      // save the file pointer position
   }
   else //    if file already exists
   {
      fclose(stream);
      stream=fopen(filename,"at+"); //      amend the file with new data
   }
   fprintf(stream,"%6.4f\t%6.4f\t%6.4f\t%6.4f\t%6.4f\t%6.4f\t%6.4f\t%6.4f\n",
                  vc1,vp1,vqf1,qf1,vc2,vp2,vqf2,qf2);
   fclose(stream);
   return(filepos);
}
```

1.9 The histogram function

```
/*
Function name: histogram, histograms the collected data, chops off 10% form top and
                         bottom of the histogram to reduce noise, and finds the mean
                         of remaining data points

Arguments types and variables: unsigned far far* buff: pointer to data in extended memory.

Returned value type: unsigned int: the mean of the filtered data

Functions called: none
*/

#include"header.h"

#define AD_STEPS 16384
#define N_SAMPLES 50
#define PORTION 5

unsigned histogram(unsigned far far* buff)
{
    int count=0,col=0,avg_count=0, chop=0, head=0, tail=0, portioncount=0, pflag=0;
    unsigned long avg=0;
    unsigned mean=0;
    static unsigned far far* hist;      // use extended memory
    float far far* fistvalue;

    if (!(hist = new unsigned[AD_STEPS]))
    {
        printf("Insufficient memory for histogram");
        exit (1);
    }
    for(count=0;count<AD_STEPS;count++)
        hist[count]=0;
    for(count=0;count<N_SAMPLES;count++)
        hist[buff[count]]++;

/*  Test routine for debugging purposes only
    for(count=0;count<AD_STEPS;count++)
    {
        if(hist[count]!=0)
        {
            col++;
            printf("hist[%d]=%d\t",count,hist[count]);
            if(col==3)
            {
                printf("\n");
                col=0;
            }
        }
    }
    getch();
    clrscr();
*/
```

```
// filters off the top 10% of the histogram
for(count=AD_STEPS-1,portioncount=0;count>0&&chop!=1;count--)
{
    if(hist[count]!=0)
    {
        hist[count]+=portioncount;
        if(hist[count]==PORTION)
        {
            hist[count]=0;
            portioncount=0;
            chop=1;
        }
        else
        {
            if(hist[count]>PORTION)
            {
                hist[count]=hist[count]-PORTION;
                portioncount=0;
                chop=1;
            }
            else
            {
                portioncount=hist[count];
                hist[count]=0;
                chop=0;
            }
        }
    }
}
tail=count+1;
chop=0;
/* Test routine for debugging purposes only
for(count=0;count<AD_STEPS;count++)
{
    if(hist[count]!=0)
    {
        col++;
        printf("hist[%d]=%d\t",count,hist[count]);
        if(col==3)
        {
            printf("\n");
            col=0;
        }
    }
}
getch();
clrscr();
*/
```

```
    // filters off the bottom 10% of the histogrm
    for(count=0,portioncount=0;count<AD_STEPS&&chop!=1;count++)
    {
        if(hist[count]!=0)
        {
            hist[count]+=portioncount;
            if(hist[count]==PORTION)
            {
                hist[count]=0;
                portioncount=0;
                chop=1;
            }
            else
            {
                if(hist[count]>PORTION)
                {
                    hist[count]=hist[count]-PORTION;
                    portioncount=0;
                    chop=1;
                }
                else
                {
                    portioncount=hist[count];
                    hist[count]=0;
                    chop=0;
                }
            }
        }
    }
    head=count-1;

/*  Test routine for debugging purposes only
    for(count=0;count<AD_STEPS;count++)
    {
        if(hist[count]!=0)
        {
            col++;
            printf("hist[%d]=%d\t",count,hist[count]);
            if(col==3)
            {
                printf("\n");
                col=0;
            }
        }
    }
    getch();
    clrscr();
*/

    // find the mean of the filtered data
    for(count=head;count<tail+1;count++)
    {
            avg+=(long)hist[count]*count;
            avg_count+=hist[count];
    }
```

```
    if(avg_count!=0)
        mean=(unsigned)floor((double)avg/avg_count);
    else
    {
        clrscr();
        printf("Error:avg_count=0\n");
        exit(1);
    }
    delete[] hist;
    return(mean);
}
```

2 General purpose functions

2.1 The audio functions flow chart

2.1.1 The sound function source code

