IMCOPCO (task 2.1)

Description and initial test of 8 principles for in-kiln measuring and end-point control of wood moisture content

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Principals: The EU-Commission
Project no.: SMT4-CT95-2023

Summary

The objective of this project was to give a general description and to perform initial comparative testing of the most relevant principles for in-kiln monitoring of wood moisture content and end-point moisture control.

The principles described and tested are weighing, electrical resistance, capacitance, shrinkage, neutron moderation, temperature drop, equalising and drying models.

The 8 principles tested show a great difference in accuracy due to the limitation in the principle itself and due to different degrees of calibration and development. Therefore the comparison focuses on the *potential accuracy* of each of the systems, given their calibration curve (relation between meter reading and actual moisture content) is ideal. As a measure upon the potential accuracy a 95 % confidence interval for the best curve describing the relationship between meter reading and actual moisture content is used.

The different systems show a great variance in potential accuracy, ranging from about 0,4 % to 6 % by use of the oven-dry method as reference.

Only the electrical resistance system, the capacitance system and the drying models are commercially available at the moment. Most of the other systems are presently either being further developed or upgraded by the different manufacturers.

In spite of varying performance of the different principles during the comparative testing, most principles have a potential for being further developed into a level of accuracy and applicability which is acceptable as a means for improved in-kiln wood moisture control monitoring and end-point determination.

Keywords: Wood drying, MC measuring.

Preface

The project ”Comparative test of 8 principles for in-kiln MC measuring and end moisture content control” is a part of the EU-project IMCOPCO (Improvement of moisture content measuring systems and testing strategies to enable precise process and quality control of kiln dried timber) with the contract number SMT4-CT95-2023.

Nine different partners from eight countries have participated in the IMCOPCO-project, which is divided into five main tasks with the following subtasks:

Partner 1	Bundesforschungsanstalt für Forst- und Holzwirtschaft (D)	Johannes Welling (project coordinator)
Partner 2	Danish Technological Institute (DK)	Jan Buchter
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Partner 4	Swedish Institute for Wood Technology (S)	Bjørn Esping
Partner 5	Technical Research Center of Finland (SF)	Holger Forsén Veikko Tarvainen
Partner 6	TNO Centre for Timber Research (NL)	Wolfgang Gard Michel Riepen
Partner 7	Institut für Holzforschung der Universität für Bodenkultur (A)	Helmut Resch
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Partner 9	Brookhuis Micro-Electronics (NL)	Arnold Brookhuis Peter Rozema

The EC contact person has been Mrs. I. de Froidmont-Görtz.

This project deals with task 2.1, where the Norwegian Institute of Wood Technology has been responsible.

The work has been made possible thanks to the funding from EC within the 4th framework programme, and participation of three Norwegian sawmills, Bruvoll Sag og Høvleri A/L, Løvenskiold Trelast AS and Moelven Soknabruket, which have placed their kilns, trucks and kiln operators at disposal for the project.

We express our sincere thanks to EC for the financial support, and to the companies and the people who have been involved.

Oslo, December 2000

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Contents

1. Introduction

In order to optimise the drying process and to hit the target moisture content (MC) it is imperative to have systems able to measure or predict the progress in MC during drying and final treatment of wood.

Requirements to timber from buyers and from new drying standards are more and more focusing on the importance of obtaining the correct final MC. In the coming CEN-standard on drying quality the requirements to MC will be given as an allowable range in mean MC combined with a maximum standard deviation.

The allowable deviation in mean MC will probably range from 1,0 % to 2,0 % depending on the end use requirements.

Figure 1 shows test results from 80 Norwegian industrial kilns as to the ability to hit the target MC, results which should be representative for kilns all over Europe. The tests clearly indicate that it is necessary to find methods to improve the ability to hit the target MC.

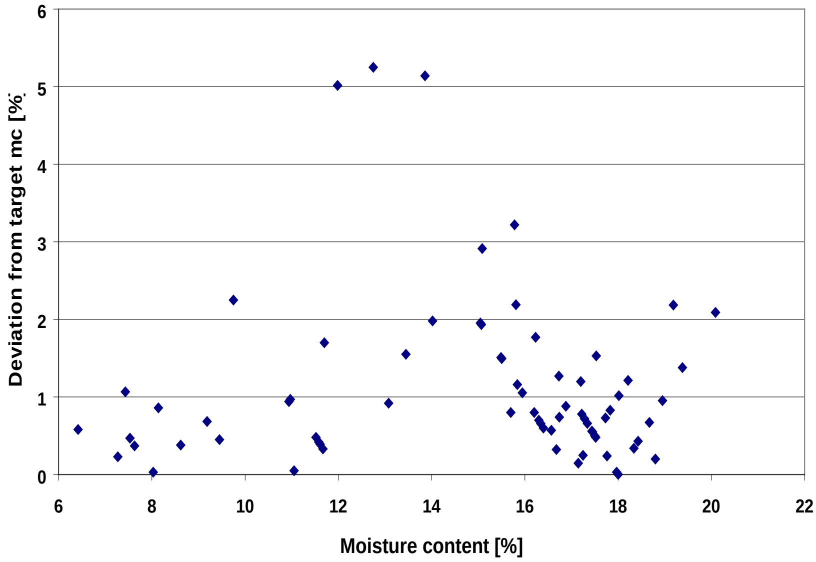


Figure 1. Deviation from target MC by 80 industrial tests (NTI)

On this background it is of great importance to study existing and find new methods which can improve the moisture control in the drying process.

After initial laboratory tests in the laboratory kiln at NTI, comparative testing of different methods for determination of wood MC during kiln drying were performed. The industrial tests were carried out a three different sawmills in Norway, with the main tests at Løvenskiold Vækerø AS - Fossum Bruk (eight principles) followed by Bruvoll Sag & Høvleri A/L and Norske Skog AS -

Soknabruket with testing of four principles each. The sawmills will be called sawmill 1, 2 and 3, respectively, throughout the report.

The tests focused on the measuring principles and did not involve comparison between different products utilising the same measuring principle. Where available, commercial products have been tested, but prototypes have also been included in the tests, along with systems developed during the project. Table 1 summarises the testing methods at the three sawmills.

Table 1. Instrumentation and location of the test kilns.

Measuring principle	**Sawmill 1**	**Sawmill 2**	**Sawmill 3**
Weighing	*X (4 packages)*	*X (12 samples)*	
El. resistance	*X (10 channels)*		*X (8 channels)*
El. capacitance	*X*		
Shrinkage	*X*	*X*	*X (top load)*
Nuclear MC-meter	*X*		
TDAL	*X*	*X*	*X*
Model evaluation	*X*	*X*	*X*
Heat-Flux	*X*		

Additionally, the “equalising principle” has been tried out in the laboratory kiln at NTI.

The “heat flux principle” was also tested during the industrial tests, but the reporting of the principle is carried out by partner 6 (TNO) and 7 (BOKU), who are responsible for the design and evaluation of the principle.

2. Description of measuring principles

2.1. Weighing

Weighing, oven drying and re-weighing is the most common way of determining the MC of wood samples when a high degree of accuracy is required. The method is simple and reliable, because it measures exactly what we want, namely the weight of the water present in the wood sample. The method, however, is destructive in the way that it requires samples to be cut from the timber. In industrial kilns you therefore need to enter the hot and humid climate in the kiln to collect samples if you want to use the oven-dry method to follow the moisture development during drying. In laboratory kilns the method is applicable, but for industrial use it is not feasible for other than sampling tests after the drying is ended and the timber has more or less cooled down.

The procedure for MC determination with the oven-dry method (according to the last CEN-proposal[i]) is that each individual sample is weighed accurately (0,1 to 0,01 g precision, depending on sample size), and then oven-dried at 103 ±2 °C until the rate of change of mass is less than 0,1 % in a 2-hour interval. The sample is then re-weighed, and the MC calculated on basis of the weight of the removed water.

$$MC = \frac{Raw\ (green)\ weight - ovendry\ weight}{Ovendry\ weight} \times 100\%$$

Knowing the green volume of a sample (sample MC above the fibre saturation point), the basic density can also be calculated in the process. The basic density [kg/m^3] is the dry weight of the sample divided by the green volume of the sample. This property can further be used to estimate the MC of a larger load of timber when knowing only the total weight and green volume of the load.

$$MC = \left(\frac{Total\ weight}{Basic\ density \times raw\ volume} - 1 \right) \times 100\%$$

As the dry weight of the timber is constant during the drying, the actual weight is the only variable, and the MC can be calculated continuously.

In the same way the actual MC can be calculated from the actual mass (weight) when knowing only the initial mass and initial MC:

$$MC_{(actual)} = \left(\frac{Actual\ weight \times \left(1 + \frac{Initial\ MC}{100}\right)}{Initial\ weight} - 1 \right) \times 100\%$$

There are mainly two types of weighing systems for continuous MC monitoring commercially available today: systems that weigh the entire load or a substantial part thereof, and systems that weigh a limited number of sample boards that represent the load in the kiln.

The first system is always based on continuous weighing of the load, while the latter can be either continuous or based on periodical removing and weighing of the selected sample boards. In hardwood drying periodical weighing of sample boards has been a common method for MC determination, but as the equipment for continuous weighing has become cheaper and more reliable, this method has the greatest potential. For systems that weigh all, or a large portion, of the load there are mainly two problems that arise. Inaccuracy of the measuring equipment (load cells) and difficulties in the estimation of density or initial MC.

The inaccuracy of the weighing equipment is mainly caused by temperature variations in the kiln during drying and some creeping, but it is also affected by the rough conditions under which it works. Loading and unloading with forklift trucks and a corrosive atmosphere are factors that are causing deterioration of the weighing equipment.

To obtain the best possible results with regard to both temperature compensation and environmental influence, different types of load cells have been suggested used for in-kiln measurement. Karlson and Nordin[ii] analysed nine different sensor types, and rated hydraulic sensors highest with regard to suitability for use in dry kilns. These have the great advantage that all the electronic equipment can be placed outside the kiln, and thereby avoid the corrosive kiln climate.

A hydraulic weighing system would consist of a number of oil-filled bellows placed underneath the load. The bellows connect to a pressure sensor outside the kiln through pipelines. When load is applied the system's pressure rises, and the load can be calculated from the pressure readings outside the kiln.

Among other sensors analysed the resistance type load cell was given a high rating. This type of cell is the most common for in-kiln use, and there are systems commercially available today that utilise such sensors. In laboratory kilns resistance type load cells are frequently used with good results, which also is the case in NTI's laboratory kiln. The most pronounced problem so far has been that the aluminium chassis, where the cells are mounted, expands when the temperature rises, and in that way introduces shearing stress (momentum) in the load cells, causing them to read false values. To avoid such effects, the cells must be installed in a way that let both the load and any chassis expand and contract without introducing shearing stresses in the load cells. In figure 2, the arrangement used in the NTI laboratory kiln is shown.

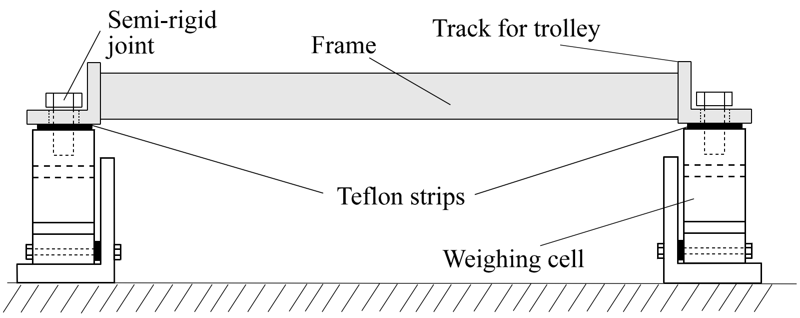


Figure 2. Frame supporting the loading trolley in the NTI laboratory kiln. Teflon strips and semi-rigid connections keep the load cells isolated from influence of any thermal expansion and contraction of the frame.

It has even been practised that load cells have been fitted underneath the entire kilns. In that way the load cells are not subjected to the harsh kiln climate and they are also isolated from temperature fluctuations during drying, which can influence on load cell accuracy. The solution is, however, limited to smaller kilns and laboratory kilns due to dimensions and total load.

2.2. Electrical resistance

The electrical resistance in wood strongly depends upon the MC and is commonly used as a measure thereupon. The measuring principle is based on the fact that the electrical resistance, which is easily measurable, increases with decreasing MC. Measurement is done by inserting two electrodes into the wood, apply a specific voltage (usually 5-10 V), and read the electrical resistance. The wood MC, which depends upon the resistance is calculated from calibration curves, figure 3.

The equation for the calibration curve for pine and spruce is:

$$R = 10^{(10^{(A \times u + B)} - 1)}$$

where: R - electrical resistance [MΩ]
u - MC of wood [%]
A *and* B - constants

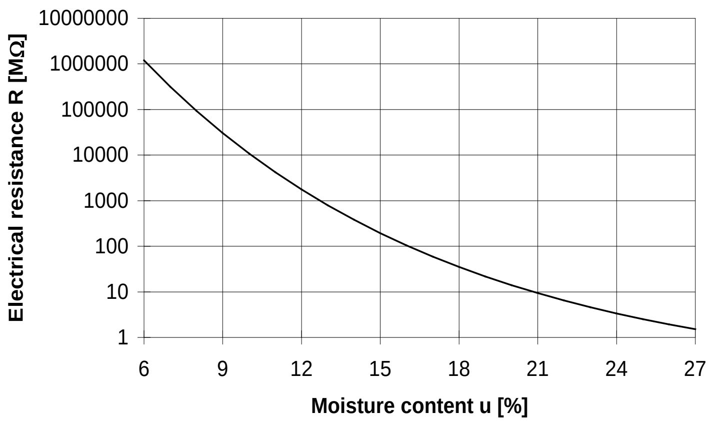


Figure 3. Calibration curve for Norway Spruce (Picea Abies) at 20°C.

The electrical resistance is not, however, solely depending upon the wood MC. A range of other factors, such as temperature, wood species, density, resin content, heat treatment and preservatives also influence the resistance. This means that there must be different calibration curves for different species and temperature levels, figure 4, and that one must consider other sources of influence when interpreting measuring results. Industrial wood MC meters automatically make corrections based on the input of temperature and wood species. Some meters even come with a designated wood temperature probe to give the exact internal wood temperature. This is a favourable option, since it is often difficult for the operator to estimate the internal temperature of the wood, especially for timber that comes directly from a dry kiln, and still contains a temperature gradient. In an in-kiln system this is even more complicated, since the internal wood temperature changes from a value near the wet-bulb temperature in the beginning of the drying process, to a temperature near the dry-bulb at the end of drying. In in-kiln systems it is therefore very important to measure the internal wood temperature.

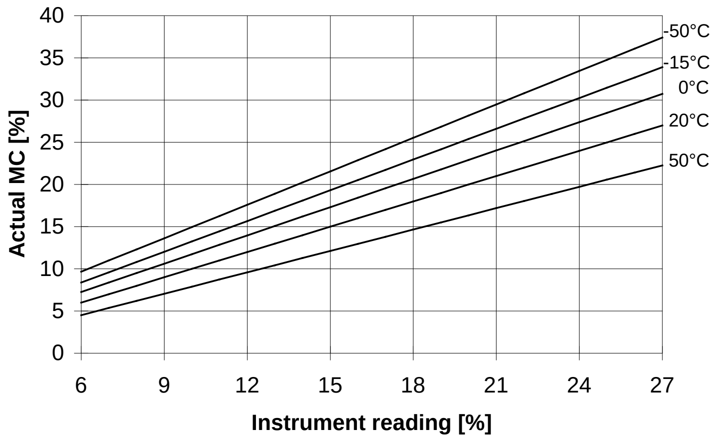


Figure 4. Dependency of instrument reading upon wood temperature.

Temperature correction equation (Pfaff og Garraham, Forintek):

$$u_{corr} = \frac{u + 0{,}567 - 0{,}0260 \cdot (t + 2{,}8) + 0{,}000051 \cdot (t + 2{,}8)^2}{0{,}881 \cdot 1{,}0056^{(t+2{,}8)}}$$

where: u_{corr} - MC corrected for temperature
u - MC reading [%]
t - wood temperature [°C]

New temperature correction equations for pine will be worked out by VTT within the IMCOPCO project.

The working range for electrical resistance MC meters is typically 7 - 28 % wood MC. For lower values of MC the resistance of the wood increases dramatically, and the relationship between MC and electrical resistance weakens. At higher MC the electrical resistance tends to depend more and more upon ions dissolved in the water contained in the wood, and again the relationship between MC and electrical resistance weakens.

There are different effects that govern the electrical resistance in wood at different levels of MC[iii]. Over the MC range from 0 to 20 %, the number of charge carriers in the wood is the major factor affecting the conduction mechanism. At higher MC the degree of dissociation of absorbed ions is sufficiently high so that the mobility of ions may become the major factor in determining the electrical conductivity.

When direct current is applied to wood at high MC a phenomenon called polarisation is experienced. Polarisation is caused by the dielectric behaviour of the water molecules contained in the wood. Each water molecule has a positive and a negative "end", and after being exposed to an electric field for a while, the water molecules will turn and line up along the electric field lines. This is illustrated in figure 5. Polarisation causes the electrical resistance to increase and the readings from a wood MC meter to decrease. The effect is most pronounced at low temperatures, and it is therefore believed that the time-constant for such polarisation shortens at elevated temperatures. It is also believed that at higher temperatures the polarisation occurs so quickly (within a few seconds) that it does not affect the meter reading. At lower temperatures the polarisation goes on for some time, and causes the reading of the electrical resistance to change with time.

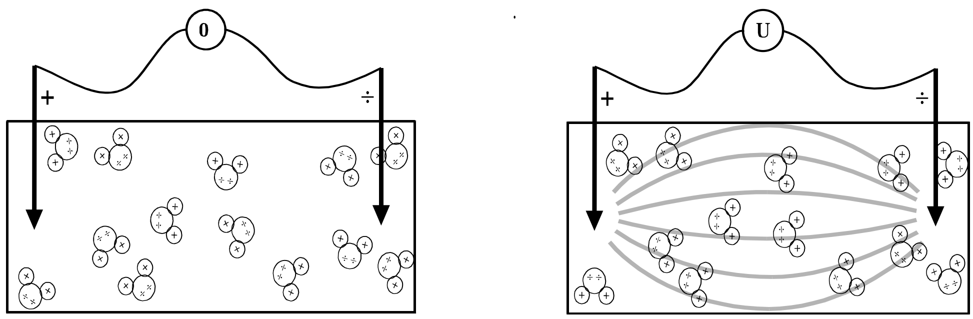


Figure 5. The phenomenon of polarisation of water molecules in an electric field.

Electrical resistance is the most commonly used measuring method for wood MC in the industry today, and it is used both for on-line measurement, in-kiln measurement and for on-the-spot measurement. Its simplicity in use and quick response time makes it a good choice, but the principle does have some limitations that must be considered, especially for in-kiln use.

As electricity always will find and use the path of least resistance between the electrodes, what we measure with electrical resistance MC-meters is always the wettest part of the timber in the sensor area. What is most frequently wanted to be measured, however, is the average MC of the timber or the MC in a specific part thereof. The measuring of a specific part, or in a specific depth of the timber, can be dealt with by using insulated electrodes, which have only a limited area stripped of insulation. Only the stripped area will function as an electrode and the MC reading will be the actual MC in the depth at which the electrodes are inserted. By reading the MC at different insertion depths of the electrodes we get a picture of the moisture gradient within the timber. This information can be of great importance in kiln drying, because there is a strong connection between the moisture gradient during drying and the drying rate, the degree of casehardening and the occurrence of checking.

The main concern in kiln drying, however, is the average MC of the timber. The average MC will appear somewhere between the surface and the middle of the cross section, see figure 6, and in the recommendation from the EDG-group it was proposed that an insertion depth of 1/3 of the plank thickness should represent the average MC[iv]. This gives a bit too high average MC during the drying period, but for timber that has been re-wetted, either by rain ,high relative humidity or by means of a conditioning period in the drying kiln, it usually predicts a fairly good average MC. This is because the moisture gradient has flattened, or even become higher at the surface than deeper into the cross section.

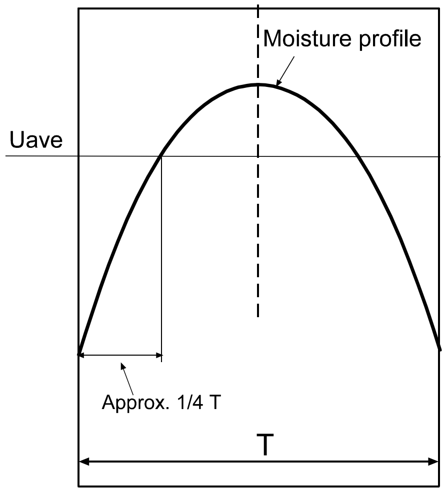


Figure 6. Moisture distribution within a plank during drying.

Numerous practical tests have shown that the average cross-sectional MC after drying is obtained by a penetration depth of the electrodes of 1/4 to 1/3 of the plank/board thickness. A practical compromise in the building up of a CEN-standard on electrical resistance meters has ended in a recommended penetration depth of 0,3 x thickness of the board/plank.