```
/*
Function name: sounds: provides two tunes, based on the received argument

Argument type and variable: int number: this is the number of the selected tune

Returned value: void

Functions called: bleep, beep
*/

#include"headfile.h"

void bleep(void);
void beep(void);

void sounds(int number)
{
    switch(number)
    {
        case 1:
            bleep();
            break;

        case 2:
            beep();
            break;

        defaule:
            clrscr();
            printf("error occured in the sound module\n");
            getch();
            exit(1);
    }
}
```

2.1.1.1 The bleep function source code

```
/*
Funciont name: bleep: used to prompt the user to the next stage of the experiment

Argument type: void

Functions called: sound(), delay(), nosound()
*/

#include "header.h"

void bleep(void)
{
    int i=0;
    unsigned freq=0;
    for(i=0;i<8;i++)
    {
        freq+=150;
        sound(freq);
        delay(50);
    }
    nosound();
}
```

2.1.1.2 The beep function source code

```
/*
Funciont name: beep: used to prompt the user to connect the sample

Argument type: void

Functions called: sound(), delay(), nosound()
*/

#include <dos.h>

void beep(void)
{
    sound(150);
    delay(400);
    nosound();
}
```

2.2 The circuit response plot function

```
/*
Function name: get_graph: plots a graph of circuit response for a sweep of available capacitance
               and offers the option of printing the result using the ESPSON printer driver.

Arguments types and variables: none

Returned value type: none

Functions called: da_handler, get_a2d_value, printer
*/

#include "header.h"

#define MAX_COUNT 16383    // 14 bits resolution
#define OFFSET 3
#define CLIP_ON 1   /* activates clipping in viewport */
#define VPOFFSET 20
#define MARGIN 60
#define TIME 100

void da_handler(char, unsigned);
unsigned get_a2d_value(unsigned char); // gets voltage from a2d channels
printer(float far far*, unsigned);

void get_graph(void)
{
   unsigned char a2d_channel_number='1'; // pin 23
   unsigned da_value=0;
   unsigned ad_value=0;
   int gdriver = DETECT, gmode, errorcode;
   int lable=0,count=0;
   struct viewporttype viewinfo;
   char lablestring[5],started='0';
   static float databuff;
   unsigned samples=466;
   char ch=0;

   clrscr();
   static float far far* printbuff;
   if(!(printbuff=new float[samples]))
   {
      printf(" Data buffer error");
      exit(1);
   }
   for(count=0;count<samples;count++)
      printbuff[count]=0;

      /* request auto detection */
   /* initialize graphics and local variables */

   initgraph(&gdriver, &gmode, "C:\\BC\\BGI");
      /* read result of initialisation */
   errorcode = graphresult();
```

```
if (errorcode != grOk)  /* an error occurred */
{
    printf("Graphics error: %s\n", grapherrormsg(errorcode));
    printf("Press any key to halt:");
    getch();
    exit(1); /* terminate with an error code */
}
rectangle(VPOFFSET-1,VPOFFSET-1,getmaxx()-VPOFFSET+1,getmaxy()-VPOFFSET+1);
    /* create a smaller viewport */
setviewport(VPOFFSET,VPOFFSET, getmaxx()-VPOFFSET,
                                        getmaxy()-VPOFFSET, CLIP_ON);
getviewsettings(&viewinfo);
setfillstyle(SOLID_FILL,BLUE);
bar(0,0,viewinfo.right,viewinfo.bottom-VPOFFSET);
/* display some text */
setcolor(WHITE);

settextstyle(DEFAULT_FONT, VERT_DIR, 0);
outtextxy(viewinfo.left-VPOFFSET+MARGIN/2,viewinfo.bottom-2*MARGIN-getmaxy()/2,
                                                    "Resonance voltage (volt)");
settextstyle(SMALL_FONT, VERT_DIR, 0);
for(count=0,lable=0;count<=320;count=count+32,lable=lable+1)
{
    sprintf(lablestring,"%d",lable);
    outtextxy(MARGIN-18,viewinfo.bottom-VPOFFSET-MARGIN-5-count,lablestring);
}
for(count=0;count<=480;count=count+48)
    outtextxy(MARGIN+count-6,viewinfo.bottom-VPOFFSET-MARGIN-2,"-");
settextstyle(SMALL_FONT, HORIZ_DIR, 0);
for(count=0,lable=0;count<=480;count=count+48,lable=lable+1)
{
    sprintf(lablestring,"%d",lable);
    outtextxy(MARGIN+count,viewinfo.bottom-VPOFFSET-MARGIN+5,lablestring);
}
for(count=0,lable=0;count<=320;count=count+32,lable=lable+1)
{
    sprintf(lablestring,"%d",lable);
    outtextxy(MARGIN-5,viewinfo.bottom-VPOFFSET-MARGIN-5-count,"-");
}
settextstyle(DEFAULT_FONT, HORIZ_DIR, 1);
outtextxy(viewinfo.left-VPOFFSET+4*MARGIN,viewinfo.bottom-VPOFFSET-MARGIN/2,
                                                         "D/A output (volt)");

// draw the y axis
line(MARGIN,MARGIN,MARGIN,viewinfo.bottom-VPOFFSET-MARGIN);

// draw the x axis
line(MARGIN,viewinfo.bottom-VPOFFSET-MARGIN,
    viewinfo.right-VPOFFSET-MARGIN,viewinfo.bottom-VPOFFSET-MARGIN);
```

```
    for(da_value=0,count=0;da_value<=16310;da_value=da_value+35,count=count+1)
    {
        da_handler('2', da_value);
        delay(TIME);
        setcolor(WHITE);
        outtextxy(VPOFFSET,5,"plotting");
        delay(50);
        ad_value=get_a2d_value(a2d_channel_number);
        if(ad_value!=0)
            databuff=(float)ad_value*10/MAX_COUNT;
        // The plotting routine starts here.
        setcolor(BLUE);
        outtextxy(VPOFFSET,5,"plotting");
        putpixel(MARGIN+count,(int)viewinfo.bottom-VPOFFSET-MARGIN-databuff*32,
                                                                    WHITE);

        printbuff[count]=databuff;
    }

    /* clean up */
    setviewport(0,0,getmaxx(),2*textheight("T"),CLIP_ON);
    clearviewport();
    setcolor(WHITE);
    outtextxy(VPOFFSET,5,"Press P to print or any other key to continue.");
    ch=getch();
    if(ch =='p' || ch=='P')
    {
        clearviewport();
        outtextxy(VPOFFSET,5,"Please wait for your print out.");
        printer(printbuff,samples);
    }
    delete[] printbuff;
    closegraph();
}
```

2.2.1 The EPSON LQ570+ printer driver function source code

```
/*

Function name: printer: printer driver for EPSON LQ570+

Arguments types and variables: float far far* data: pointer to RAM where data to be printed
                               is stored, unsigned samples: the number of data points to be
                               printed

Returned value type: void

Functions called: none
*/

#include"header.h"

#define OFFSET 30
#define ESC 27
#define SP 32
#define setx for(j=0;j<4;j++) fputc(set_x[j],stdprn)
#define sety for(k=0;k<7;k++) fputc(set_y[k],stdprn)
#define setrelx for(j=0;j<4;j++) fputc(setrel_x[j],stdprn)
#define setrely for(k=0;k<7;k++) fputc(setrel_y[k],stdprn)

void printer(float far far* data, unsigned samples)
{
    const int init[2]={ESC,'@'}; // printer specific commands required
    const int chartable[8]={ESC,'(','t',3,0,0,1,0};
    const int prncomm[5]={ESC,46,1,10,10};
    const int selchtab[3]={ESC,'t',0};
    const int charspace[3]={ESC,SP,1};
    const int hrzpitch[4]={ESC,'c',8,0};
    const int linespc[3]={ESC,'+',5};
    const int selgrafmod[6]={ESC,'(','G',1,0,2};
    const int comm=250,axdev=43,space=32,t=10;
    int set_x[4]={ESC,'$',30,0};
    int set_y[7]={ESC,'(','V',2,0,30,0};
    int setrel_x[4]={ESC,'\\',1,0};
    int setrel_y[7]={ESC,'(','v',2,0,5,0};
    int i=0,j=0,k=0,count=0,lable=49;