2.3. Dielectric-type moisture meter

In general the dielectric-type moisture meters work by penetrating the wood with an electric field (often in the radio-frequency range). The power-loss or the capacitance of the field is normally measured when the electrode(s) is in contact with the wood. Some meters even combine theses two measuring principles, and measure both power-loss and capacitance. They are called capacitance admittance meters, and are the most common dielectric MC meters for in-kiln use.

2.3.1. Power loss type

When a dielectric material such as wood is penetrated by a constant electric field it will absorb some energy and store it as potential electric energy. If the material is a perfect dielectric, all the energy is recovered when the field is removed. If not, some of the energy will be dissipated as heat, and it is this heat that represents the power-loss of the material. The power-loss factor is the ratio of power (heat) absorbed by the specimen to the total energy input, and for wood this factor increases with increasing MC.

If the electric field is oscillating, the dissipation of heat will equal the product of the power loss factor and the frequency at which it is oscillating. The electric field is generated from an electrode coupled to an oscillator and an amplifier in the meter. As heat is generated in the specimen the load on the oscillator increases, which in turn reduces its amplitude. It is the amplitude of the oscillator that is actually measured and relates to the wood MC.

2.3.2. Capacitance type

In capacitance type moisture meters the dielectric constant of the wood is used as a measure on the MC. The dielectric constant is a measure on the amount of potential electric energy that the material can hold when placed in an electric field. By definition the dielectric constant is the *ratio of the capacitance of a capacitor, using the material as a dielectric, to the capacitance of the same capacitor with a vacuum (in practical usage, air) as the dielectric*[v].

The actual measurement of the dielectric constant is done by generating an oscillating electric field that penetrates the material. According to the effect of the material on the capacitance of the capacitor, the frequency of the oscillator changes, and a frequency discriminator generates a signal proportional to the frequency change. This signal relates to the dielectric constant, and thereby to the MC of the specimen.

2.3.3. Capacitive-admittance type

This type of instrument involves a resistance-capacitance bridge circuit where the electrode constitutes a capacitive element. The RF electric field is generated in the same way as mentioned above and as the electrode contacts the wood specimen its capacitance and losses are increased and the bridge circuit becomes unbalanced. This imbalance is proportional to the amount of moisture present in the wood specimen, and can therefore be related automatically to the wood MC. The instrument, which is the normal type of dielectric MC for in-kiln use, uses only a single electrode and grounding of both the kiln structure and the instrument completes the circuit.

2.3.4. Practical use

In contrast to resistance type moisture meters the electrodes of the dielectric moisture meter is an integral part of the instrument. This means that the electrodes are specially designed for each meter type and are not interchangeable with other instruments.

The electrodes are of the non-penetrating type, and depending on the type of instrument and field of usage, the instruments are supplied with one or two electrodes. Two electrodes are usually supplied with in-line MC meters, while one electrode is the most common solution for in-kiln systems. For in-kiln systems, the electrode(s) have the shape and placement of a thin sticker, and therefore maintain fairly good contact with the wood at all times during measuring. The circuit is then completed by contact via grounding of both kiln load and instrument, and is independent of the extra electrode.

The measuring depth for dielectric type moisture meters are normally up to 50 mm, which means that planks of up to 100 mm thickness can be measured.

The measuring principle is, however, influenced by moisture gradients within the wood, and the shell MC of the wood is predominant. The moisture distribution within the load also affects the moisture reading, and the layers in the immediate surrounding of the electrode will dominate the meter reading[vi].

Density has a considerable effect on the performance of dielectric moisture meters and has been studied by, among others, Qarles and Breiner[vii]. They conclude that high frequency meters where more depending upon density than lower-frequency meters. Incorporation of the density information in the relation between moisture meter reading and MC resulted in improved correlation coefficient ($r^{2)}$ and a smaller prediction interval for the high-frequency meter, but did not affect the reading of the lower-frequency meter.

The temperature has also an influence on the dielectric constant resulting in a typical increase in the meter reading with increasing temperature.

Different sources state different working ranges for dielectric type moisture meters. Manufacturers state up to 240 % MC, while most independent articles state a range from around 0 till 30-40 % MC to obtain reasonable accuracy. Breiner and Quarles[viii] conducted some experiments with the Wagner Model 778 Kiln Alert, and the results indicated that the accuracy decreased from ± 1,5 % in the 8-20 % range, to ± 2,5 % in the 20-30 % range. Other experiments show that this deviation continues to increase when MC increases[ix]. Nevertheless, the dielectric MC meters can still be used as a rough prediction of the MC in the range above 30 %. Although their accuracy decreases, the dielectric meters will still indicate the MC level above the fibre saturation.

2.4. Shrinkage

When drying wood below the fibre saturation point (FSP) the wood starts shrinking. The shrinkage is most significant in the tangential direction, and for typical northern species (pine and spruce) the tangential shrinkage is about 8 % when drying to 0 % MC, compared to about 4 % in the radial direction.

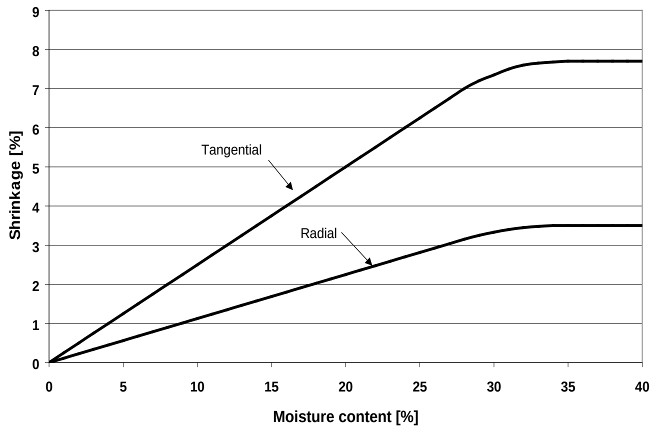


Figure 7. Shrinkage of spruce as a function of MC.

Between the fibre saturation point (approx. 28 %) and 0 % MC the shrinkage is a linear function of the MC. The shrinkage can therefore indirectly be used as a measure on the MC.

Monitoring the shrinkage of wood can be done in a number of ways, and an obvious way is to measure the height of one or more packages of timber in the kiln. To avoid the twisting effect of the upper layers the easiest solution is to put some weight on top of the pile, and measure how much the weight moves during the drying time. The registration can be conducted either by a mechanical or an electronic transducer. In both cases it is important to consider the effect of the temperature on the measuring equipment.

The actual measuring should then be no problem, but the result will be influenced by a number of factors. First of all, not only the timber, but also the stickers will shrink or swell, according to the equilibrium MC in the kiln at all times. This can be avoided either by using non-hygroscopic stickers (plastic or aluminium), or by closely controlling the stickers' MC prior to using them in the kiln. If the stickers' MC from the start equals the desired end-MC of the drying batch, their influence on the package height will add up to zero over the whole drying cycle. The latter method will, however, demand that the stickers are stored in a climate conditioned according to the end-use MC, and that the packages are stickered immediately before the kiln is loaded. This will make the handling and storing of stickers a lot more complicated than what is usual today, and is therefore not the most likely solution.

Another way of avoiding the influence of the stickers is by using a laser or scanning camera technique for measuring the thickness of the individual planks/boards (between the stickers) in the package. The result will then not be influenced either by the sticker MC or by the fact that the timber is compressed underneath the stickers, causing the package to shrink even when the MC is constant.

Using a scanning technique would also eliminate the possible effect of planks that deform (twist, bow and cupping) due to drying stresses and thereby cause the package to expand.

Scanning does, however, have one major weakness in addition to possible technical challenges: it measures only the edge of each plank. In addition to year ring orientation effects (see below) the moisture gradients within a cross section of the plank will make the edges drier (and thereby thinner) than the average plank thickness. The indicated MC will thereby be lower than the average MC, see figure 8. Measurement of the height of the package will produce the opposite effect, as the midsection (the thickest part) is determining the height. The magnitude of this effect will be most pronounced when using a scanning technique, and must be studied further if scanning is to be used for a shrinkage measuring method.

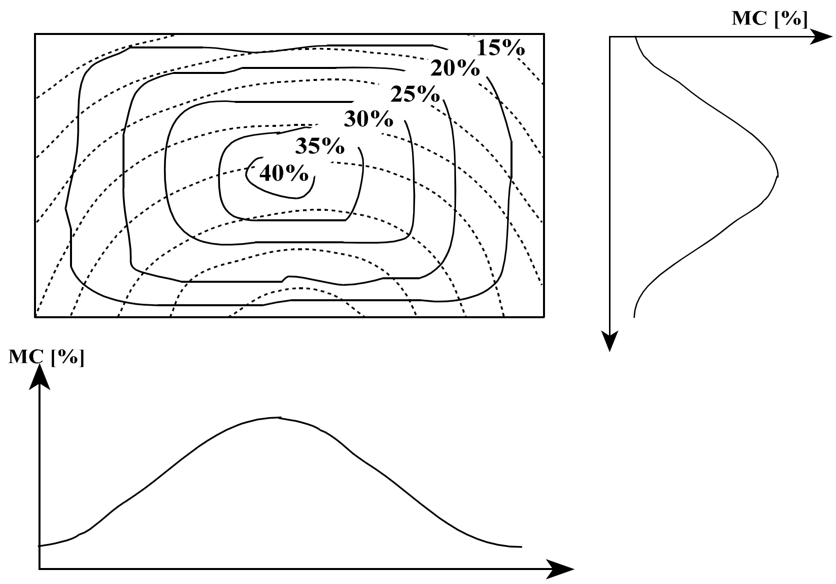


Figure 8. Moisture gradients within a cross section of a plank produce differences in shrinkage between the edges and the midsection.

In connection with shrinkage as an MC monitoring method, it is also very important to consider the influence of the angle of the annual rings. As mentioned earlier the tangential shrinkage for pine and spruce from the FSP to 0 % MC is about 8 % and the shrinkage in radial direction is about 4 %. This means that for thin boards from the outer parts of the logs, with a small annual ring angle the shrinkage will approach 4 % when dried to zero. For planks from the inner parts of the log, on the other hand, the angle is steep and the shrinkage on the edges approaches 8 %, but will still be 4 % in the centre, see figure 9. Apart from the cupping effect the radial shrinkage will probably have the predominant effect on the total degree of shrinkage of the packages.

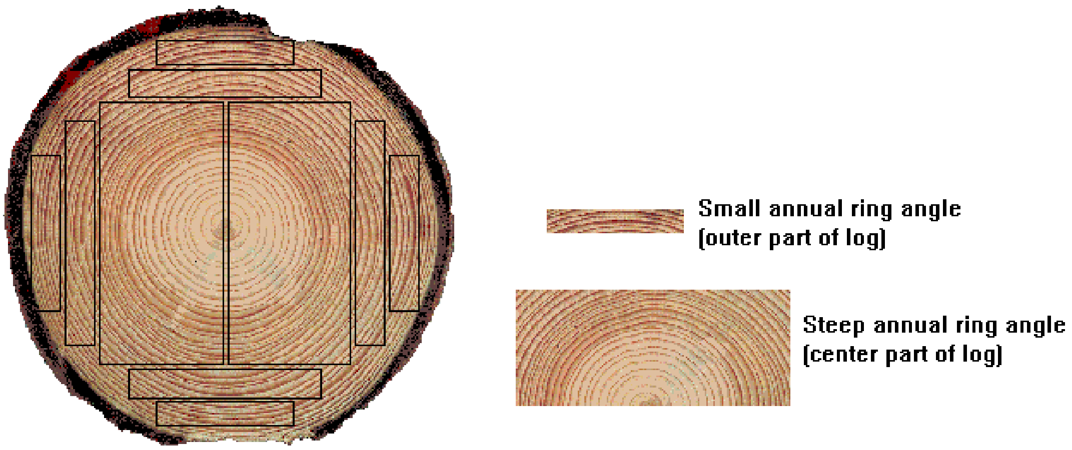


Figure 9. The angle of the annual rings strongly depends upon the position of the board/plank in the log cross-section.

2.4.1. Practical use

The relationship between shrinkage and wood MC is thoroughly described by Skaar[x] and many others, but when it comes to using shrinkage as an MC monitoring method little has been written or done. There is, however, one Swedish kiln manufacturer that uses the method, but this is yet at an early stage. The results so far are reported as promising and they do offer the system for new plants.

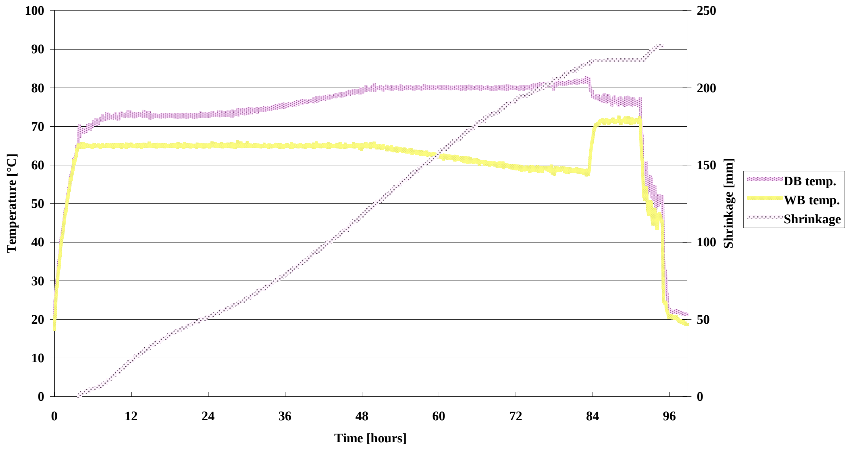


Figure 10. Drying curve that shows the shrinkage of a pile of timber during drying. Note that the shrinking resumes after conditioning, when the timber is cooling. This emphasises on the importance of a controlled cooling period with a sufficiently high relative humidity (by courtesy of ProPac AB, Sweden).

The Swedish system uses weights (moveable fan deck) on top of the timber pile, and a wire secured to the weights indicates the shrinkage on a monitor in the control room. The weights are manoeuvred up or down with hydraulic cylinders to make room for loading and unloading the kiln. While drying, however, the weights are freed from the cylinders, so that the pile can shrink or swell freely.

As can be seen from figure 10, some shrinkage is measured even during cooling of the timber, after a stagnant period while conditioning the timber.

2.5. Nuclear MC meter

A neutron source and detector can be used to measure the hydrogen concentration of a material. In dry wood, the concentration of hydrogen is fairly constant, i.e. 6,1 mass-% for spruce (*Picea abies*), and in water the concentration is 11,11 %. This relationship can be used to calculate the MC of wood based on the total hydrogen concentration of a specimen.

From a nuclear source high-velocity neutrons are spread out into the material to be measured. The initial energy level of the neutrons is up to 10 MeV. Inside the material the neutrons «collide» with other atoms and gradually lose energy until they are in equilibrium (with respect to kinetic energy) with the surroundings. At 293K equilibrium corresponds to an energy level of 0,038eV. The process where the neutrons lose energy through collisions is known as «moderation» of the neutrons, and an average of 18 collisions is required for complete moderation of a high velocity neutron. When moderated, the neutrons are in equilibrium with the surroundings and absorb the same amount of energy that they liberate during further collisions. The neutrons then start a «random movement» within the material, with a net transport towards areas of lower concentration. Such movement is known as diffusion.

When the high-velocity neutrons are moving through the wood sample, they will collide not only with hydrogen atoms, but also with the nucleus of other atoms, mostly oxygen and carbon. Hydrogen, however, has a much higher reducing effect on the neutron's energy than other atoms. This arises from the fact that the nucleus of a hydrogen atom has almost exactly the same mass as a neutron. When a high-velocity neutron collides with a hydrogen nucleus of the same mass in an elastic collision, the neutron will liberate more kinetic energy than it would in a collision with a heavier atom. It is like a bouncing tennis-ball; if bouncing into something heavy like a concrete wall, the ball gets most of its speed back, in the opposite direction. If bounced against another tennis-ball, on the other hand, both balls will move, and share the kinetic energy. Generally therefore, lighter atoms have a greater reducing effect on high-velocity neutrons than heavier atoms. In wood, oxygen and carbon account for about 93 % of the mass at dry basis and have masses of 16 and 12 times the mass of hydrogen, respectively. Because of this the moderation of high-velocity neutrons in wood mainly arises from collisions with hydrogen atoms.

Based on the above it is clear that the amount of moderated neutrons in the sample can be used as a measure of the water content of the wood. A special gas ionisation detector detects the moderated neutrons. The detector counts only fully moderated neutrons, and it is placed beside the source, in the same casing, underneath the timber. This placement is chosen to minimise the influence of wood density on the measurement and to make the instrument compact.

The neutrons are spread into the timber in a half-sphere with its centre in the source. To prevent disturbance from the background (ground) radiation the instrument is isolated from the ground with a cadmium plate that is impermeable to moderated neutrons.

For green timber, with a high concentration of hydrogen atoms, the travelling distance for the high-velocity neutrons is relatively short, because the required 18 collisions occur relatively near to the source. As the timber dries, the distance between the hydrogen atoms increases, and the frequency of collisions decreases. This causes the «half-sphere of moderation» to move away from the instrument (source and detector). As the moderation occurs farther away from the instrument, the likelihood of moderated neutrons to travel back to the detector via diffusion decreases, and the number of counts go down. As the front of moderation moves away, the number of counts will decrease exponentially, and this increases the sensibility of the instrument compared to a lay-out were the sensor and detector are placed on either side of the material to be measured upon. If the detector were placed opposite the source relative to the sample, the moderation zone would gradually move closer to the detector as the hydrogen density decreased, giving a shorter distance for random movement. For a more detailed description, see Engøy[xi].

The measuring principle is strongly depending upon the geometry of the package that is being monitored. The package should be a good representative of the entire load when it comes to both density and MC, and it is very important that each layer is tightly stacked. Gaps between individual boards will influence on the reading, as it will cause neutrons to slip away into open air. The measuring volume consists of a half sphere, increasing in radius when the drying progresses. For 50 mm timber the radius will typically be about 0,5-0,8 meter in radius at the start of drying, increasing to about 1,0–1,5 meters at the end of drying. The measuring radius is, however, strongly depending upon the power of the neutron source.

2.6. Temperature Drop Across the Load (TDAL)

The process of evaporating a liquid requires supply of energy from the surroundings. The water evaporating from the surface cools the drying wood, and to keep up the evaporation, a constant energy supply is needed.

The amount of heat required for evaporation is called the latent heat of vaporisation. For water, the energy required for evaporation is nearly six times greater than the energy required for heating the water from 0 °C to 100 °C. Therefore it is the evaporation of water that dominates the energy consumption in a timber drying kiln. In comparison the warming up of the kiln and timber consumes little energy.

Since the evaporation of water from the timber is constantly consuming energy the air stream is constantly giving off heat to the moist timber. This means that the air is constantly being cooled as it passes over the timber surface, where the evaporation takes place. Therefore the air temperature at the leaving-air side of the stack is always lower than the air temperature at the entering-air side during drying. The more water the wood gives away, the cooler the air-stream at the leaving-air side of the stack. This effect can be used to monitor the drying rate of the timber in a kiln.

The air temperature is monitored on both sides of the stack, and the difference between them is a measure on the drying rate. At the start of a drying batch, when the wood is very wet, the rate of drying is high. This means that the heat needed for evaporation is great, and that the cooling of the air is equally great. As the MC decreases below the FSP the drying rate also decreases, and the evaporative cooling is reduced. This leads to less temperature drop in the air stream. If the wood is totally dry (theoretically) the air temperature would be the same on both sides of the stack, since there is no water to evaporate (as long as the air and the wood are at the same temperature level).

Knowing the temperature drop and the total volume of the air-stream going through the stack, the amount of water evaporated from the timber can be calculated. As long as the MC is above the FSP, all heat taken from the air when passing through the stack will be used for evaporation of water. When the MC drops below FSP, however, we have to take the heat of sorption into account. This is energy that is needed to break the chemical and physical bindings between the water molecules and the molecules in the cell wall. The heat of sorption increases from zero at FSP until it reaches about 1100 kJ/kg at zero percent MC.

2.6.1. Practical use

The use of temperature drop along the load (TDAL) as a controlling strategy started as early as in the 1930s, when kiln operators knew that they had to maintain a certain TDAL during the whole drying period to prevent brown staining of the timber. Since then the strategy has been refined and implemented into computer control systems for dry kilns. The TDAL is seldom (if ever) used for direct calculation of the MC of the timber during drying, but is used to determine when to cut off the drying process.

Among others, Taylor and Landoch (1990)[xii] have conducted tests using TDAL to determine both the average MC and the cut-off time of drying. They found that the relationship between average MC and TDAL was poor, and that one has to introduce some restrictions into computer programs that calculate cut-off time on basis of TDAL. They found that the value of TDAL was affected by wood properties such as variations in density, sapwood content, grain direction and general MC level. In addition it is heavily influenced by fan reversal and air velocity. Altogether, this makes it a poor indicator of the actual MC level during drying, but it may still be a possible way of determining cut-off time of drying when used in a computer control system.

Taylor and Landoch suggest some restrictions that will help making TDAL a better indicator of the cut-off time:

- Not allowing drying to stop until drying has progressed for a specified minimum time. This will prevent the drying to be cut off prematurely during short unaccountable drops in TDAL that occurred during their tests.
- Using a moving average of TDAL to suppress the above-mentioned TDAL drops.
- Imposing a time constraint that requires TDAL cut-off value or a lower value be maintained for a specified time period.

The overall conclusion of Taylor and Landoch is that if TDAL was used as the only determining factor concerning when to stop drying, all their test-runs would have been stopped too early. A likely reason for this is that in connection with fan-reversal the TDAL value always drops until a new temperature profile is established.

2.7. Equalising principle

The ”equalising principle” is based on the fact that wood is a hygroscopic material that will attain a certain MC when it is exposed to a certain climate expressed through one relative humidity and one temperature. This relationship between MC and climate is expressed through the so-called equilibrium MC curves (EMC-curves). By using this phenomenon it should in principle be possible, after finishing the normal drying phase, to set the EMC in the drying air equal to the target MC and through an equalising process eliminate (minimise) possible deviations in MC from the target MC.

One problem with this method is the hysteresis phenomenon of the EMC-curves leading to higher EMC-values by drying (desorption) than by wetting (adsorption) at exactly the same climate. An example of this hysteresis is shown in figure 11 with EMC-curves for pine at 20 °C. At for example 60 % RH the EMC is 13 % by desorption and 11 % by adsorption, with an average EMC of 12 %.

If as an example the target MC is 12 % and the actual MC in a piece of timber at the end of the drying phase is 14 %, an equalising process with 60 % RH (12 % mean MC) will maximum be able to lower the MC level down to 13 %. If the actual MC is 10 % the equalising process can maximum raise the MC to 11 %, which means that the equalising process at 20 °C at best can correct the final MC to a level of± 1,0 %.

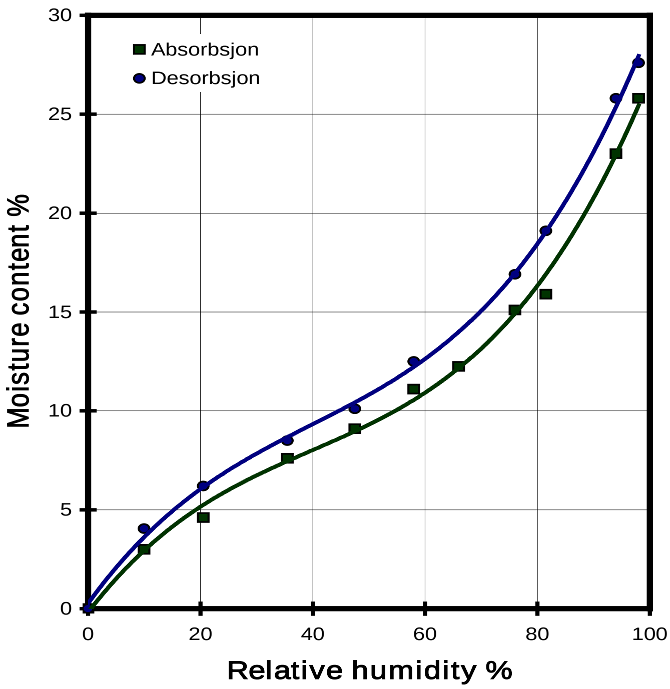


Figure 11. EMC-curves for pine (Pinus sylvestris) at 20°C (desorption and adsorption) (NTI).

The hysteresis of the EMC-curves decreases by increasing temperature and almost disappears when the temperature exceeds 75 °C. In figure 12 results from experiments made by L. Weichert[xiii] at 75 °C is shown together with experiments made at NTI at 20 °C. From the diagram it can be seen that at 75 °C the hysteresis is negligible (adsorption and desorption forms a single curve).

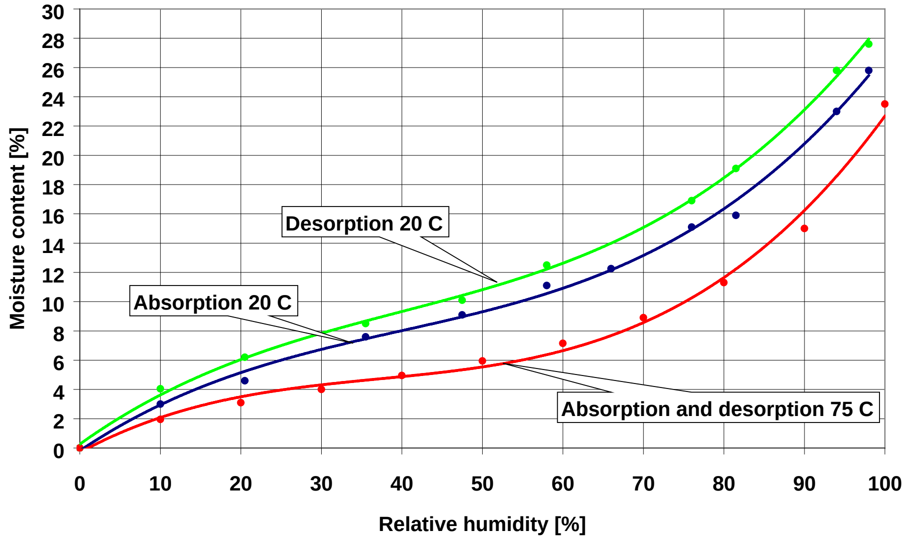


Figure 12. EMC-curves for pine at 20°C (NTI) and at 75°C (L. Weichert).

The merging of the desorption and adsorption curves from about 75 °C makes it theoretically possible to use the equalising principle to correct deviations from the target MC, as the temperature in modern kilns can be kept at 75 °C and more.

Figure 12 shows that at a target MC of 12 % the sorption curves at 75 °C and a relative humidity of approximately 82 % will give an EMC of 12 % independent of whether the timber goes through desorption or adsorption in the equalising process.

The conclusion is therefore that by temperatures above 75 °C the equalising principle is theoretically possible as a means of correcting the final MC towards the target MC.

2.8. Drying model

A number of theoretical models exist for calculation of drying rate, moisture gradient and residual stresses in wood during drying. Some of them were presented at the 5th International IUFRO Wood Drying Conference in Canada, and are described in the proceedings from that meeting[xiv].

In principle, they use information about the drying wood, ambient climatic conditions and parameters like the air flow velocity, to calculate the progress of drying and stress development during drying.

The calculation of drying rate, MC and moisture gradient are based on knowledge of the physical mechanisms that occur in and near the surface of wood when drying. Depending on the complexity of the model, the number of parameters that are considered varies. Hukka[xv] presents his model as shown in figure 13.

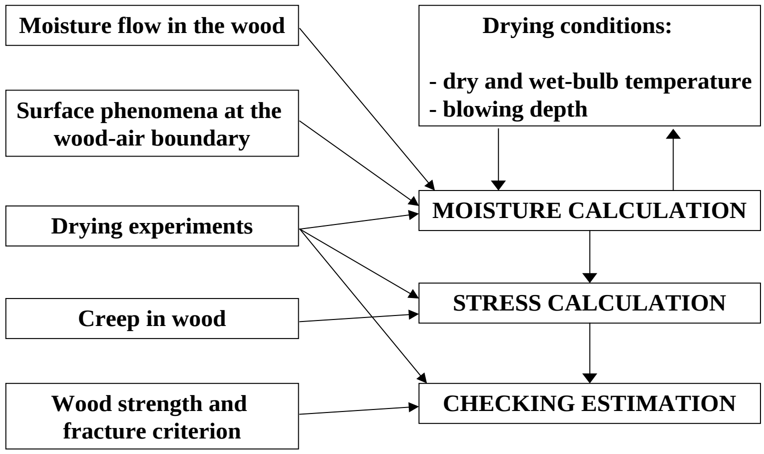


Figure 13. Structure of a simulation program[xvi]

As the different drying models are calculating the MC-development as a function of the drying time based on the input parameters, the models should be an effective means for determining the cut-off time for reaching a certain target MC. The level of accuracy in meeting the target MC is expected to be very much depending on the accuracy of the input parameters.

3. Survey of current status

Of the different measuring principles for in-kiln moisture and end-point control, the electrical resistance principle is by far the one most frequently used. The other measuring principles are either used by few producers or are still at the developing stage.

The use of equalising climate and drying models to hit the target MC are promising methods, but are per definition no measuring principles. The equalising method is well known, but is in principle more used for reducing the spread in final MC. The use of drying models is gaining momentum as the models are further developed and are now more and more common as an integrated part of the kiln control system.

In table 2 the different principles are listed with indication of some of the manufacturers/developers. The list only gives an indication of the level of use of the different principles and is not intended to be complete.

Table 2. List of principles and some suppliers of equipment for end-point MC determination (1999).

Name	Measur. principle	Manufacturer/ product name	Distribution/Use			
			High	Medium	Litttle	Under developm.
Electrical meters	Electrical resistance		x			
		BES Bollmann-D				
		Brookhuis-NL				
		CSA Electronics-D				
		Brunner-Hildebrand				
		Delmhorst-US				
		Gann-D				
		Vanicek-A				
		Wsab Lignomat- S/D/US				
		SII Dry Kilns-US				
		Coe Manuf. (Series 22M)-US				
		Energie FEI Inc.-CND				
		Cathild -F				
Capacity meters	Dielectric. Measurement				x	
	of capacitance and power	Wagner-US				
	loss	Dry Zone_NZ				
Weighing	Weighing				x	
		Alfsen og Gunderson - N				
		Delmhorst Instruments-US				
		Coe Manuf. (Series 22M)-US				
		SII Dry Kilns				
TDAL	Temp.drop along the load				x	
		Coe Manuf. -US				
		Drying Techn. Inc.(DTI)-US				
Heat flux	Heat flux	Developed and tested by				x
		BOKU-A				
		TNO-NL				
Shrinkage	Shrinkage				x	x
		Alent-S				
Nuclear meter	Termalization of neutrons					x
		IFE-N				
Equalizing	EMC = end mc	Can be used by all normal			x	
		kiln control systems				
Drying models	Model calc. of mc-develop.			x		
		SAHA-SF				
		SALINA(Torksim) SF/S				
		DIFF-A				
		DRYRUN-US				
		PROFIL-D				
		WD/1D- UK				
		TRANSPORE-F				
		WOODRY-RUS				
		JAM-W-S				
		WOODRY-AUS				

4. Initial laboratory tests

The initial laboratory tests was carried out only for pretesting of three systems before the main tests in the industrial kilns for achieving experience with logging and measuring.

4.1. Material and methods

4.1.1. Equipment

During the initial tests, the laboratory kiln at NTI was used.

The kiln is a BRUNNER-Labortrockner BL with the control system B 9000 COMP. In addition it is fitted with a custom-designed control and logging system from ALENT Drying AB. The two systems run in parallel, and the operator can choose which system to use as a control system in each individual drying run. The other system is then used as a logging system and as a backup if the running control system fails.

Technical specifications lab-kiln:

Drying volume:	Length:	1200 mm
	Width:	800 mm
	Height:	800 mm
Temp/climate control:		Drybulb/wetbulb (PT100) and EMC wafer sensor
MC monitoring:		Electrical resistance type (12 sensors)
Humidification system:		Selectable water spray or steam
Working range temperature:		Up to 120 °C
Drying air velocity:		Variable 0-15m/s
Control strategy:		According to measured MC (and moisture gradient), or by fixed-time control

4.1.2. Materials

The material used for the initial tests was aspen (*Populus tremula*), dimensions 50x150 mm^2. Each test consisted of 60 specimens. The initial MC and the density were determined from 30 specimens, taken at random from the batch. The endpoint MC was determined from the same 30 specimens, in addition to the twelve samples that were measured with the on-line electrical resistance MC-meter.

4.1.3. Methods

The MC-monitoring principles that were looked at during the pre-tests were electrical resistance, continuous weighing of the pile and shrinkage of the pile.

For the el. resistance MC-monitoring 12 sensors (24 electrodes) were used, each sensor driven 15-17 mm into the wood. All sensors were logged separately, and the location within the pile was the same during all tests. The control system reads both the individual MC-sensor signals and an average value. If any of the sensors are corrupted during the process, they are left out of the average MC calculation.

For the continuous weighing of the pile, four load cells were used, mounted on the kiln floor, under the rail carrying the trolley. The signal from the cells was logged directly in the kiln control system.

Measurement of the shrinkage was done manually by means of a ruler, fixed to the trolley. The position (in the height) of one of the drying pieces in relation to the ruler was logged manually at intervals during each drying run. The test piece, of which the position was read, was placed in a different layer during the different drying runs.

4.2. Results and discussion

The results from one test are shown in figure 14. The indicated initial and final MCs were determined by using the dry-weight method, and are average values for the entire batch.

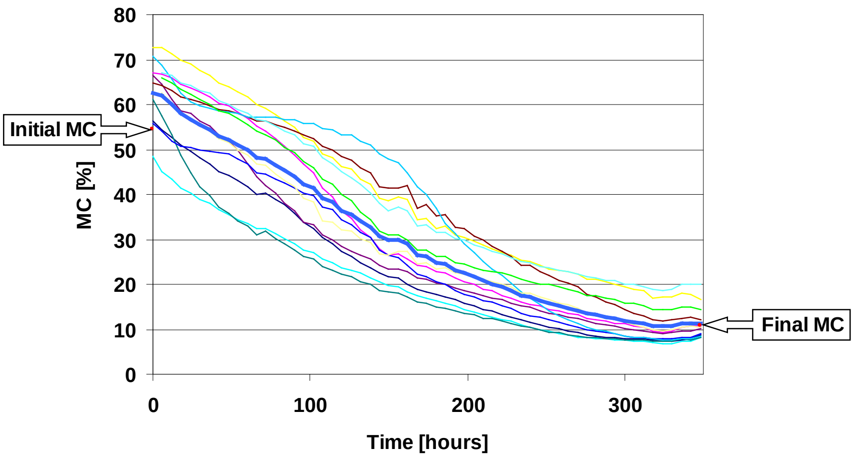


Figure 14. El. resistance type MC-meter using 12 sensors. Average of the twelve sensors is indicated with thick blue line.

As can be seen from the diagram the resistance meters gave a fairly good indication of the initial average MC and the spread in the moisture. The deviation between the measured initial average MC and the "true" average MC (from oven-dry samples) was approx. 5,5 %.

For the final MC, a comparison between the instrument reading and the true MC gave a deviation of approx. 1 %.

4.2.1. Continuous weighing of the batch

Four load cells were installed underneath the frame supporting the trolley, one under each of the trolley wheels. To avoid influence on the load cells from thermal expansion and contraction of the frame, the connections between them were not rigid, and pieces of Teflon plastic were put on the contacting surfaces, see figure 15.

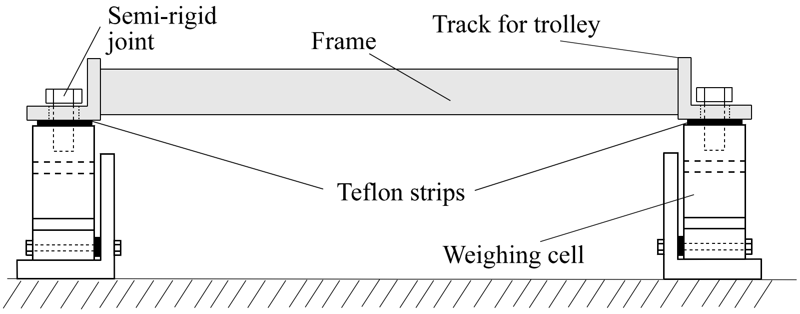


Figure 15. Frame supporting the loading trolley in the lab-kiln. Teflon strips and semi-rigid connections keep the load cells isolated from thermal expansion and contraction of the frame.

The load cells were calibrated for temperatures up to 150 °C and are especially designed for the harsh environment in a dry kiln.

In the first instant, the initial and final masses are coupled directly to the simultaneous MCs. In this way a ratio (%MC/kg) between the mass and the MC is determined which is used to calculate the instantaneous MC at each time interval.

Ex:	Initial MC:	54,3 %	
	Final MC:	10,7 %	ΔMC=43,6 %
	Initial weight:	438,0 kg	
	Final weight:	310,9 kg	ΔMass=127,1 kg

The corresponding ratio is then 2,915 kg/%, which is used to calculate the progress of the wood MC. In all tests, the “reference MC” is calculated in this way. The result from one laboratory test is shown in figure 16.

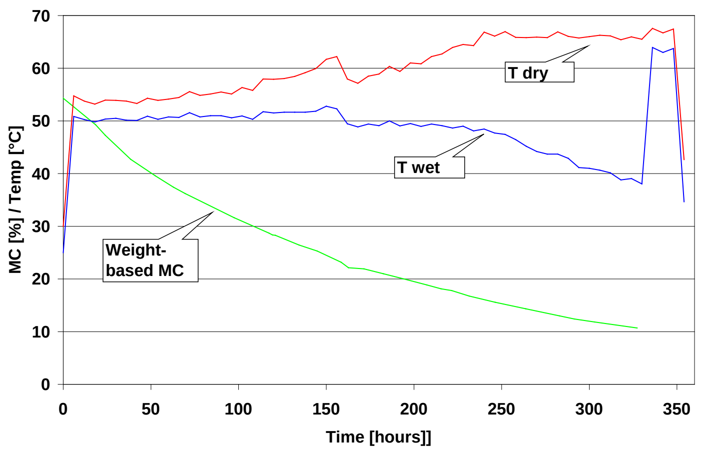


Figure 16. Weight-based MC.

The initial- and final MCs are identical with the MCs found by the oven-dry method. The intermediate MC values was then calculated with the above-mentioned method.

This principle will be used in the main test in one of the industrial kilns for establishing a reference curve for the comparison of the different systems of in-kiln control of the moisture content during drying.

It must be stressed that the accuracy of the reference curve can not be better than the accuracy of the oven dry method.

4.2.2. Shrinkage

Results from one of the first tests with shrinkage measuring are shown in figure 17.

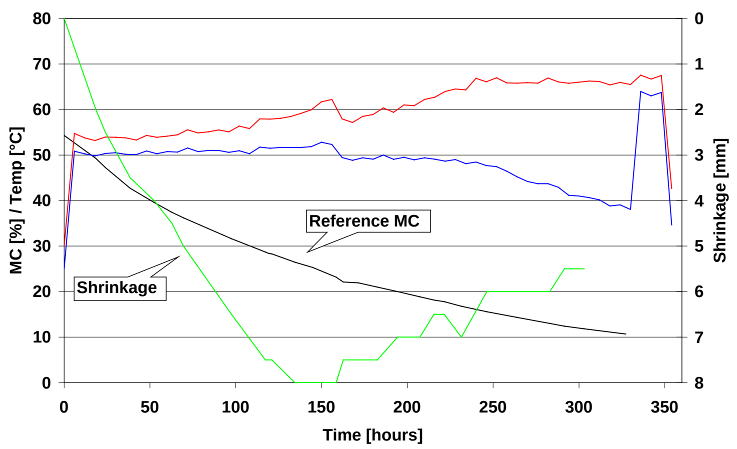


Figure 17. Shrinkage of the drying batch, when three layers of planks were left as weight above the layer that was measured.

The graph shows that the shrinkage started immediately after the kiln was loaded and the heating turned on. After (in this case) about 130 hours, the shrinkage stops, and the pile starts "lifting" after about 30 more hours. The reason for this growth was obvious when observing the timber. One could see that the planks where cupping and twisting, causing the pile to grow. This is expected to occur in connection with drying below the fibre saturation point (FSP) by small package heights.

By the industrial test with shrinkage measurements it is important to be aware of this effect. To reduce this "lifting effect" at the end of drying it is necessary to apply a load on the top of the packages and measure the total shrinkage underneath. In the industrial test kiln, where the shrinkage measurements were logged, this problem was solved by using part of the top package as a top load.

5. Comparative tests under industrial conditions

5.1. Material and methods (general)

Apart from the initial pre-tests carried out in the NTI laboratory kiln, all full-scale tests were carried out in industrial drying kilns. There were no special demands regarding species or dimensions, but it was presupposed that the timber was relatively freshly sawn before drying. Drying schedules were chosen by the kiln operators from their usual selection. The only adjustment made, compared to ordinary drying runs, was that the air velocity was kept at the same level throughout the entire drying runs.

A total of twelve drying runs were investigated, four at each of the sawmills. Table 3 summarises key data for the different drying runs.

Table 3. Key data for all tests.