    //initialise the printer
    for(i=0;i<2;i++)
        fputc(init[i],stdprn);

    //select graphics mode
    for(i=0;i<6;i++)
        fputc(selgrafmod[i],stdprn);

    //print raster graphics
    for(i=0;i<5;i++)
        fputc(prncomm[i],stdprn);

    //assign graphics character tabel
    for(i=0;i<8;i++)
        fputc(chartable[i],stdprn);
    //select graphics table
```

```
for(i=0;i<3;i++)
    fputc(selchtab[i],stdprn);
//select horizontal pitch
for(i=0;i<4;i++)
    fputc(hrzpitch[i],stdprn);

//set line spacing
for(i=0;i<3;i++)
    fputc(linespc[i],stdprn);

// print the y-axis
setx;
sety;
for(i=0;i<249;i++,count++)
{
    fputc(comm,stdprn);
    if(count==24)
    {
        count=0;
        fputc(axdev,stdprn);
    }
}

//print the lables for the y_axis
setx;
set_y[5]=0;
sety;
for(i=0,count=0,lable=49;i<249;i++,count++)
{
    if(i==0)
        fputc(48,stdprn);
    if(count==24)
    {
        count=0;
        if(lable==58)
        {
            setrel_x[2]=5;
            fputc(49,stdprn);
            setrelx;
            fputc(48,stdprn);
            setrel_x[2]=1;
        }
        else
        {
            fputc(lable,stdprn);
            lable++;
        }
    }
    fputc(space,stdprn);
}
```

```
//print the x_axis
setx;
set_y[5]=30;
sety;
for(i=0,count=0;i<499;i++,count++)
{
    fputc(comm,stdprn);
    setx;
    setrely;
    if(count==49)
    {
        count=0;
        fputc(axdev,stdprn);
    }
}

//print the lables for the x_axis
set_x[2]=20;
setx;
sety;
for(i=0,count=0,lable=49;i<499;i++,count++)
{
    setx;
    setrely;
    if(i==0)
        fputc(48,stdprn);
    if(count==49)
    {
        count=0;
        if(lable==58)
        {
            setrel_x[2]=5;
            fputc(49,stdprn);
            setrelx;
            fputc(48,stdprn);
            setrel_x[2]=1;
        }
        else
        {
            fputc(lable,stdprn);
            lable++;
        }
    }
}
```

```
    set_x[2]=30;
    setx;
    sety;
    for(i=0;i<samples;i++)
    {
        setrely;
        if(floor((double)(OFFSET+data[i]*33)>255))
        {
            set_x[2]=(int)floor((double)(OFFSET+data[i]*33))-255;
            set_x[3]=1;
        }
        else
        {
            set_x[3]=0;
            set_x[2]=(int)floor((double)(OFFSET+data[i]*33));
        }
        setx;
        fputc(comm,stdprn);
    }
}
```

2.3 *The power supply function*

/*

Function name: main: This test program was written to check the da_handler function. It allows manual set and incremental output values to be entered from the keyboard, and thus the corresponding D/A output checked with a high resolution digital multimeter.

Argument type: void

Returned value type: void

Functions called: da_handler

*/

```
#include"header.h"

#define PORT 0x170
#define MAX_BITS 16383

void da_handler(unsigned int, unsigned int);

void main(void)
{
    unsigned up_down=0;
    int value=0;
    unsigned max_x=40,max_y=20,x=0,y=0;
    float da_voltage=0.0;
    clrscr();
    printf("Power supply program\n\n");
    printf("\t.................................................................\n");
    printf("\t'+' to increase \t'-' to decrease \t's' to set value\n");
    printf("\t.................................................................\n\n");