	Test no.	*1*	*2*	*3*	*4*
Sawmill 1	Species	*Picea abies*	*Pinus silv.*	*Pinus silv.*	*Picea abies*
	Dim. [mm]	52,7x104,6	53x115,3	52,8x105,0	52,5x105,0
	MC_{init} [%]	60,1	62,4	48,1	57,6
	MC_{final} [%]	11,0	9,8	8,2	8,7
	Density [kg/m^3]	394,5	404,4	401,8	398,8
Sawmill 2	Species	*Picea abies*	*Picea abies*	*Picea abies*	*Picea abies*
	Dim. [mm]	(50x150)	(50x150)	(50x150)	(50x150)
	MC_{init} [%]	35,2	51,5	50,2	48,8
	MC_{final} [%]	12,9	19,9	16,6	16,5
	Density [kg/m^3]	-	-	-	-
Sawmill 3	Species	*Pinus silv.*	*Pinus silv.*	*Pinus silv.*	*Pinus silv.*
	Dim. [mm]	67,1x80,2	(63x100)	(63x100)	(63x100)
	MC_{init} [%]	61,2	64,7	55,6	50,6
	MC_{final} [%]	9,0	11,9	10,8	10,3
	Density [kg/m^3]	450,6	-	-	-

The sampling procedure used for determining the initial and final MCs was the same at all three sawmills. At loading, four samples were taken at random from each of the 16 packages in the kilns, in total 64 samples. The samples were weighed immediately, and their dimensions measured for determination of basic density. In addition, some samples were taken specifically for the different measuring systems, as will be stated in each case.

At the end of drying, two samples were taken at random from each package, a total of 32 samples for each drying run. The number of samples was chosen so that a certain statistical accuracy was achieved. The desired accuracy of the average MC was set at ± 5 % before drying (raw samples), and ± 0,5 % after drying (dry samples). A confidence interval of 95 % was used.

By all further evaluations of the accuracy of the different measuring principles it is important to take this into consideration.

By use of load cells in one of the industrial kilns, a reference curve for the moisture development between initial and final moisture has been worked out. This is further described in the next chapter.

Only one of the systems tested, the electrical resistance, gave a direct MC output signal. All other systems gave different signals as voltage, temperature differences etc., which could be correlated, to the reference MC.

To evaluate the different systems, a best fitted curve (optimal calibration curve) was established for two different moisture ranges, below 30 % and below 20 % MC. The accuracy of the different systems was then calculated as the width of the 95 % confidence interval for the fitted curves. This accuracy is in this report described as the potential accuracy of the system.

5.2. Weighing

Tests of the weighing methods were carried out at sawmill 1 (full scale) and at sawmill 2 (mini-scale).

5.2.1. Full scale (Sawmill 1)

Material and methods
At sawmill 1, four load cells were installed in the kiln, underneath a frame carrying the four innermost packages, row A at figure 22. The frame was made from wooden glulam beams to minimise the influence on the load cells from thermal expansion and contraction of the frame. There was no fixed connection between the frame and the load cells, only bolt heads resting on heavy metal strips, figure 18. In this way, deformation of the wooden frame would not transfer any momentum to the load cells, but merely cause the metal strips to skid on the bolt heads. Since the entire load was not fixed to the ground, the forklift operator had to show extreme caution when loading and unloading the kiln. The construction had a designed load capacity of 20 tons.

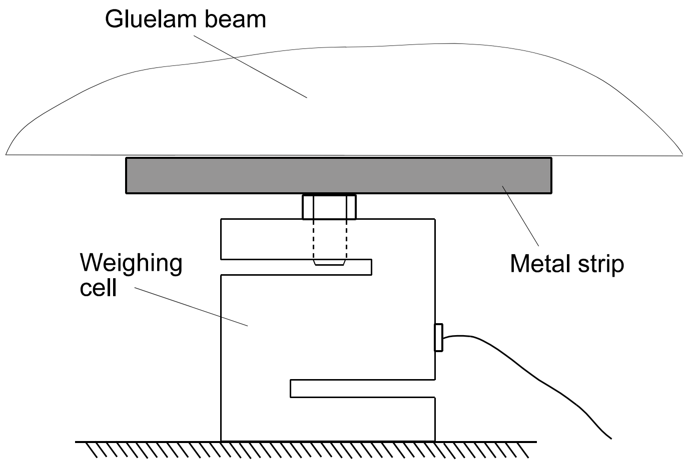


Figure 18. Load cell arrangement for momentum-free transmission of load.

During loading and unloading of test #1, all stickers from one package were weighed. A negligible weight reduction of the stickers during the drying cycle was found. During all tests, the recorded weight was corrected for the (constant) weight of the stickers.

Results and discussion

Figure 19 shows the result from the first drying run at sawmill 1. The initial and final MCs are shown, along with the curve from the continuous weighing of the four innermost packages in the kiln. The weight increases 186 kg during the heating phase when the water spraying system adds water to the kiln. Hence, the most probable cause for the weight increase is water droplets and condensation on the timber surface.

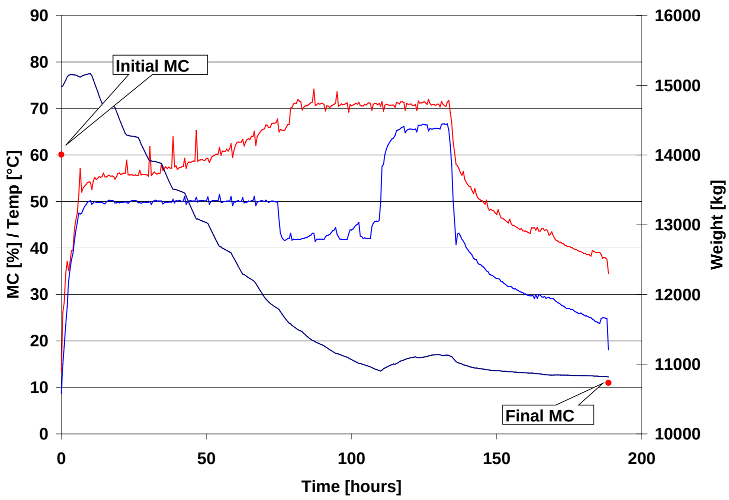


Figure 19. Weight-curve from test #1 at sawmill 1.

The “steps” in the curve that is seen during the first 50 hours of drying is caused by the fan reversal intervals. When the timber is very wet, and gives off a lot of humidity, the drying of the weighed pile (row A, figure 22) decreases or stops during periods of being on the “back” side of the air stream. This effect gradually decreases as the timber dries.

In this particular test it can also be noticed that the weight, and hence the MC of the timber, increases more than expected during conditioning. Most likely this is because of water condensation and the formation of droplets on the timber surface during water spraying. This is further substantiated by the fact that most of the weight gained during conditioning, vanishes quickly during the subsequent cooling period.

A weight-based prediction of the MC at any time during drying can be calculated by using the formula below, where m_{total} represents the mass of the kiln load at the given moment.

$$MC = \left(\frac{m_{total} \cdot \left(1 + \frac{MC_{initial}}{100}\right)}{m_{initial}} - 1 \right) \cdot 100\%$$

In table 4 key data for the four weighed packages (row A, figure 22) and the entire kiln load during all tests are shown.

Table 4. Key data for the weighed part of the load (row A) and the entire kiln load.

	Test #1		**Test #2**		**Test #3**		**Test #4**	
	Row A	**Kiln load**	**Row A**	**Kiln load**	**Row A**	**Kiln load**	**Row A**	**Kiln load**
$MC_{initial}$ [%]	55,3	60,1	62,8	62,4	39,3	48,1	57,6	50,9
$m_{initial}$ [kg]	14498		15093		13308		13476	
m_{final} [kg]	10366		9909		10199		9514	
MC_{final} [%]	11,4	11,0	9,5	9,8	8,1	8,2	8,6	8,9
Basic density [kg/m^3]	403,3	394,5	399,2	404,4	375,1	401,8	391,9	390,4

As seen from the table, there is little difference in the final MCs of “row A” and the average final MC in the entire kiln load. This means that a good prediction of the MC of row A would also be a good prediction of the MC of the entire kiln load. Using the equation above with data for initial MC, initial weight and final weight gives the results presented in table 5.

Table 5. Predicted final MCs compared to measured final MCs.

	Test #1	Test #2	Test #3	Test #4
$MC_{predicted}$ [%]	11,0	6,9	6,8	11,3
MC_{final} [%]	11,0	9,8	8,2	8,9
Deviation [%]	0,0	-2,9	-1,4	2,4

The inaccuracy in determining the final MC of the entire kiln load was at its greatest, at 2,9 %, during test #2. In the calculation, the data for row A was used, based on 16 MC samples before drying, and the progression of the mass of row A during drying. If all 64 samples (from the entire kiln load) had been used as an estimate of the initial MC, the deviation from the final MC would reach a maximum of 5,4 %, during test #3. This is because the initial MC of row A (and hence its weight) is different from the average MC of the entire batch.

This shows how vulnerable the system is to inaccurate estimates of the initial MC. However, the estimate of the final MC is not so much influenced by the initial MC deviation between row A and the entire batch when using row A, as a batch representative during the hole drying process.

Even though the weighing system produces a substantial deviation from the measured final MC when used for final MC prediction, it is a very good representative of the slope of the MC curve during drying.

Throughout this report the weight-curve is fitted to the measured initial and final MCs, and used as the reference MC curve, when displaying curves for other measuring systems. This does not necessarily make weighing a better system for MC prediction than the other systems, since both the initial and final MCs must be known to do the curve fitting. The system does, however, represent the slope of the drying curve very well.

By the judgement of this measuring principle and the following principles it is important not to forget that the determination of the initial and final moisture content by use of the oven dry method in it self gives an uncertainty of about ± 5 % and ±0,5 % at 95 % confidence interval respectively due to the limited sample numbers. All the evaluations as to the different systems ability to predict the initial and final moisture content, and the intermediate MCs, are based on the average values from the oven-dry measurements and the fitted weight curves.

As stated in the description of the measuring principle, the MC may also be calculated on basis of the weight, knowing only the basic density and green volume of the timber, using the following formula:

$$MC = \left(\frac{Total\ weight}{Basic\ density \times raw\ volume} - 1 \right) \times 100\%$$

Measuring systems in the production line can provide quite accurate data on the green (raw) volume of the timber in a kiln batch. The density, on the other hand, must be estimated either on behalf of average values for the species or by experience at the specific sawmill. Deviation between estimated and actual density will produce inaccuracy in the calculation.

During all tests at sawmill 1 the standard deviation for density ranged between 40 kg/m³ and 60kg/m³, This is likely to produce substantial variations also in the average density. Table 6 shows the deviation between actual values for final MC with measured densities and calculated final MCs using table (literature) values and average test-values for the two species..

Table 6. Calculation of final MC using known volume and estimated basic density.

Test no:	Actual values		Table density values			Average species density		
	Density [kg/m³]	**MC [%]**	**Density [kg/m³]**	**Calc. MC [%]**	**Dev. [%]**	**Density [kg/m³]**	**Calc. MC [%]**	**Dev. [%]**
1	394,5	11,0	385	16,3	5,3	392,5	14,1	3,1
2	404,4	9,8	430	0	-9,8	403,1	5,9	-3,9
3	401,8	8,2	430	-6,9	-15,1	403,1	0	-8,2
4	390,4	8,9	385	13,3	4,4	392,5	11,1	2,2

The deviation from the actual MC is substantial when using estimates for density in calculating the final MC. When table values for species are used, the deviation during the tests ranged between –15,1 % and +5,3 % MC. Using average species density for the tests involving similar species (test 1 and 4, and test 2 and 3) produces somewhat better results in the range of –8,2 % to +3,1 % MC.

Conclusion

The weighing principle measures the amount of water removed from the drying batch or a part thereof, with good accuracy. To use the system for practical end point determination the initial moisture content must, however, be determined with a high degree of accuracy. This requires a great number of samples to be taken from each batch, which is not realistic in everyday operation. The standard deviation for green wood MC is so high (20 %-40 %) that even with 100 samples taken from a normal kiln load, the accuracy in determining the average initial MC will be in the range of ± 6-7 % (95 % confidence interval). This again produces inaccuracy in predicting the final moisture content in the range of ± 4-5 %. Even lower accuracy is obtained by calculating the dry weight based on measured volume and estimated density. During the tests such calculations produced deviation between measured and calculated values of up to 15 % MC.

5.2.2. Mini scale (Sawmill 2). Weighing of sample boards

Material and methods

As mentioned earlier the periodical removing and weighing of sample boards is to a certain extent being done in connection with drying of costly hardwoods. The process involves manual work, and is more cumbersome compared to continuous weighing. The reason for its popularity is of course its simplicity and minimal use of costly and fragile equipment.

Today's dry kiln systems with electronic kiln control makes this method less attractive, since these systems easily can be connected to in-kiln load cells. There is, however, still some activity in the field of weighing sample boards instead of weighing a great portion of the kiln load.

The Norwegian supplier of wood drying systems, Alfsen & Gunderson, have developed their own system. It consists of a well-insulated mini-kiln that is connected to the mother kiln by means of a stainless steel pipeline. The pressure drop over the main air circulation fans drives a small part of the drying air through the mini-kiln, which is loaded with a limited number of stickered wood samples from the kiln load. The entire load of the mini-kiln is weighed on an electronic scale underneath the mini-kiln through four steel-rods sticking out of the mini-kiln bottom.

Since the sample load consists of just a few boards, the capacity of the weighing device does not have to be high. In fact, a high-accuracy small scale can be used. The scale is placed outside the kiln (and the mini-kiln) and is therefore not subjected to the corrosive kiln climate. Another advantage is that the density and volume of the sample boards can be determined with a high degree of accuracy, which increases the accuracy of the total system. The disadvantage is of course that only a small part of the timber is weighed, and that the selecting of representative samples is an almost impossible task, (unless the number of samples is large).

Results and discussion

At sawmill 2, 12 samples contained in a small, well-insulated compartment mini-kiln in the inspection corridor above the dry kiln, was weighed continuously by means of an electronic scale. The wood samples were placed on a cradle inside the mini-kiln, supported by steel rods down to the electronic scale underneath the mini- kiln. The layout is shown in figure 20.

Drying air from the mother kiln is lead through the mini-kiln via insulated ventilation ducts, the driving force being the pressure drop over the main fans. The ventilation ducts are fitted with butterfly valves, so that the air velocity through the mini-kiln can be adjusted to equal the air velocity through the timber batch in the mother kiln.

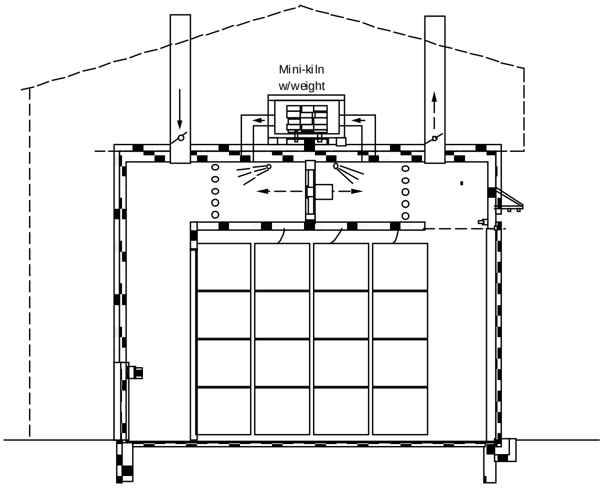


Figure 20. Dry kiln with mini-kiln in overhead inspection corridor.

During the tests twelve samples from twelve different packages were selected at random, equal number from top end and root end of the logs. All samples, each of 30 cm length, were end-sealed with silicon rubber. The load was made up of four layers, separated by 25 mm aluminium stickers. Figure 21 shows results from test #3 at sawmill 2, mini-kiln data in green.

The weight curve in the figure is not calibrated or fitted to the measured MCs. It reads in kilograms and shows how the weight of the test samples decreases during drying. It even shows an increase of weight during the heating-up and conditioning periods (when water spraying is active).

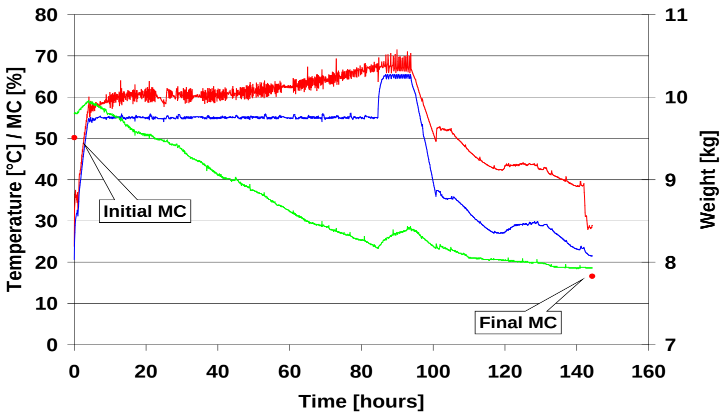


Figure 21. Test #3 at sawmill 2. The green curve denotes readings from the mini-kiln electronic scale.

Table 7 gives the results when the final MC is predicted by using the recorded data for initial MC, initial weight and final weight.

Table 7. Results from final MC prediction when using mini-kiln.

	Test #1		Test #2		Test #3		Test #4	
	Mini kiln	Main kiln	Mini kiln	Main kiln	Mini kiln	Main kiln	Mini kiln	Main kiln
$MC_{initial}$ [%]	36,3	35,2	-	51,5	50,8	50,2	-	48,8
$m_{initial}$ [kg]	11,31	-	10,47	-	9,80	-	9,89	-
m_{final} [kg]	9,42	-	7,51	-	7,93	-	8,41	-
MC_{final} [%]	13,1	12,9	17,6	19,9	14,7	16,6	17,2	16,5
$MC_{final,predict}$ [%]	13,5	12,6	-	8,7	22,0	21,5	-	26,5
Deviation [%]	0,4	-0,3	-	-11,2	7,3	4,9	-	10,0

For tests #2 and #4, the initial MC was not determined.

As can be seen from the table, the inaccuracy reaches levels of up to 11,2 % MC in the worst case. One source of inaccuracy is that the drying rate in the mini-kiln is not identical to the rate in the main kiln, even though the difference is not severe. A more important cause is obviously that the scale does not at all times read the correct values. This can be seen from test #3, where there is a discrepancy between the initial and final MC and calculations based on the initial and final masses. If the scale showed the correct values, this discrepancy would not be possible.

Conclusion

As a conclusion, the use of “mini-scale” weighing systems to control the development in MC during drying have, independently of system solutions, limitations as to accuracy due to the limited number of samples. Anyway, by use of accurate scales and correct climatic conditions these systems will be of great help in indicating the MC-development during drying.

The use of a few sample boards for weighing may predict the MC development of the sample boards with very good accuracy. This requires that the sample board MC is determined with a high degree of accuracy, which in practice is no problem. The representation of the sample boards with regard to the entire kiln batch will be highly dependent on the number of samples. The standard deviation does, however, narrow in as the timber dries, increasing the accuracy correspondingly.

5.3. Electrical resistance

5.3.1. Material and methods

Electrical resistances MC measuring systems were tested at sawmill 1 and sawmill 3. In both cases, commercially available units were used. Electrodes were inserted according to the specifications from the suppliers.

At sawmill 1 the sensors were spread out into the entire batch according to figure 22. The sensors were inserted into the flat side, in the middle part, of a plank in the second top layer of the packages. The result of one test is shown in figure 23, and figure 24, where in the latter the measurements have been compared to the reference curve based on sample-corrected weighing data.

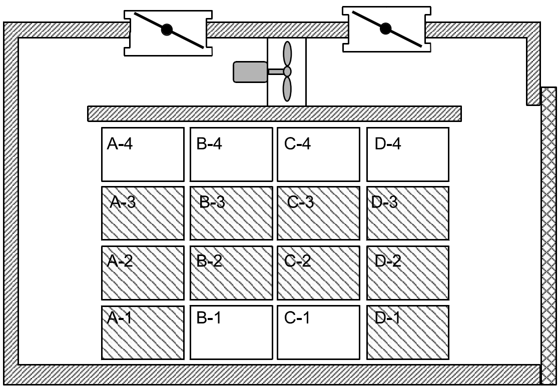


Figure 22. Placement of electrodes at sawmill 1. Each of the shaded packages was measured with el. resistance.

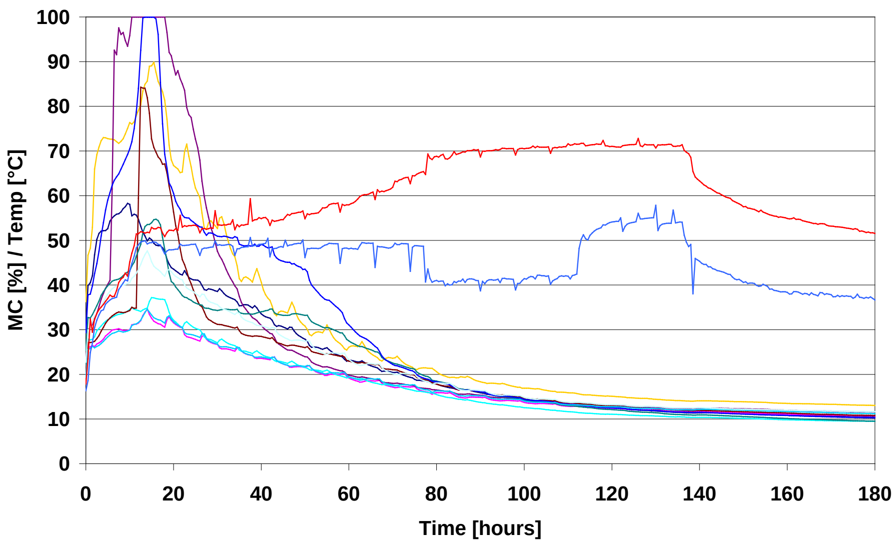


Figure 23. Ten-channel el. resistance MC measurement during test #4 at sawmill 1.

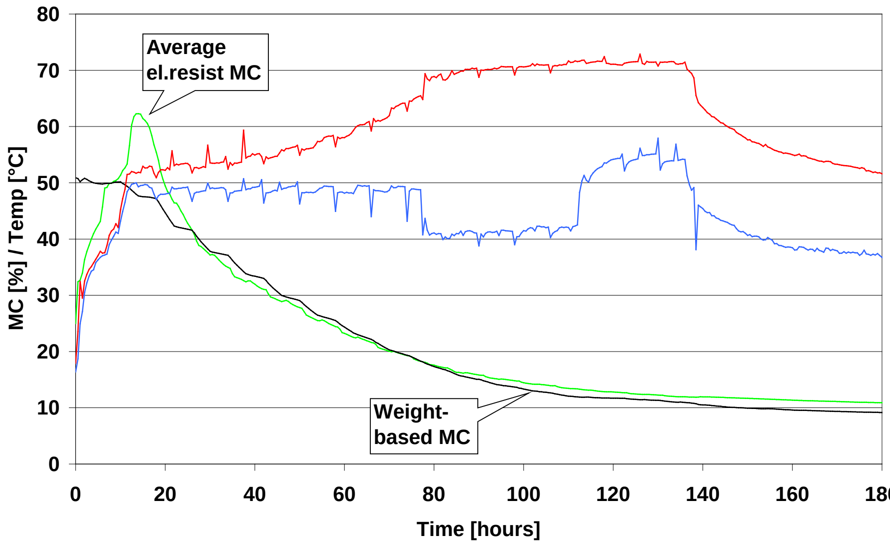


Figure 24. Average el. resistance MC during test #4 at sawmill 1. Weight-based MC used as reference.

As can be seen from the curves, there is a great variation between the channels in the start of drying. Some of them even go out of range (above 100 %) during the first hours. This also causes the instruments' average MC reading to increase rapidly and reach an unlikely high level for some hours. After about 30 hours the deviation to the reference curve decreases, and the average MC approaches the reference curve at about 40 % MC.

At about 16 % MC the deviation from the reference increases a little, and stays fairly constant until the end of drying, at 180 hours.

At sawmill 3 a different strategy for placing the electrodes was used. All eight sensors were put into the innermost, bottom package (package A-1 in figure 22), at the edge of the planks, facing the innermost inspection corridor of the kiln. This strategy has been utilised for several years at the sawmill, and they report satisfying results with it.

This is based on the fact that the sawmill has a high production rate, and that each drying batch is sawn and loaded into the kiln within hours. Tests have shown that the internal difference between packages is minimal, thereby making the one package a good representative of the entire batch. Figure 25 shows the result from test #4 at sawmill 3.

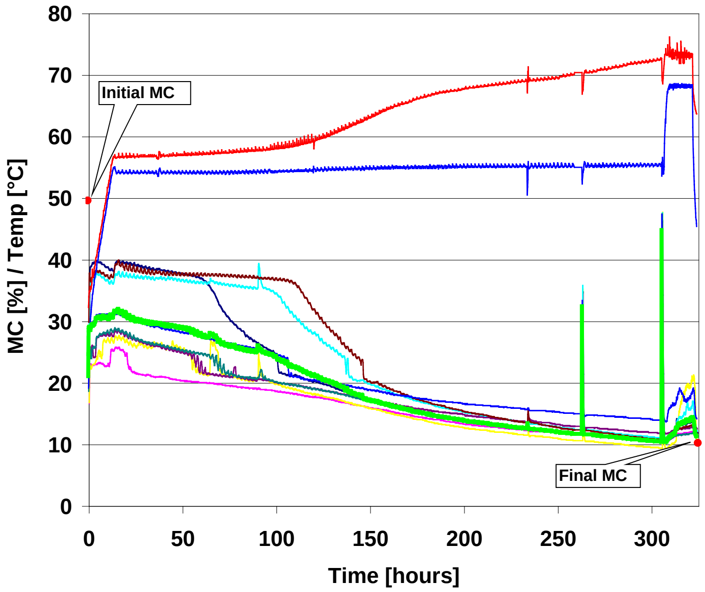


Figure 25. Eight-channel el. resistance MC measuring at sawmill 3 test #4. Thick green line indicates average value.

The figure shows that the deviation from the measured initial MC is significant, but that the deviation decreases as the drying cycle proceeds. The readings at the end of the drying cycle are clearly influenced by the conditioning period, but until then approaches a probable final MC.

5.3.2. Results and discussion

All further results are related to the MC range below 30 %, and readings from the conditioning period are excluded since they are likely to be influenced by excess water on the timber surface.

Figure 26 shows the relation between the readings from the el. resistance meter and the reference MC for all tests performed at *sawmill* 1. The results for pine and spruce are kept apart, even though the calibration curve used is the same for the two species. A fitted line is included for each of the tests.

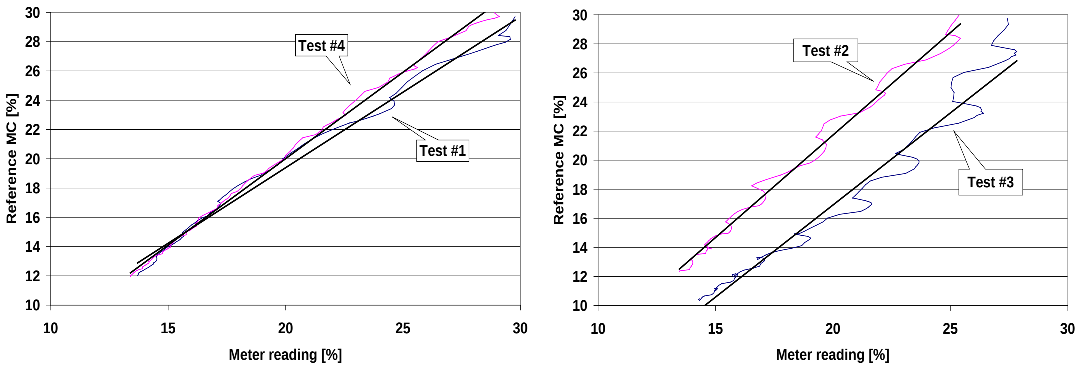


Figure 26. Relation between meter reading and reference MC for spruce (left) and pine (right) during tests at sawmill 1.

The deviation between meter reading and reference MC is shown in figure 27.

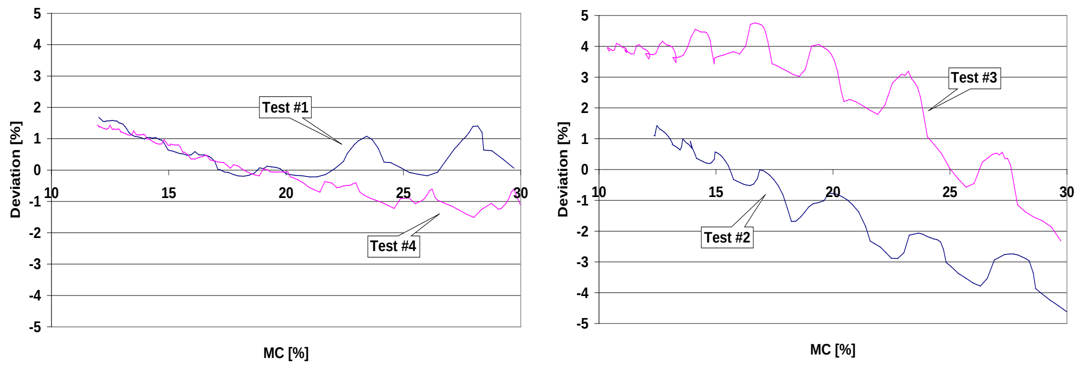
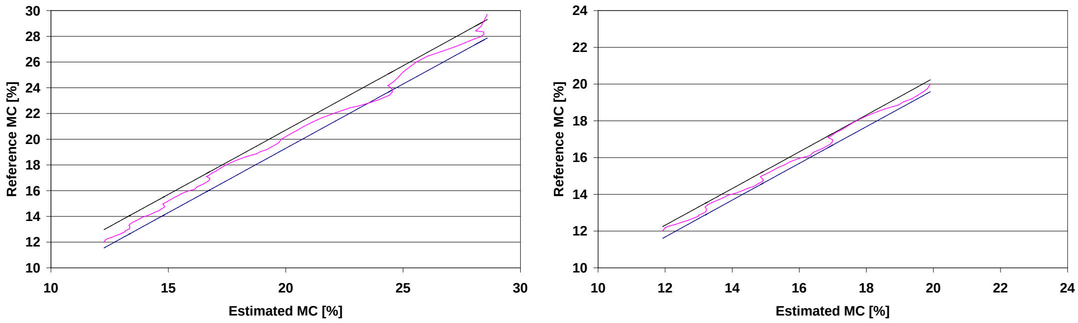


Figure 27. Deviation between meter reading and reference MC for spruce (left) and pine (right).

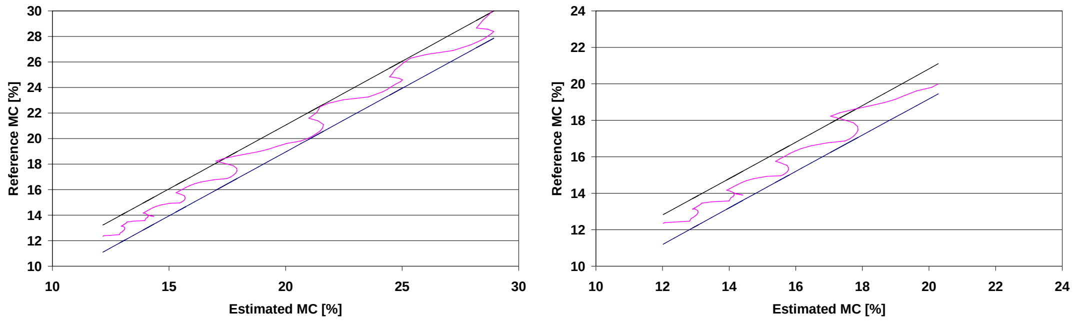
As can be seen from the curves, the deviation is more significant for pine than for spruce, and the repeatability is weaker. The figure also shows that in all but one test, the deviation from reference MC increases as the MC decreases, even though the MC level is above 10 % in all tests. In the lower MC range this would be expected, as the resistance increases to higher levels than can be measured, but not in the MC range above 10 %. This implies a systematic error in the calibration curve.

I fig. 28 the measured values have been recalculated to ideal curves corrected for systematic errors, giving an indication of the potential accuracy of the system. The accuracy is tested at two levels –below 30 % and below 20 %.

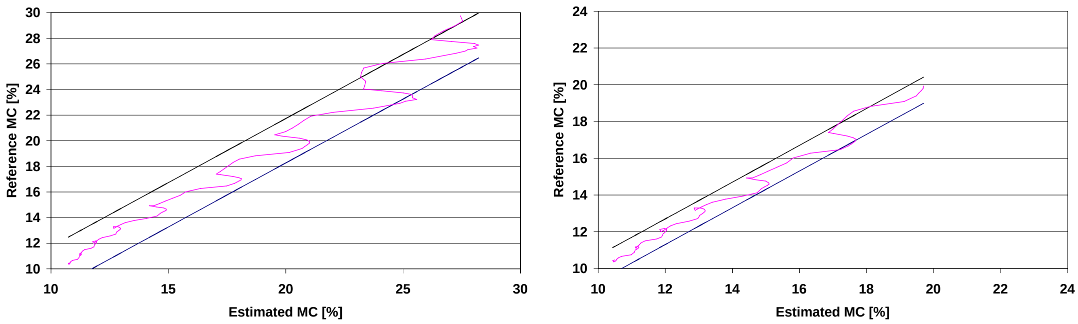
For each test a 95 % confidence interval for the individual values has been fitted



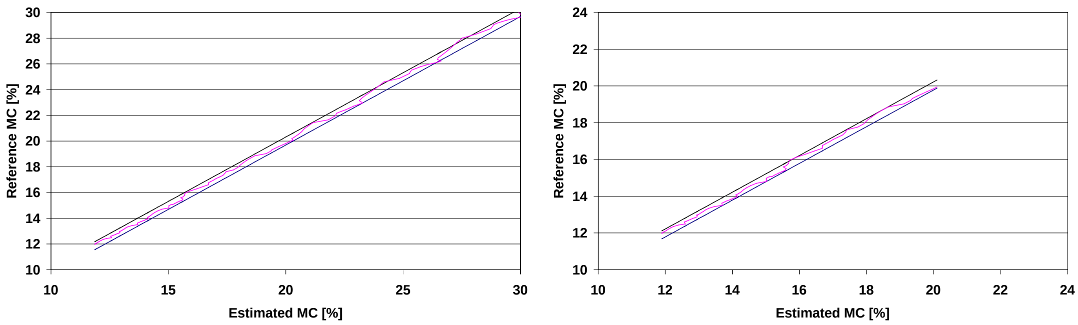
Test #1 (Spruce)



Test #2 (Pine)



Test #3 (Pine)



Test #4 (Spruce)

Figure 28. Potential accuracy of el. resistance measurement during all tests for MC range below 30 % (left) and below 20 % (right).

Table 8 shows the width of the confidence intervals for all tests by optimal calibration, both in the 30 %-range and in the 20 %-range.

Table 8. Width of 95 % confidence intervals for the coherence between meter reading and reference MC by optimal calibration

	Width of confidence interval	
Test no.	**Below 30 %**	**Below 20 %**
1	1,44	0,65
2	2,12	1,66
3	3,48	1,42
4	0,62	0,44

To further investigate the measuring principle accuracy not so closely related to the calibration curve, a recalculation was performed, giving the resistance in ohm instead of the calculated MC. Figure 29 shows the relation between this recalculated resistance and the reference MC for the tests at *sawmill* 1.

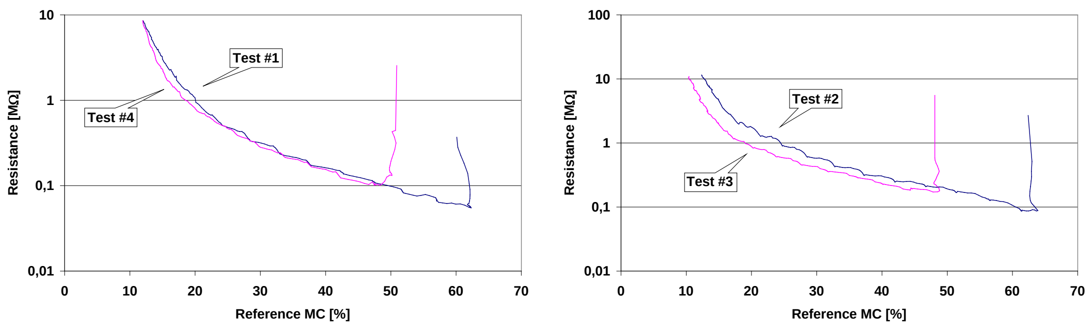


Figure 29. Relation between measured (recalculated) resistance and reference MC for spruce (left) and pine (right).

The usual regression model to use for this relationship is:

$$MC = \frac{\log(\log R + 1) - B}{A}$$

The coefficients A and B were calculated according to table 9 for the four tests at *sawmill* 1. The coefficients were calculated for the resistance data in the MC range below 18 %, because the wood temperature is stable in this range.

Table 9. Calculated coefficients for the regression curve between MC and resistance. Model made at a wood temperature of 69 °C.

Test no.	**Coefficient A**	**Coefficient B**
1	-0,0371	0,7312
2	-0,0362	0,7615
3	-0,0395	0,7130
4	-0,0460	0,8211

5.3.3. Conclusion

Of the eight principles investigated the electric resistance principle is by far the most developed and widespread. During the tests, the accuracy of the system was mainly influenced by the MC level measured and the calibration curve used. After the initial heat-up period, when the MC was still above the FSP, the measured accuracy (deviation between meter reading and oven-dry value) in the range of ± 5-8 % was reached. In the range below 20 % MC, the accuracy increased, resulting in an accuracy in the range of 2,0-2,5 %.

However, the tested system used the same calibration curve for both pine and spruce. This introduced inaccuracy into the measurement, since the two species do show a different behaviour as regards electrical resistance. If an optimal calibration curve is used for each species, the system with 10 electrodes had a potential of determining the average MC below 20 % with an accuracy of approx. ± 0,6 %.

The electrical resistance system is therefore a suitable system for in-kiln moisture control, and will be even more practical in use with the development of wireless signal transmission.

5.4. Dielectric-type moisture meter

5.4.1. Material and methods

The instrument used during the tests was a four-channel capacitance-admittance meter, slightly modified with one voltage output signal.

A strip of sheet metal (3 mm thick) was bolted to the concrete kiln floor and grounded according to instructions from the manufacturer. The same grounding source was used for the instrument and its housing. Figure 30 shows the principle layout of the instrumentation.

The four electrodes were spread out into the kiln load, one electrode in each pile of timber. Each electrode was placed above the tenth layer of timber in the bottom packages, approximately 70 cm from the floor, following the manufacturer's instructions. The electrodes were put into the gap between two layers of timber, resting directly on the timber with no fastening to the timber surface.

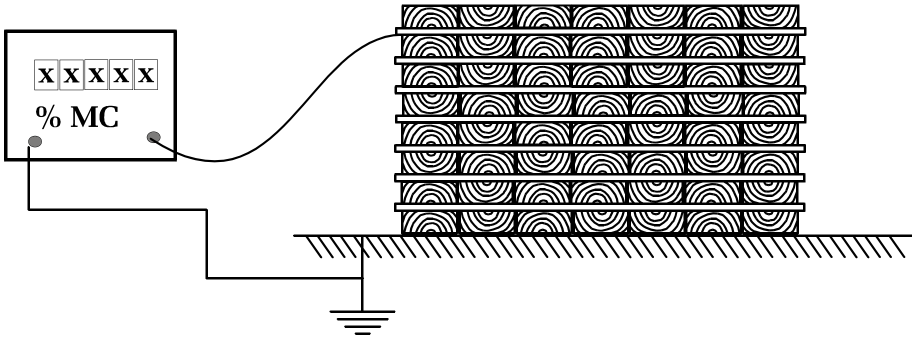


Figure 30. Principle drawing of the instrumentation at sawmill 1 (showing one channel).

The instrument delivered a signal from one channel at a time through the voltage output, but with no indication of which of the channels that were submitted each time. It was therefore not possible to separate the signals from the different channels in the analysis. The instrument delivered a voltage signal proportional to the measured wood MC.

The system was not included in test #1, and failed during test #2, leaving only test #3 and #4 valid for analysis.

5.4.2. Results and discussion

Figure 31 and 32 show the results from test #3 and test #4. As can be seen from figure 31, the capacitance signal corresponds well with the reference MC, even though there is some "noise" during the first hours. The fluctuations in the range 20-50 hours are most likely caused by the alternating direction of the airflow. After about 50 hours, however, the signal becomes more stable.

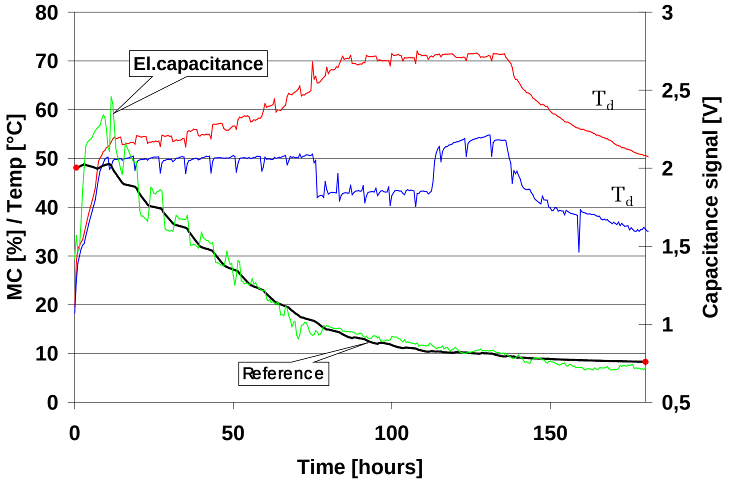


Figure 31. Results from the capacitance instrument during test #3.