    while(1)
    {
        up_down=(unsigned)getch();
        switch(up_down)
        {
            case 'U':
            case 'u':
            case    43:     if((value+10)<=(MAX_BITS+1)) // 43 detects the up arrow key
                                value+=10;
                            else
                            {
                                window(max_x/2,max_y/2,max_x/2+30,max_y/2+2);
                                x=wherex();
                                y=wherey();
                                cprintf("Max. Voltage warning"
                                            ", press RETURN to continue.");
                                getch();
                                gotoxy(x,y+1);
                                clreol();
                                gotoxy(x,y);
                                clreol();
                            }
                            break;
            case 'D':
            case 'd':
```

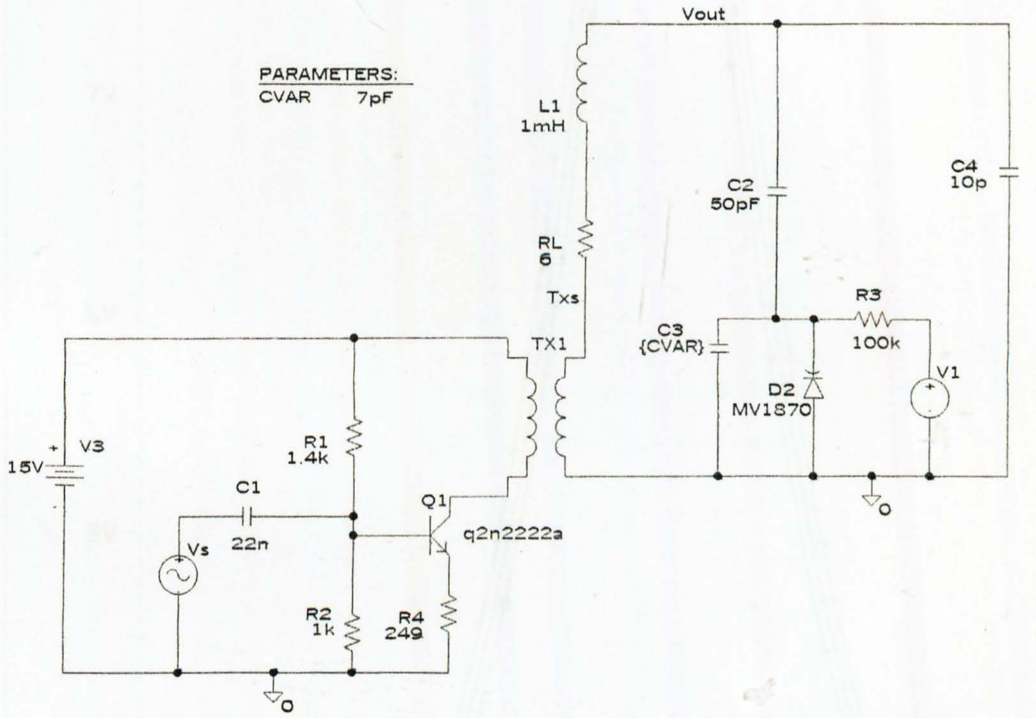
```
        case    45:     if(value-10>0)     // 45 detects the down arrow key
                            value-=10;
                        else
                        {
                            window(max_x/2,max_y/2,max_x/2+30,max_y/2+2);
                            x=wherex();
                            y=wherey();
                            cprintf("Not configured for -ve voltage"
                                    ", press RETURN to continue.");
                            getch();
                            gotoxy(x,y+1);
                            clreol();
                            gotoxy(x,y);
                            clreol();
                        }
                        break;

        case 's':
        case 'S':
                        window(max_x/2,max_y/2,max_x/2+30,max_y/2+1);
                        x=wherex();
                        y=wherey();
                        cprintf("Enter D2A value in volts: ");
                        scanf("%f",&da_voltage);
                        gotoxy(x,y);
                        clreol();
                        if((da_voltage<=10)&(da_voltage>=0))
                            value=da_voltage*MAX_BITS/10;
                        else
                        {
                            window(max_x/2,max_y/2,max_x/2+30,max_y/2+2);
                            x=wherex();
                            y=wherey();
                            cprintf("Output between 0 - 10 volts"
                                        "     Press RETURN to continue");
                            getch();
                            gotoxy(x,y+1);
                            clreol();
                            gotoxy(x,y);
                            clreol();
                        }
                        break;