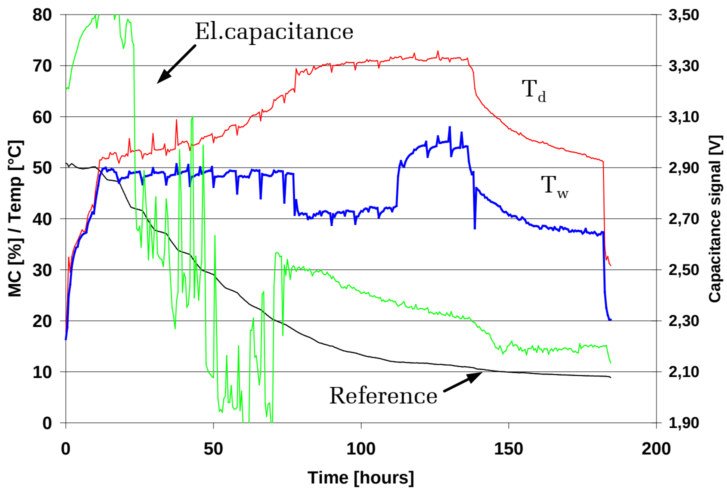


Figure 32. Results from the capacitance instrument during test #4.

As can be seen from figure 32, the performance during test #4 was much poorer than during test #3. This was caused by an instrument failure, as two of the channels kept "falling out" during the first 120 hours and, as earlier described, they could not be separated from the others for the analysis.

The correlation between the reference MC and the capacitance signal is shown in figure 33.

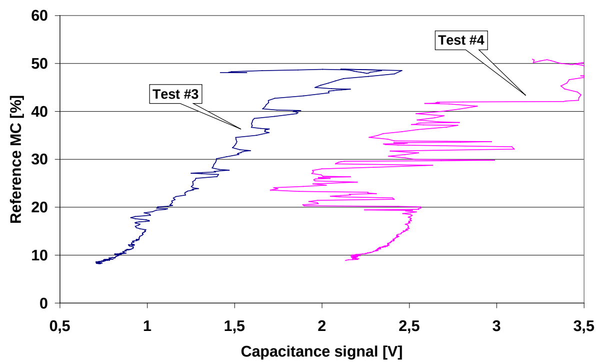
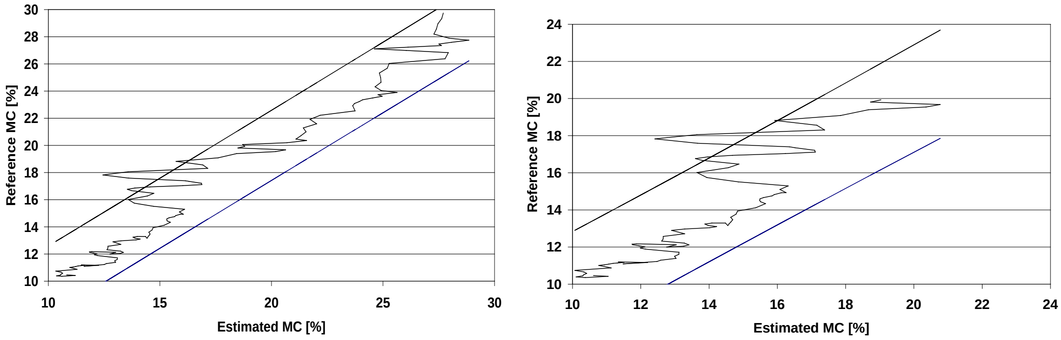
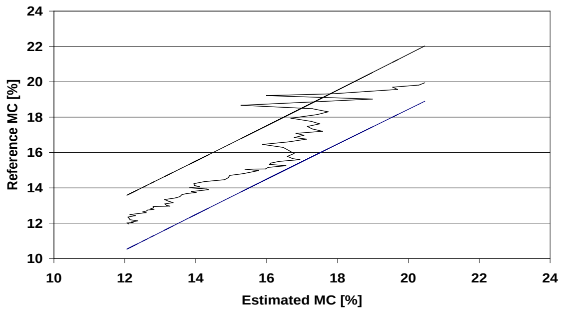


Figure 33. Correlation between capacitance instrument signal and reference MC during test #3 and #4.

The capacitance signal range during the two tests differs with about 1,5V at the same MC level. Since the set-up was similar and no adjustments were made between the tests, the shift most likely represents difference in density between pine (test #3) and spruce (test #4). A second-degree polynomial curve was fitted to the data from each test in the range below 30 % MC and in the range below 20 %. From the curves estimated MCs for each test were calculated, and 95 % confidence intervals for the predictions were calculated. This is shown graphically in figure 34 for test #3 and #4. For test #4 the data above 20 % were left out, since they were affected by the instrument failure described above.



Test #3 (Below 30 % left, below 20 % right.)



Test #4 (Below 20 %)

Figure 34. Estimated MCs and their confidence intervals for the capacitance meter (Test 3 and 4).

The width of the confidence interval, and thereby the inaccuracy of the measuring system is greater in test #3 than test #4 in the lower MC range as can be seen from table 10.

Table 10. Width of 95 % confidence interval for the MC estimates based on the capacitance MC meter data by optimal calibration.

	Width of confidence interval	
Test number	**Below 30 % MC**	**Below 20 % MC**
3	5,19	5,84
4	---	3,13

The reason for this can be seen in figure 31, where the data for test #3 temporarily (at 16-18 % MC) drift away from the reference MC. In the range between 20 and 30 % MC, however, the estimates for test #3 are better, tending to narrow in the overall accuracy.

For test no. 4 the accuracy between 10 and 20 % MC, expressed as the width of the 95 % confidence interval was 3,13 %, giving a corresponding accuracy of max ± 1,6 % (with no systematic error).

Unfortunately, the instrument used for the tests was old and did not function satisfactorily during the tests. In fact, it produced reliable results only during test #3, and at the end of test #4.

The measuring principle should, however, with further development and use of modern electronics, easy calibration and monitoring, be an interesting alternative for in-kiln measurement of wood MC. As can be seen from figure 31 the results in the MC range 30-50 % have about the same accuracy as the results below 30 %.

5.4.3. Conclusion

The dielectric principle as tested with the capacitance meter indicated that the system itself has a potential as an easy and non-destructive method for monitoring the in-kiln MC. It has the advantage of measuring a great number of planks in each of the monitored packages, increasing the accuracy in determining average MC.

The actual output signal from the tested instrument was a voltage signal proportional to the wood MC. The manufacturer supplied no calibration curve for the relationship between the voltage signal and the MC, but if a calibration curve ideally fitted for each test was used, a potential accuracy level below 30 % of approximately ± 2,5 % at 95 % confidence interval was calculated.

5.5. Shrinkage

5.5.1. Material and methods

Shrinkage was measured at all three sawmills during all tests. At *sawmill* 1 and *sawmill* 2, the measurement was done over 47 and 53 layers of timber respectively, as shown in fig. 35. For the test at both sawmills the recording of shrinkage started 7-9 layers below the top layer to avoid the influence of twisting of the upper layers.

Any twisting or cupping of the timber will reduce the shrinkage of the pile, and may even cause the pile to grow, as was the case during the initial laboratory tests.

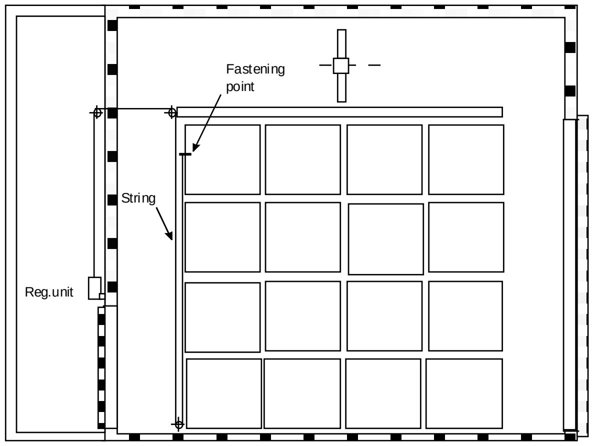


Figure 35. Arrangement for measuring the shrinkage.

At sawmill 3 a slightly different strategy for shrinkage measuring was used. The sawmill utilises top loads on the timber in the dry kilns to keep cupping and warp at a minimum. By recording the displacement of the top load during drying, the shrinkage of an entire pile (4 packages) was measured.

All shrinkage measurements were performed by using cable position transducers, each with a span of 763 mm. The actual transducers were placed outside the kiln, with only the cable running into the kiln compartment.

5.5.2. Results and discussion

A typical example of shrinkage measurement results is shown in figure 36, test #2 at sawmill 1.

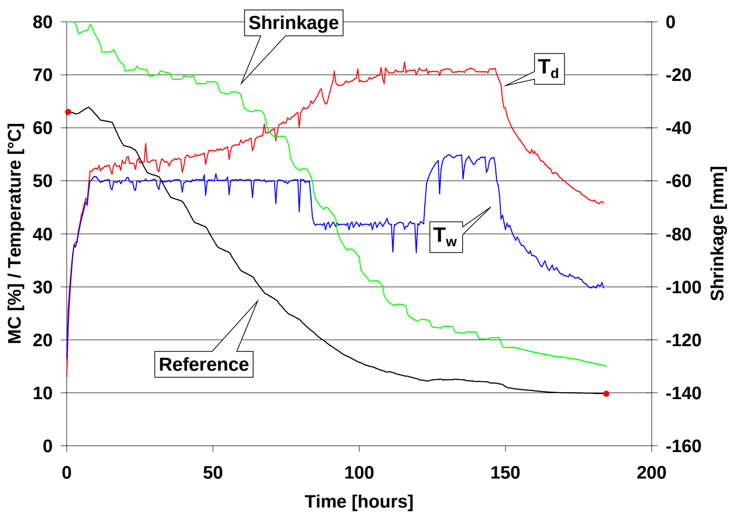


Figure 36. Shrinkage measurements at sawmill 1 during test #2.

The figure shows that the pile of timber starts shrinking immediately after the start-up of drying. After about 20 hours the rate of shrinkage decreases and levels out, until the MC reaches a level of about 35 %. Then the rate of shrinkage again starts to increase, and the rate stays fairly constant until the MC reaches about 15 %. Below that the rate is levelling out.

The “shrinkage” in the earliest stage of drying is probably caused not only by shrinkage of the individual pieces of timber, but rather by initial local compression of the wood in the area around the stickers, especially in the lower parts of the pile.

Figure 37 shows how the shrinkage develops as a function of the MC. As seen from the curve, and as expected, the rate of shrinkage approaches linearity as the drying proceeds below the fibre saturation point (FSP). There is, however, a transition area between 20 % and 35 %, as more and more of the timber cross section dries below the FSP.

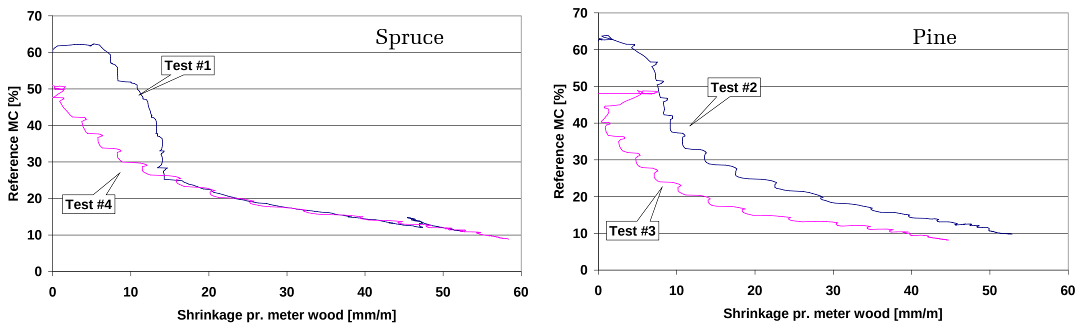


Figure 37. Shrinkage of one pile of timber in relation to the MC. The shrinkage is calculated as millimetre height reduction of the pile per meter timber thickness.

In figure 38 a linear regression line is fitted in the MC range below 20 %. The correlation factor R-square varies in the range 0,94-0,99, indicating a very good correlation coefficient shrinkage and MC.

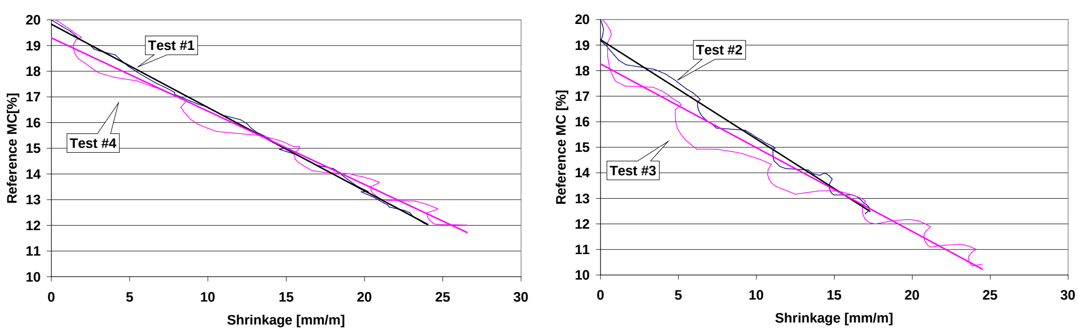


Figure 38. Regression lines fitted to shrinkage curves below 20 % MC, for spruce (left) and pine (right).

The formula for the regression line for one test can be used to predict MC values for another test based on its shrinkage data. As an example the regression line for test #1 is used to predict MC during test #4 from the shrinkage data of test #4. The maximum deviation between the reference curve and the predicted MC in the range below 20 % is then 0,92 % for spruce (shown in figure 39) and 1,87 % for pine.

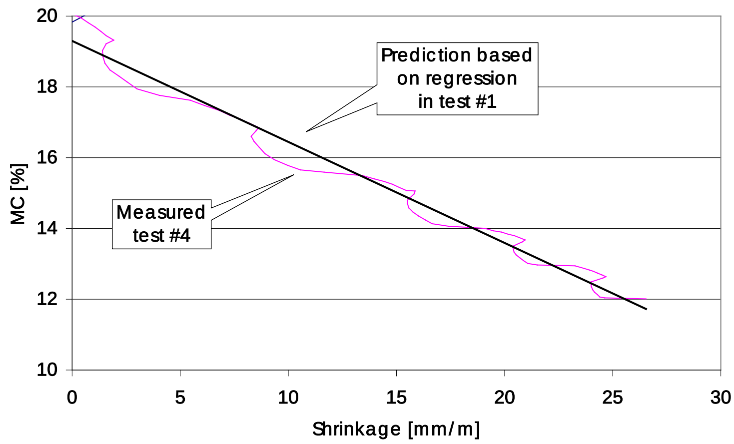
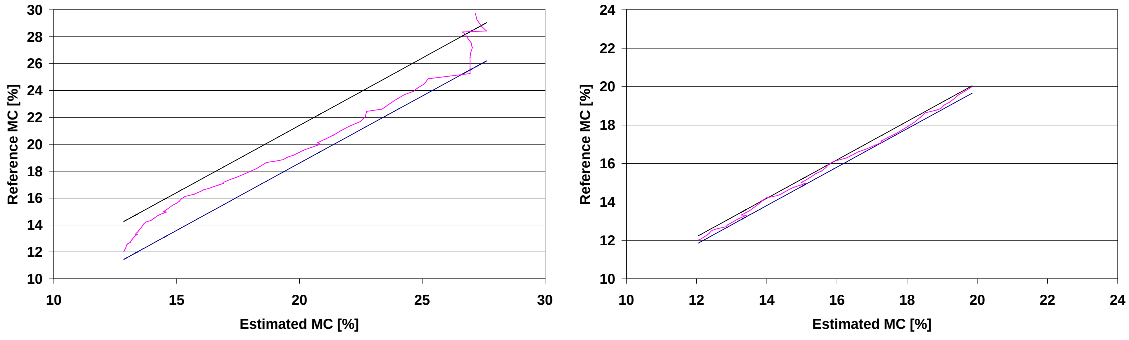
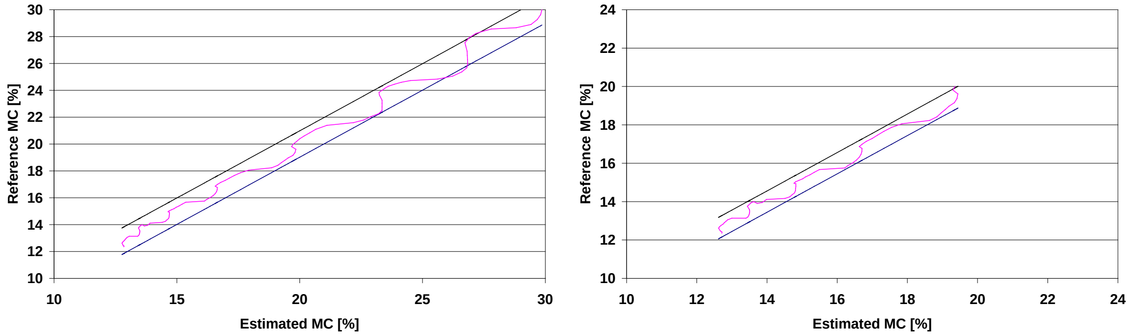


Figure 39. Regression line from test #1 used to predict MC during test #4.

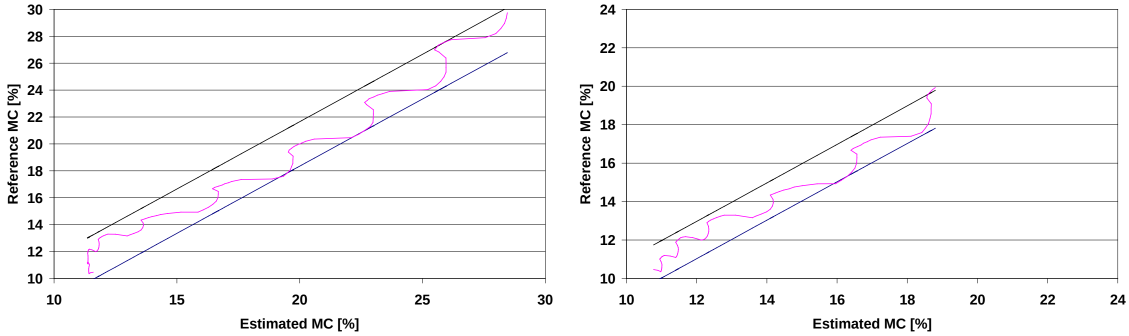
The accuracy of the measuring system is determined in the same way as for the other systems. A second-degree polynomial curve fit was used to predict the MC values from the measured data in each data set. A 95 % confidence interval for the prediction is used as a measure upon the system’s accuracy. This procedure was used on the data in the range below 30 % MC, and in the range below 20 % MC. Figure 40 shows the results from all tests.



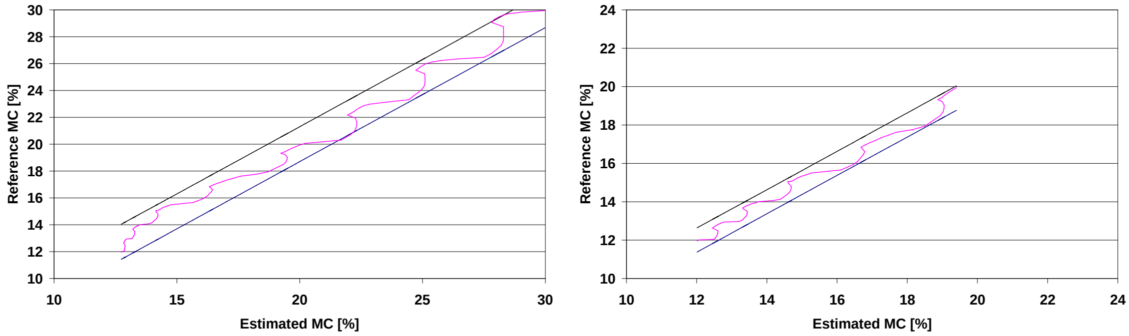
Test #1 (spruce)



Test #2 (pine)



Test #3 (pine)



Test #4 (spruce)

Figure 40. Potential accuracy of the shrinkage measurement during all tests at sawmill 1 for MC ranges below 30 % (left) and below 20 % (right).

Table 11 shows the width of the confidence intervals for all tests at sawmill 1.

Table 11. Width of 95 % confidence interval for the MC estimates based on shrinkage measurement by optimal calibration.

	Width of confidence interval	
Test number	**Below 30 % MC**	**Below 20 % MC**
1	2,84	0,39
2	2,00	1,14
3	3,34	1,97
4	2,64	1,28

The table shows that the inaccuracy in shrinkage measurements between 30 % and 20 % was at a maximum of 2,8 % for spruce and 3.3 % for pine. In the range below 20 % the maximum inaccuracy was 1,3 % and 2,0 % for spruce and pine, respectively.

5.5.3. Conclusion

The repeatability of the shrinkage measurements was poor in the higher MC range, but proved to be very good in the range below 20 % MC, when measuring shrinkage over a great number of layers. The most likely reason for this behaviour is that the timber stack "sets" during the first phases of the drying cycle, correspondingly causing unpredictable shrinkage of the stack. In the range below 20 % all "setting" is nearly completed, and the actual shrinkage of the timber is the predominant effect of what we measure. The potential accuracy below 20 % MC was approx. ± 0,6 % at 95 % confidence interval.

One possible way to reduce the effect of setting is by the use of top load on the timber stack. This will also have a positive effect on the deformation of the timber. There is, however, limits to the load that can be applied, since the weight on the bottom layers may cause compression of the wood when green. Further work is needed in this field, to optimise the use of top load, and to investigate the possibility of using adjustable top loads.

Another strategy for shrinkage measurement is to monitor individual pieces of timber, but then the problem of selection appears. The annual ring orientation will also have to be carefully considered when measuring individual pieces.

5.6. Nuclear MC meter

The nuclear MC meter was originally developed and tested for the Norwegian Institute of Wood Technology at the Institute for Energy Technology in Norway. Since then it has been tested as a prototype instrument in several drying kilns. As the instrument still was a prototype, it was in this test only possible to install the instrument at one sawmill, sawmill 1.

5.6.1. Material and methods

The instrument was installed in the test kiln at sawmill 1, partly lowered into the ground underneath the innermost pile of timber in the kiln, figure 41. This is the same pile where the load cells were installed. The frame supporting the load cells provided for a constant distance between the top of the instrument and the bottom layer of timber, a distance that is crucial for the measuring principle.

As the area of operation for the instrument is a half-sphere of 0,5-1 m in radius from the top of the instrument, only the bottom package (A-1 in figure 22) influences on the measurements. To get a better measurement for the MC in this package (A-1) 64 MC samples were therefore taken from the package before drying and 32 samples after drying.

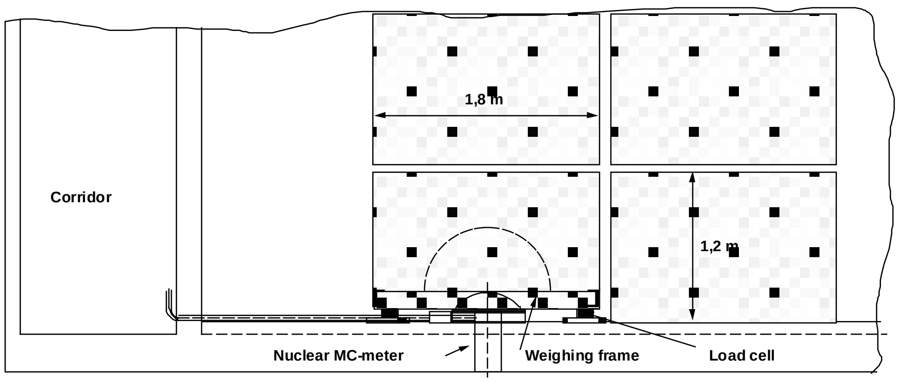


Figure 41. Details from the structure supporting the load cells and the installation of the nuclear MC meter.

5.6.2. Results and discussion

Figure 42 shows the results from test #4 at sawmill 1, using the weight-based MC as a reference. The figure indicates a good correspondence between the reference MC curve and the nuclear measurement curve. The nuclear instrument shows a greater MC increase during the first few hours than the reference. One possible explanation may be that the instrument is placed at the bottom of the kiln, measuring in the bottom package. During periods of water spraying, any excess water droplets will most likely hit the lower timber packages. The bottom part is also the coldest part of the kiln, and thereby most likely to cause condensation of the humid air during warm-up of the kiln.

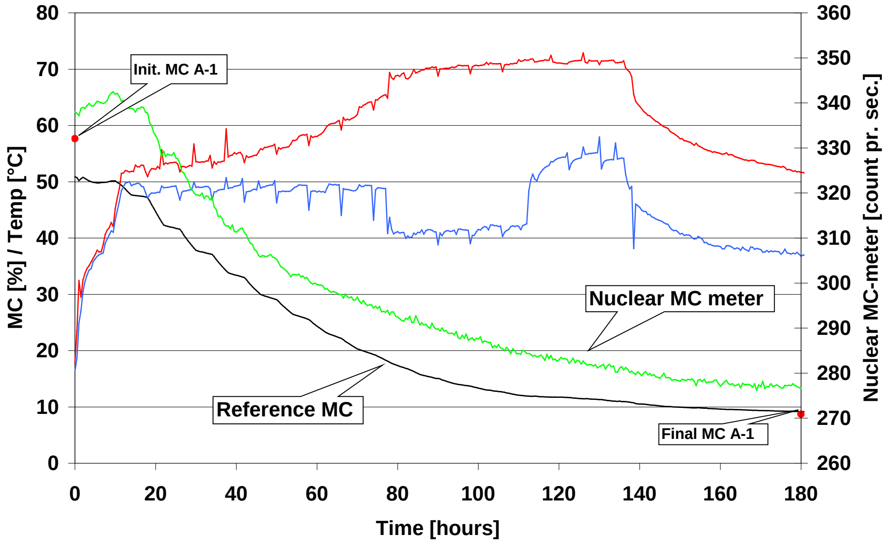


Figure 42. Results from test #4 at sawmill 1, showing the nuclear MC meter in comparison with the reference MC based on weighing.

During the tests, the geometry of the weighing frame was slightly modified, increasing the distance between the top of the nuclear MC meter and the timber package with 15 mm during test 3 and 4, compared to test 1 and 2. According to the manufacturer, this will cause an offset of the curves, but it will not affect their slope. To compensate for this offset, all curves were modified so that they by the actual geometry configuration read 30 counts/s at 20 % MC. Figure 43 shows the relation between the reference MC and the meter reading for the modified curves.

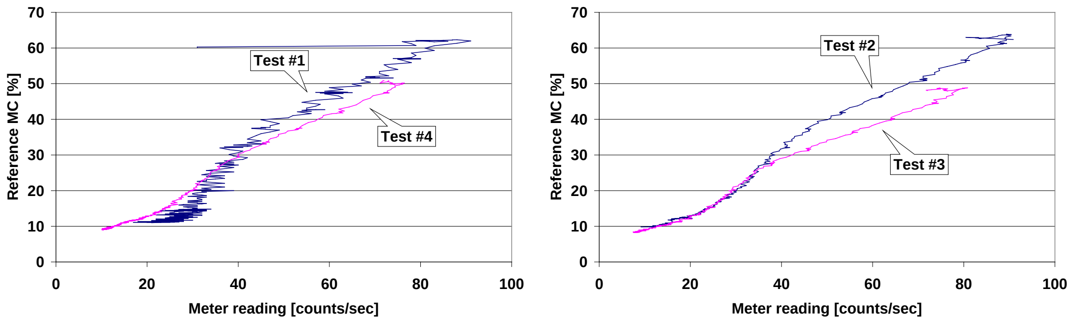


Figure 43. Progress of readings from the nuclear MC meter compared to the progress of the reference MC for spruce (left) and pine (right).

During test #1, a separate data logging device was used for the nuclear MC meter, utilising a different logging strategy than the logger used for the other systems (including the reference). This logging device recorded only instantaneous values at the time of recording instead of average values over the logging interval as for the main system. This explains why the curve from test #1 shows more “noise” than the curves from the other tests. When evaluating the data from test #1 this must be kept in mind.

For each of the tests two different second-degree polynomial curves were fitted to the data. One of the curves was fitted to the data in the MC range below 30 % and down to the final MC. The other curve was fitted to the data in the range 20 % and down to the final MC. An example is shown in figure 44. The R-squared values for the fitted lines were all higher than 0,98, except for test #1, which should not be focused on in this regard.

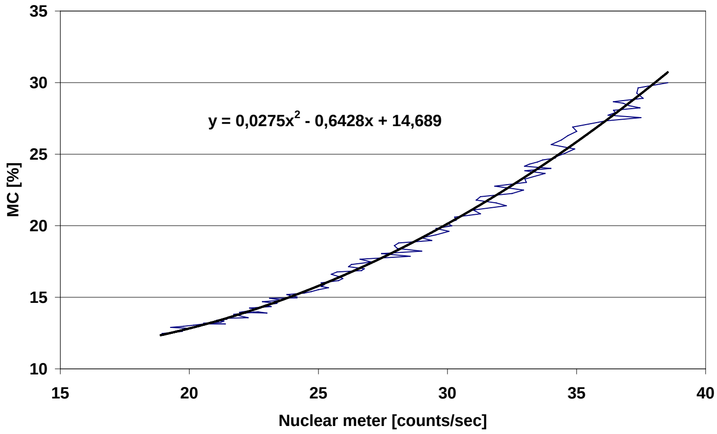


Figure 44. Second-degree polynomial curve fitted to the data in test 2, in the MC range below 30 %.

The curve functions were used to estimate the wood MC based on the nuclear MC data, and in figure 45 the estimates are plotted against the reference MC. A perfect estimation would give a straight line from the bottom left corner to the upper right corner. 95 % confidence intervals for each data set are also shown in the figures.

The width of the confidence interval is used as a measure upon the accuracy of the wood MC measuring system. Table 12 gives the interval width values for all tests. The wide confidence interval for test #1 is caused by the logging strategy rather than the measuring system, and must therefore not be emphasised. Separate confidence intervals were calculated for values below 20 % MC, and are shown in the table.

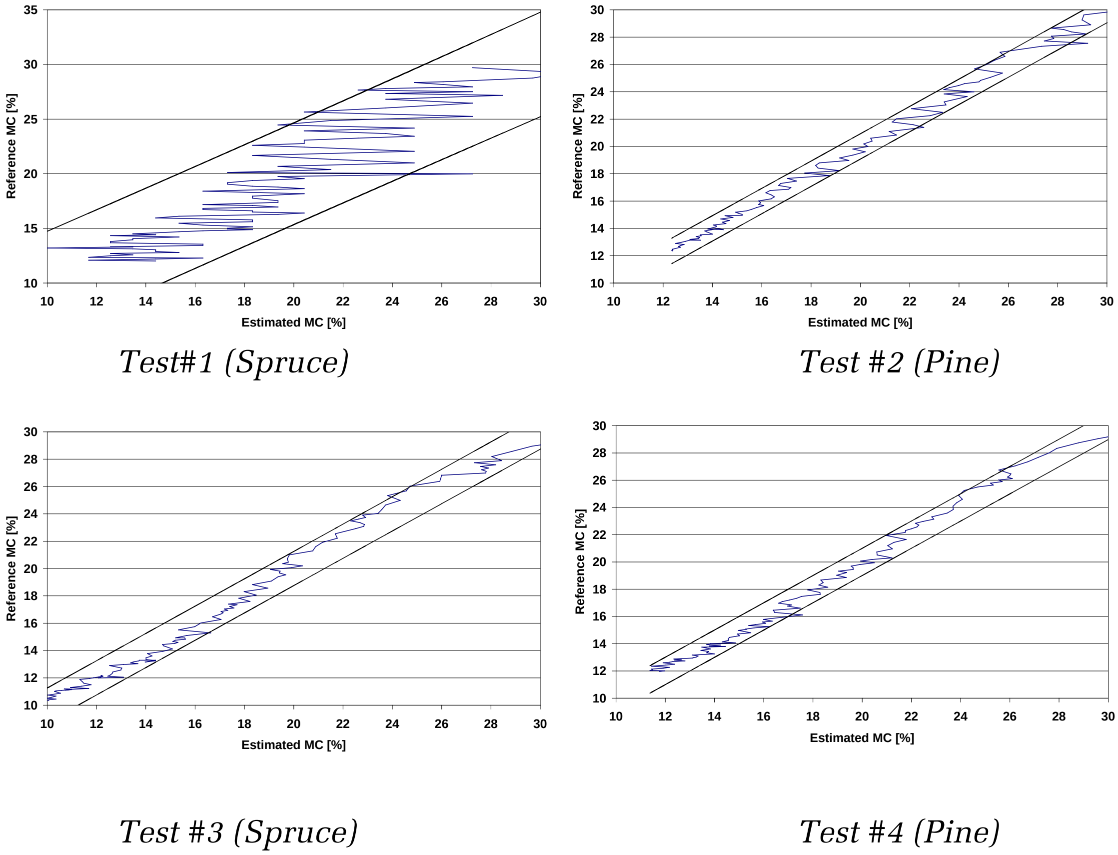


Figure 45. Estimated MCs from 30 % to 10 % plotted against reference MC for the four tests with 95 % confidence levels.

As can be seen from table 12, the potential accuracy of the measuring system for pine (test 2 and 3) was at a maximum of 2,5 %-points during the tests when based on the data below 30 % MC. For spruce in the same range the accuracy varied between 9,35 % and 2 %-points. Below 20 % MC, the accuracy was 1,2 %-points and 1,3 %-points, respectively, apart from test 1.

Table 12. Width of 95 % confidence interval for the MC estimates based on the nuclear MC meter data by optimal calibration

	Width of confidence interval	
Test number	**Below 30 % MC**	**Below 20 % MC**
1	9,35	5,87
2	1,86	1,20
3	2,51	1,18
4	2,01	1,32

5.6.3. Conclusion

The nuclear moisture meter showed promising results and repeatability in the lower MC range, especially below 20 % MC. A potential accuracy of ± 0,7 % was calculated in this range, given an ideal calibration curve. Above 30 % the test results were not as good, with differences between calculated and measured MC values of up to 7-10 %. The relatively poor accuracy in the higher MC ranges can partly be explained by a change that was made in the system set-up during the tests, as the distance between the instrument and the bottom package was increased by 10-15 mm.

This illustrates that the accuracy of the system is very much depending on the geometrical configuration of the package directly above the instrument, which have to be given great concern in further development of the instrument.

The system does, however, have the advantages of non-destructive measuring and minimal labour consumption in everyday use, and should therefore be very interesting to develop further. The instrument, in its present configuration, should also be suitable for use in continuous kilns, as it is lowered into the ground and is not in direct contact with the wood.

5.7. Temperature Drop Across the Load - TDAL

5.7.1. Materials and method

Measurement of TDAL was done in all tests at sawmill 1 and sawmill 3, and in the last two of the tests at sawmill 2. At sawmill 2 and sawmill 3 the control system temperature readings were used to calculate TDAL. This means that the temperature was only measured at one point on each side of the load.

At sawmill 1 additional temperature probes were installed, four on each side of the load. These were put just outside the gaps between plank layers, and were distributed over the kiln height.

5.7.2. Results and discussion

The TDAL is calculated as the absolute value of the temperature difference over the load. During conditioning this may be erratic, since humidity from the air may condense on the wood surface and thereby releasing its heat of evaporation. This part of the drying cycle is therefore not included in the analyses. Results from test #1 at sawmill 1 are shown in figure 46.

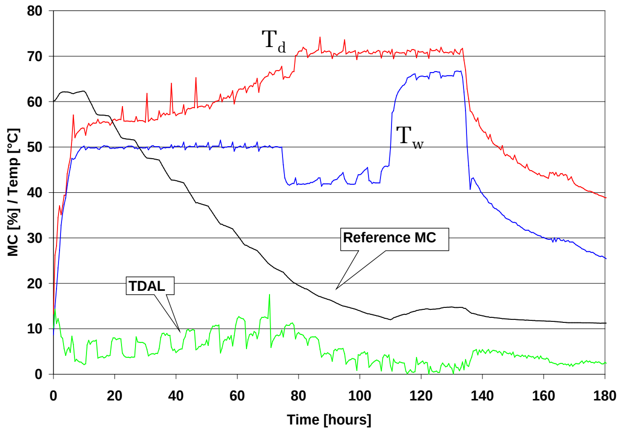


Figure 46. TDAL during test #1 at sawmill 1.

As can be seen from the figure, TDAL shows a tendency to increase during the first phase of drying (about 70 hours). This arises from the increasing wet-bulb depression during the same period. When the wet-bulb depression levels out and stays constant during the last phase of drying (80-115 hours), TDAL decreases steadily. It is in this phase the TDAL is of greatest interest, since the development in the drying rate in this period will not be affected by a change of climate.

In figure 47 the TDALs for all drying tests at sawmill 1 are shown. As can be seen from the figure, they all have a cyclic course, which arises from the change of direction of the air stream. This is also seen in figure 46 where the level of TDAL changes with up to 5 °C according to the direction of the drying air. A higher air velocity when the fans are blowing in one direction compared to the opposite direction is the most probable cause of this effect.

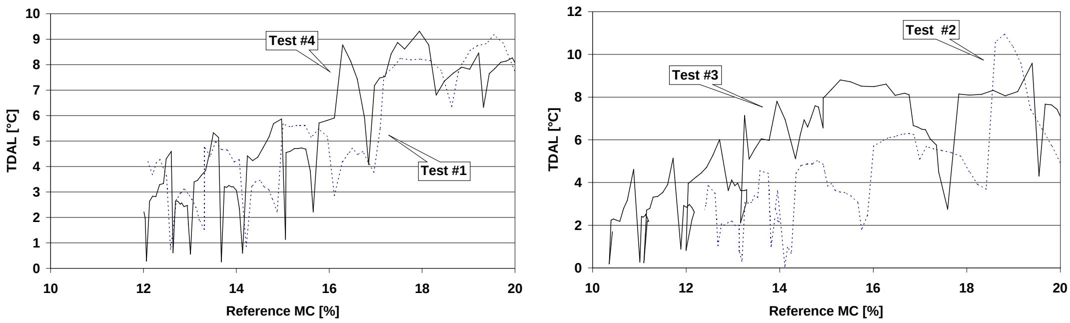
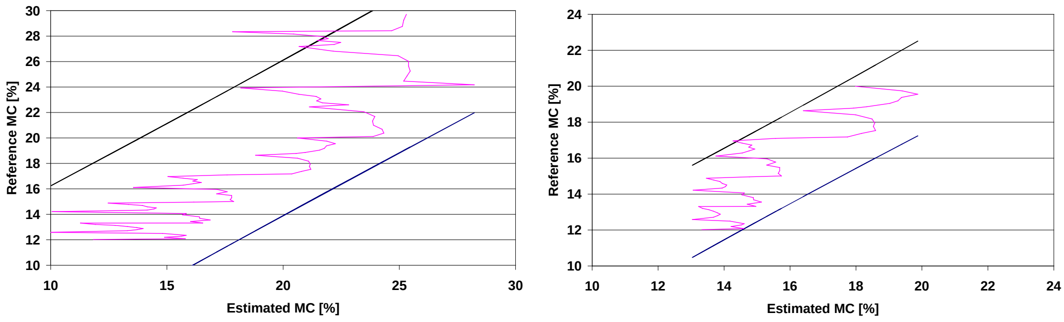
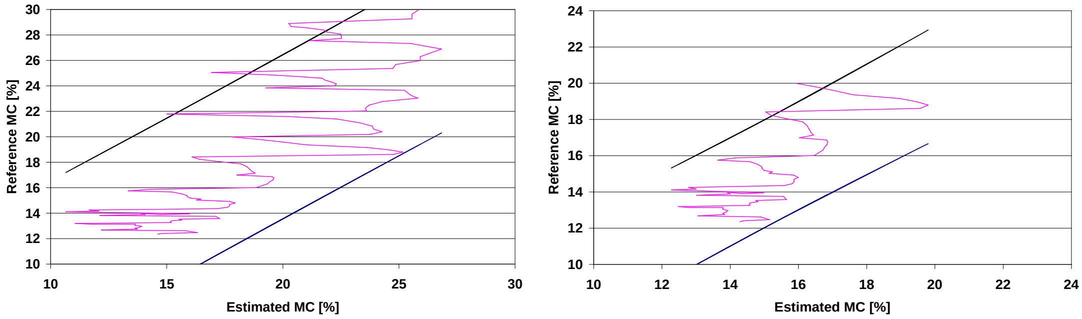


Figure 47. Progress of TDAL in relation to wood MC in the drying phase of constant wet-bulb depression.

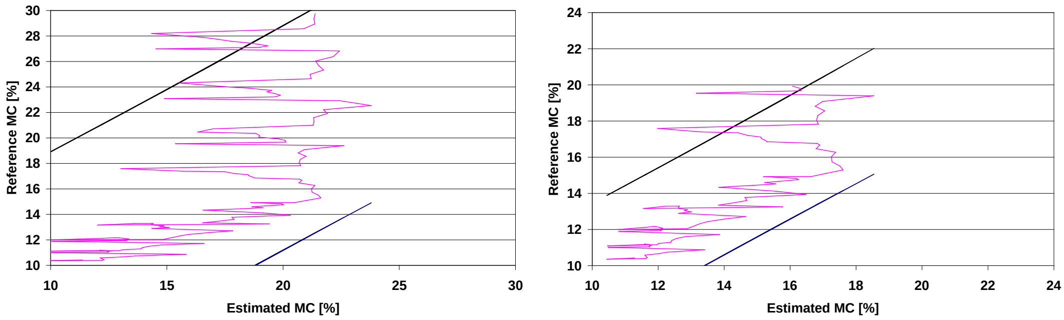
The diagrams show that the TDAL-curves have a great scattering even during the drying phase of constant kiln climate. In figure 48 second-degree curves have been fitted to the data from all drying tests at sawmill 1, and confidence intervals have been drawn for each of them, both for the range below 30 % MC, and the range below 20 % MC. The last one represents constant climate periods.