                        default : value=0;
                        da_handler(2,value);
                        exit(1);
      }
      da_handler(2,value);
   }
}
```

Appendix E

SPICE simulation results for the measurement system used in Chapter 6.

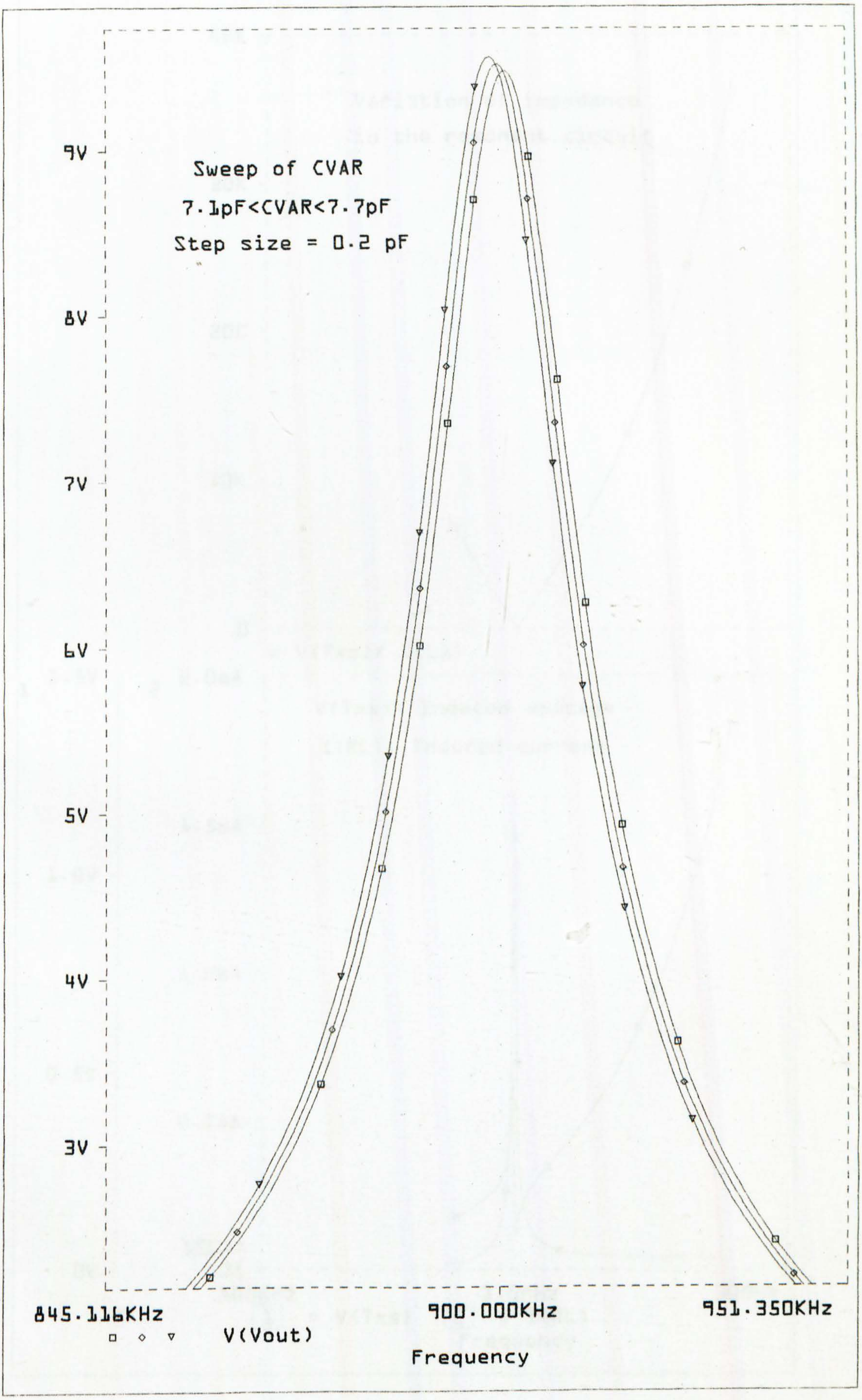
The circuit design used in the study detailed in Chapter 6, is based on the well known method of resonance detection. Here, a calibrated varicap diode was used to compensate for the effective additional capacitance introduced into the resonance tank, due to the introduction of the sample under test.

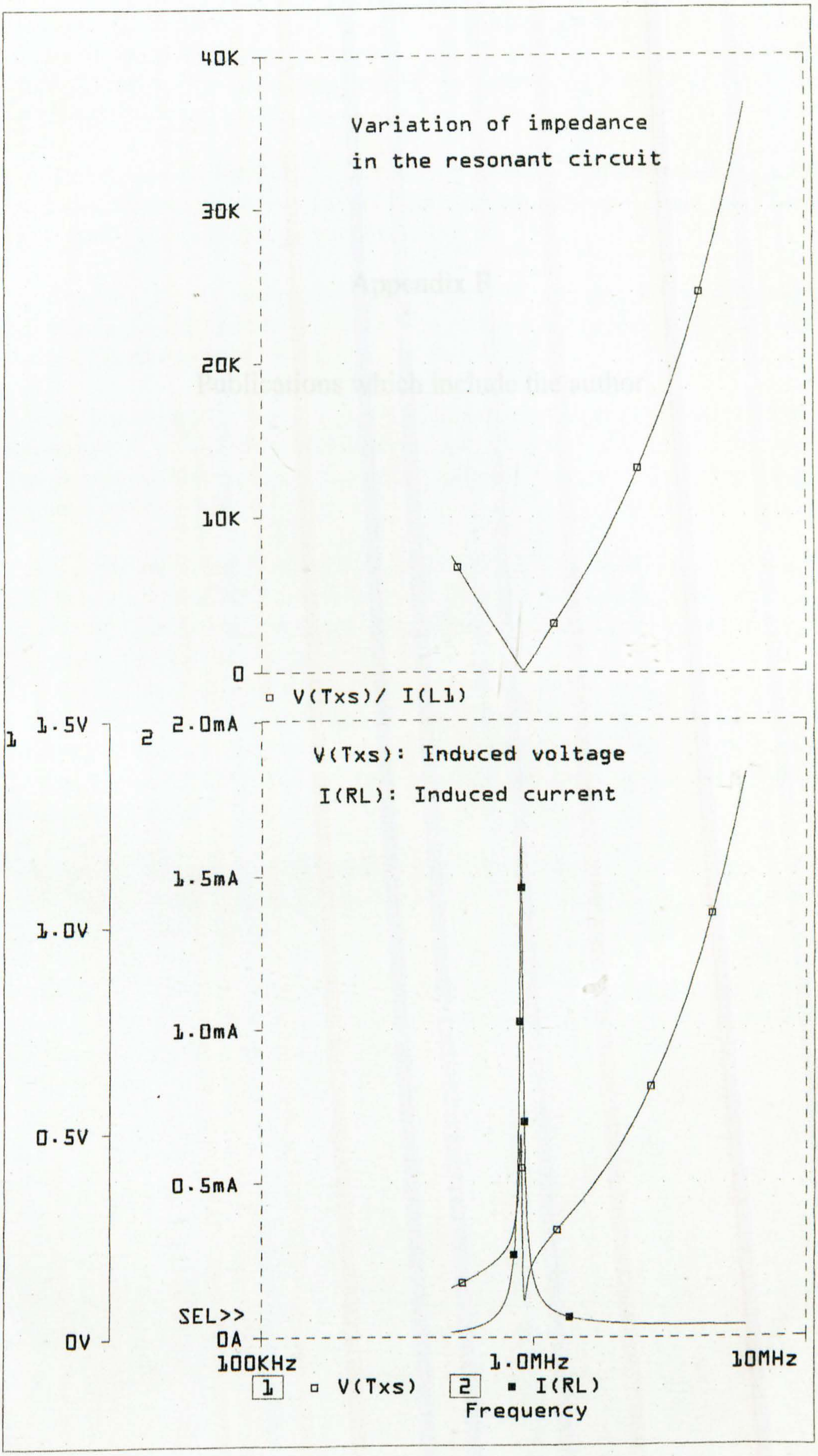
Initially SPICE was used to simulate the principle involved in the operation of the circuit. The following section shows the initial simulation results.



Simulated circuit:

C4 used to simulate peak detector diode capacitance
C3 is the electrode-sample capacitance
RL is dc resistance of L1


9V
8V
7V
6V
5V
4V
3V
Sweep of CVAR
7.1pF<CVAR<7.7pF
Step size = 0.2 pF
845.116KHz
900.000KHz
951.350KHz
V(Vout)
Frequency


Variation of impedance
in the resonant circuit
40K
30K
20K
10K
0
V(Txs)/ I(L1)
V(Txs): Induced voltage
I(RL): Induced current
1 1.5V
1.0V
0.5V
0V
2 2.0mA
1.5mA
1.0mA
0.5mA
SEL>>
0A
100KHz
1.0MHz
10MHz
1 V(Txs) 2 I(RL)
Frequency

Appendix F

Publications which include the author

1 Jazayeri S, Ahmet K, 12 – 13 April 1999, Moisture gradient studies in timber by measurement of dielectric parameters using a multiple electrode arrangement, Third Workshop on Electromagnetic Wave Interaction with Water and Moist Substances, Georgia, USA

2 Ahmet K, Dai G, Jazayeri S, Tomlin R, Kaczmar P and Riddiough S, Jan/Feb 1999, Equilibrium moisture content of timber commonly used in building, Journal of the Association of Building Engineers, pp 24 – 27

3 Ahmet K, Dai G, Jazayeri S and Tomlin R, January 1999, Experimental procedures for determining the equilibrium moisture contents of twenty timber species, Forest Products Journal, **49**:1 pp 88 – 93

4 Jazayeri S, Ahmet K, 6 – 8 April 1998, Moisture gradients studies in timber by measurement of dielectric parameters, Proceedings of the Third International Symposium on Moisture and Humidity, National Physical Laboratory, London, England, pp 179 – 186

6 Hall G, Ahmet K and Jazayeri S, October 1996, European Standards for dried timber and means of verification, Proceedings of Drying Pacific North-west Species for Quality Markets Conference, Forest Products Society, Madison, Wisconsin, pp 51 – 56

7 Ahmet K, Jazayeri S and Hall G, 19 – 23 May 1996, Standardisation of conductance-type timber moisture meters, Proceedings of the 7th International Conference on the Durability of Building Materials and Components (7DBMC), Stockholm, Sweden, (**2**) pp 546 - 553

8 Ahmet K, Jazayeri S and Tomlin R, Hall G, Kaczmar P and Taylor G, April 1996, The moisture content of internal timber – 2, Journal of the Association of Building Engineers, pp 10 – 14.

9 Ahmet K, Jazayeri S and Tomlin R, February 1996, Monitoring the moisture content of internal in-situ timber over a two year period: results and conclusions, Internal document, University of Luton

Dissemination of findings throughout the research period was carried out through various publications and reports; a list for each chapter follows.

Chapter 2 : Evaluation of Moisture Content Standards for Timber in Internal Use

Jan/Feb 1999, Equilibrium moisture content of timber commonly used in building, **Journal of the Association of Building Engineers**, pp 24 – 27

1996, DOE report **: Joint report with TRADA Technology Ltd., DOE report No RTT/g0011/2, see reference [23] for further details.**

April 1996, The moisture content of internal timber – 2, **Journal of the Association of Building Engineers**, pp 10 – 14.

February 1996, Monitoring the moisture content of internal in-situ timber over a two year period: results and conclusions, **Internal document**, University of Luton

Chapter 3 : A Comparative Study in Performance of Nine Commercially Used Conductance-type Moisture Meters

Joint publications with Dr. Gavin Hall, Technical Director, TRADA Tech. Ltd.

October 1996, European Standards for dried timber and means of verification, Proceedings of Drying Pacific North-west Species for Quality Markets **Conference, Forest Products Society, Madison, Wisconsin, pp 51 – 56**

May 1996, Standardisation of conductance-type timber moisture meters, Proceedings of the **7th International Conference on the Durability of Building Materials and Components** (7DBMC), Stockholm, Sweden, (**2**) pp 546 - 553

Chapter 6 : Moisture Gradient Studies in Timber by Measurement of Dielectric Parameters

April 1999, Moisture gradient studies in timber by measurement of dielectric parameters using a multiple electrode arrangement, **Third Workshop on Electromagnetic Wave Interaction with Water and Moist Substances**, Georgia, USA

April 1998, Moisture gradients studies in timber by measurement of dielectric parameters, Proceedings of the **Third International Symposium on Moisture and Humidity**, National Physical Laboratory, London, England