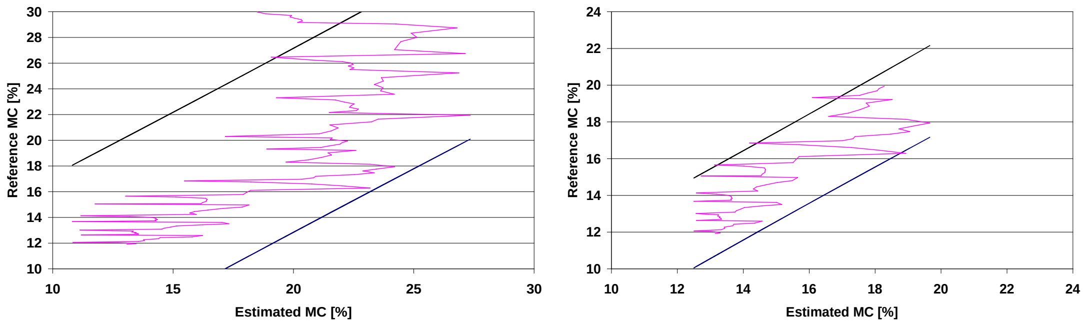
Test #1



Test #2



Test #3



Test #4

Figure 48. Potential accuracy of TDAL measurement during all tests for MC range below 30 % (left) and below 20 % (right).

The accuracy is bad as can be seen from table 13, but distinctly better for the range below 20 %, compared to the range below 30 %. This is, at least partly, explained by the fact that in the range between 20 % and 30 % the kiln climate still changes, which affects the level of TDAL.

For spruce an accuracy of 14,4 % and 5,3 % was achieved in the range below 30 % and 20 %, respectively. For pine the values are 17,9 % and 7,0 %.

Table 13. Width of 95 % confidence interval for the MC estimates based on the temperature drop across the load by optimal calibration.

	Width of confidence interval	
Test number	**Below 30 % MC**	**Below 20 % MC**
1	12,49	5,27
2	13,08	6,27
3	17,90	6,96
4	14,51	4,99

5.7.3. Conclusion

The principle of temperature drop across the load (TDAL) is easy to use, and requires no additional labour in everyday use. However, it did not show convincing results during the tests. The output signal was severely disturbed by fan reversal, and the system will be difficult to apply if using variable fan speed, which is now common.

The system reached a potential of ± 7,5 % below 30 % and ± 3 % below 20 % under constant climate and air velocity. Varying climate and air velocity will worsen the results.

5.8. Equalising principle

5.8.1. Material and methods

The tests were run in the Brunner laboratory kiln at The Norwegian Institute of Wood Technology (described in chapter 4.1.1).

The test material was freshly sawn 38 x 100 mm spruce (*Picea abies*) from a nearby sawmill. The test pieces were cut to a length of 120 cm, which is the maximum length to be dried in the lab kiln. 31 samples were taken from the load to test the initial MC by the dry weight method. A total number of 60 pieces were loaded into the kiln with 5 pieces in width and in 12 layers separated with 23 mm stickers.

All test pieces were end coated with silicone.

15 pieces were prepared for quick removal from the kiln through the inspection window for dry weight testing of the MC at intervals during the equalising period.

For continuous recording of the MC, 21 resistance sensors from two different systems were used, 11 from the built-in Brunner system and 10 from a Brookhuis system installed for the test runs. The electrodes were inserted to about 30 % of the plank thickness and were evenly distributed in the kiln load.

The test pieces were dried at a dry bulb temperature starting at 60 °C and ending at 80 °C with an EMC ranging from 18 % to 5 %. The test material was dried to an MC 2-3 % above the target MC during two tests, and to an MC 2 % below the target MC during the other two tests. The target MC was 12 % during all tests.

The drying schedule and the equalising climate, which were equal for the four tests, are shown in figure 49.

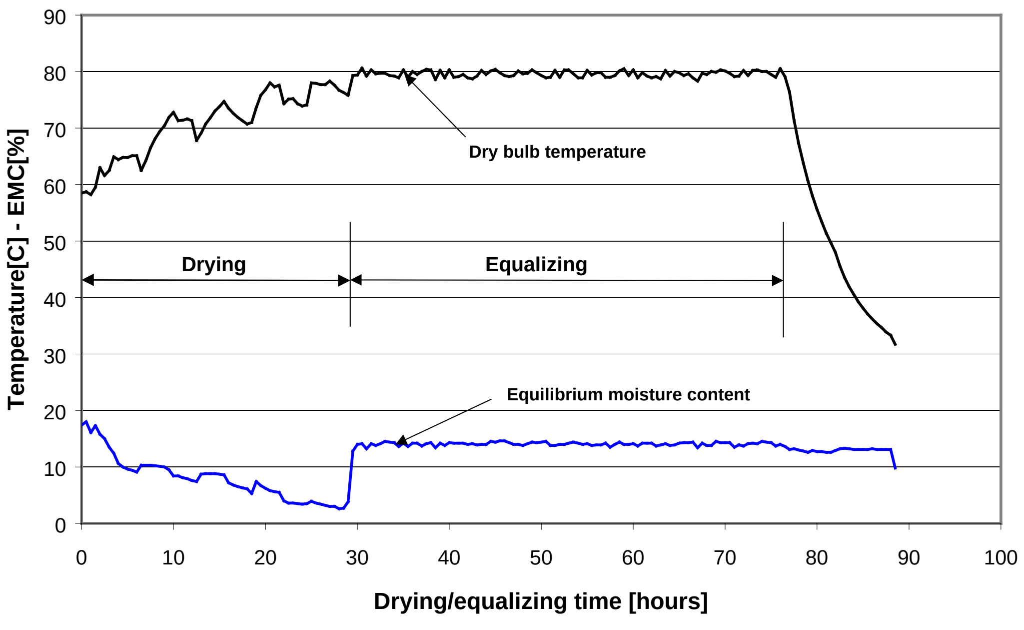


Figure 49. Drying climate by the four equalising tests.

As can be seen from the diagram the temperature during the equalising period was kept constant at about 80 °C. The EMC was set equal to the target MC at 12 %. The diagram above, taken from the Brunner logging system, indicates a bit higher EMC than 12 % (approx.13,5 %). This may be due to different measuring accuracy by the use of EMC-wafers (Brunner) compared to using wet bulb depression (reference system). The mean value of the dry bulb temperature during the equalising period was recorded at 80,5 °C and the wet bulb depression at 4,7 °C which gives an EMC of 12,0-12,5 % depending on the sources for the calculation of the EMC.

For the evaluation of the results an equalising climate of 12,3 % will be used, bearing in mind that the actual level may range between 12 –12,5 %.

During the drying period the climate and the MC were recorded by a data logger during all the four tests, but the more exact follow-up of the MC with both dry weight tests and resistance meters were only done in the equalising period. In figure 50 an example is shown of the recordings of the MC with resistance meters both in the drying and the equalising period (test 1).

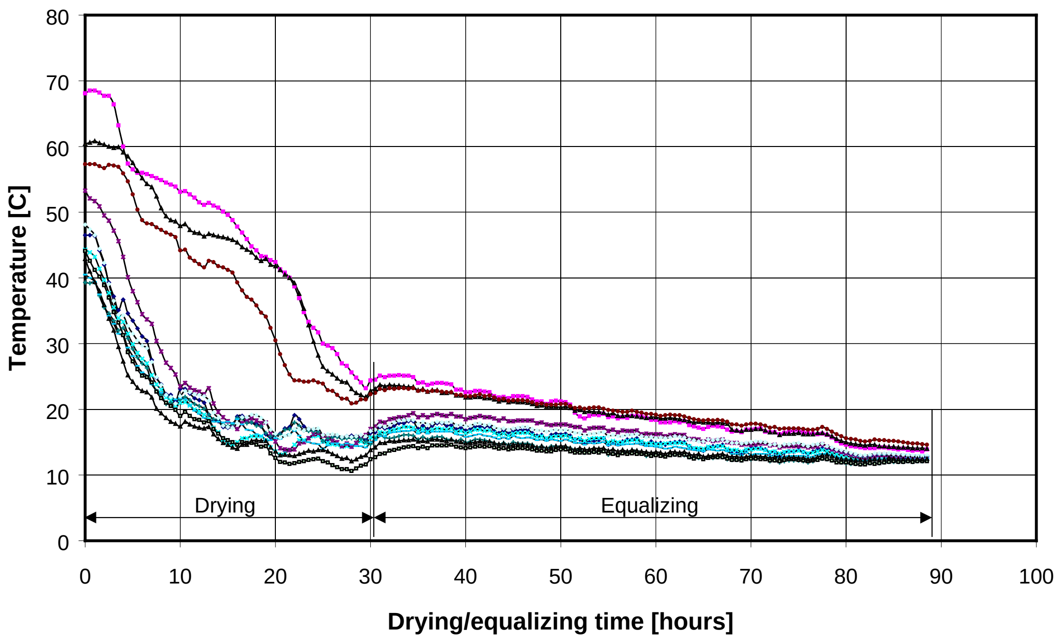


Figure 50. MC recording by resistance meters during the drying and equalising period for test no.1

For all tests the detailed registration of the MC began at the starting of the equalising period which lasted 50-80 hours. In addition to the logging of the MC by 21 resistance meters, 15 test pieces were cut from the load at intervals for controlling the MC by the oven-dry method. In test no. 4 casehardening was also tested at intervals during the equalising period.

5.8.2. Results and discussion

The results for test no.1 will be presented in detail with all the individual measurements for the MC from the 21 resistance meters. For test no. 2, 3 and 4 only the mean values for the measurements will be presented.

In test 1 the mean MC at the end of drying, before the start of the equalising process, was approx. 17 % and the standard deviation in the MC was 3,4 %.

In figure 51 we can see how the MC in 21 individual pieces and the standard deviation develops during the equalising process. The MC in test 1 is measured with 11 Brunner and 10 Brookhuis resistance meters.

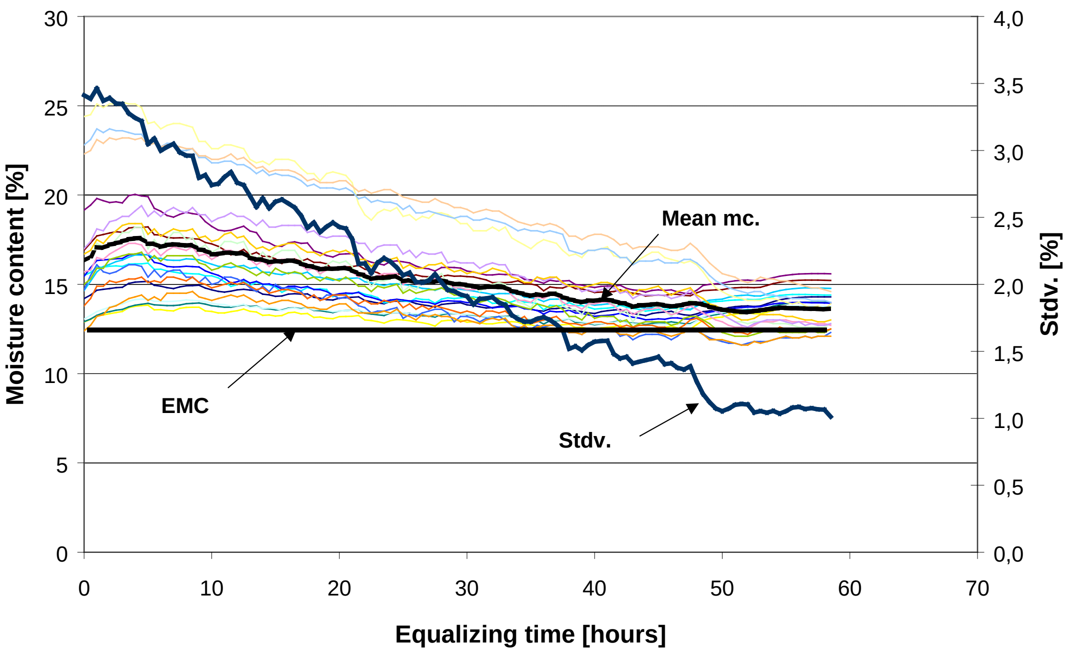


Figure 51. Development of MC and standard deviation during the equalising process in test no. 1, with an EMC-climate at approx. 12,3 %.

It can be observed that in the beginning of the equalising process the MC increases slightly before starting to decrease. This MC increase is observed in all tests and is caused by a rapid increase of the surface MC, which has been as low as 4 % at the end of the drying cycle. This MC gain in the surface layer will evidently influence on the resistance meters, which are inserted to a depth of about 30 % of the plank thickness. After this initial MC increase, the moisture in the inner parts of the planks will gradually decrease and lead to a general decrease in the mean MC.

The main observation is, however, the gradual approach of the MC in direction of the equilibrium MC, which is set to 12,3 %, and the pronounced reduction in the MC spread. At the end of the equalising process the MC is lowered from 17 % to 13,4 % and the standard deviation for the MC is reduced from 3,4 % to 1,0 %.

In figure 52 the development in the mean MC for all four tests with an EMC of appprox.12,3 % is shown. The mean values are based on registrations from 10 Brookhuis resistance meters. For test no. 4 one extreme value is omitted in the diagram.

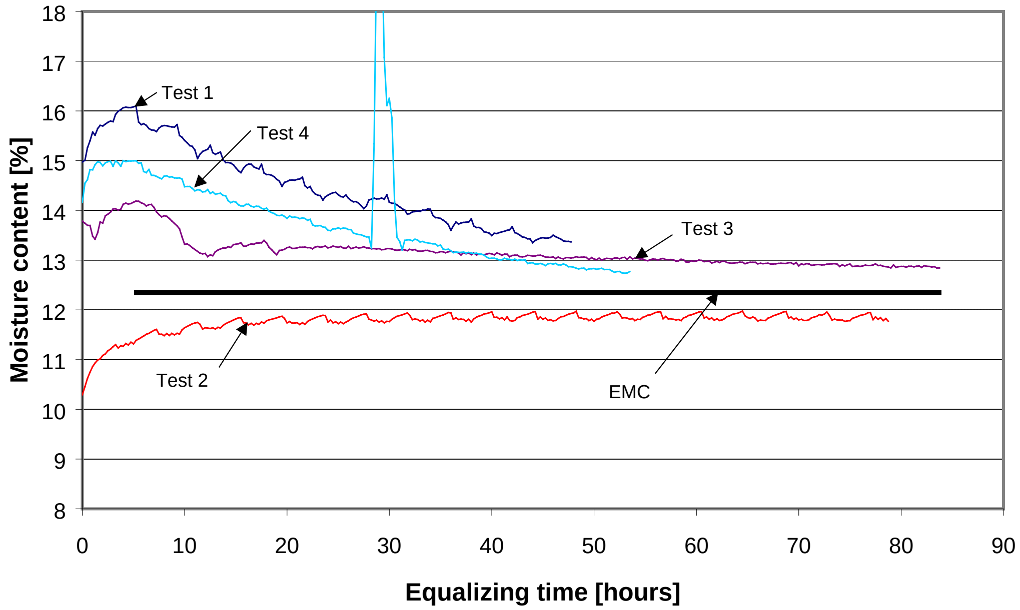


Figure 52. Development in mean MC (resistance meters) for all tests during the equalising process with an EMC of 12,3 %. (The peak in test 4 is caused by a problem with the steaming equipment.)

In figure 53 the development of the mean values for the MC measured by the oven-dry method is shown. (For test 1 the last oven-dry test failed).

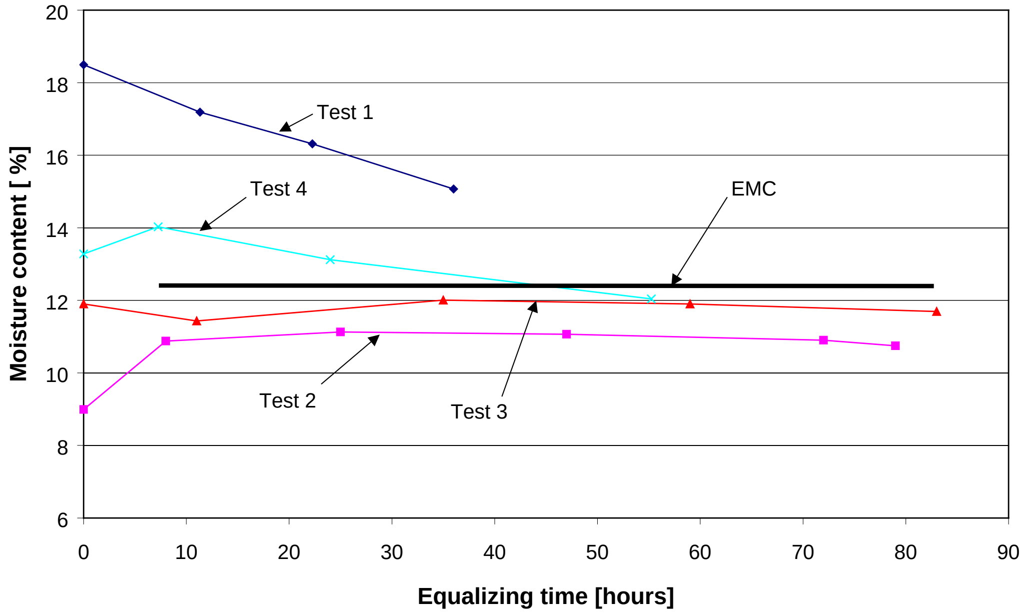


Figure 53. Development in mean MC (oven-dry method) for all tests during the equalising process with an EMC of 12,3 %.

The test results give a clear indication of the possibilities of using the equalising method to correct a miss in hitting the target MC.

From the two diagrams it can be observed that the deviation from the target MC is reduced to about one half in 24 hours and to about one third in 48 hours of equalising.

An equalising time longer than 48 hours does not seem to have any great influence on the MC, except for pieces with a MC far from the target MC.

It can also be observed from the curves in figure 52 that it is difficult to actually reach the target MC (the EMC). The difference between the actual MC and the target MC seems to reach a minimum of about 0,5 %, even after a prolonged equalising process. One possible reason for this is that the equalising in reality will need a very long time, or that there still will be a hysteresis of ±0,5 % that is impossible to overcome. However, according to the curves in figure 12 (Weichert) the hysteresis should disappear when the wood temperature exceeds 75 °C. This is not yet verified, and pinpoints the need for up-to-date sorption tests. (A test chamber is now built at NTI for sorption tests up to 100°C)

In figure 53 the values are based on the oven-dry method where test pieces were cut at time intervals from 15 planks. The wood MC-values are a bit low compared to the EMC-values. The most likely explanation for this is a systematic error in the moisture metering caused by a minor drying out of the test pieces in the process of taking out planks, cutting and weighing. Anyway the equalising is progressing in the same way as observed by the resistance meters, with an approx. difference of ±0,5 % between the actual MC and the target MC.

As a conclusion the tests have shown that by use of the equalising method at 80 °C it is possible to correct the final MC of 38 mm spruce to an accuracy of approx. ± 0,5 % in 48 hours and approx. ± 1 % in 24 hours when the initial deviation from the target MC is within ± 3 %.

5.8.3. Influence of equalising on moisture spread and casehardening

The diagram in figure 54 shows the development of the moisture spread during the equalising process for all four tests. For test 3 the results with and without one extreme value for the MC are shown as well.

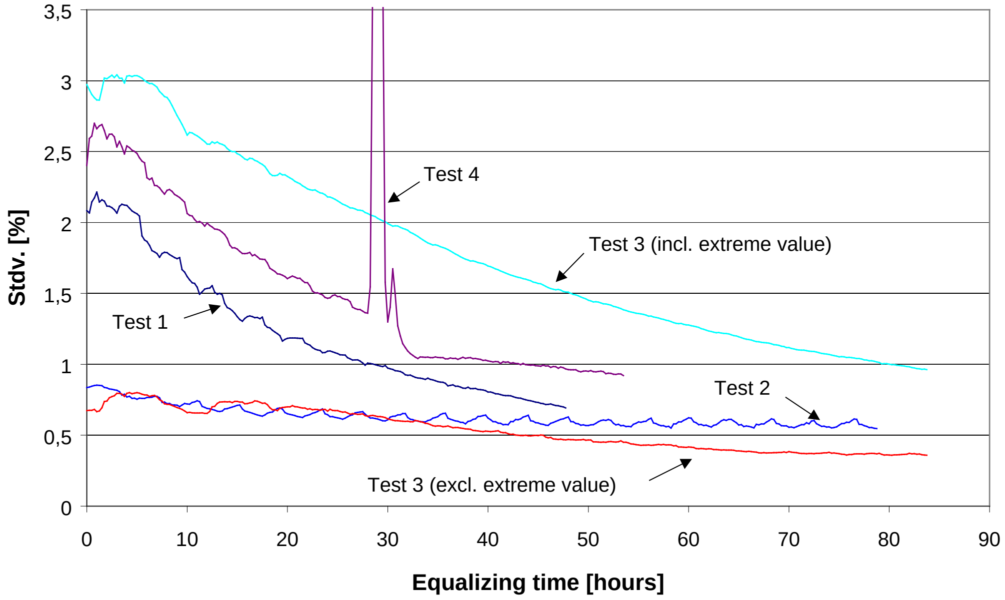


Figure 54. Development in the moisture spread during the equalising process measured by resistance meters.

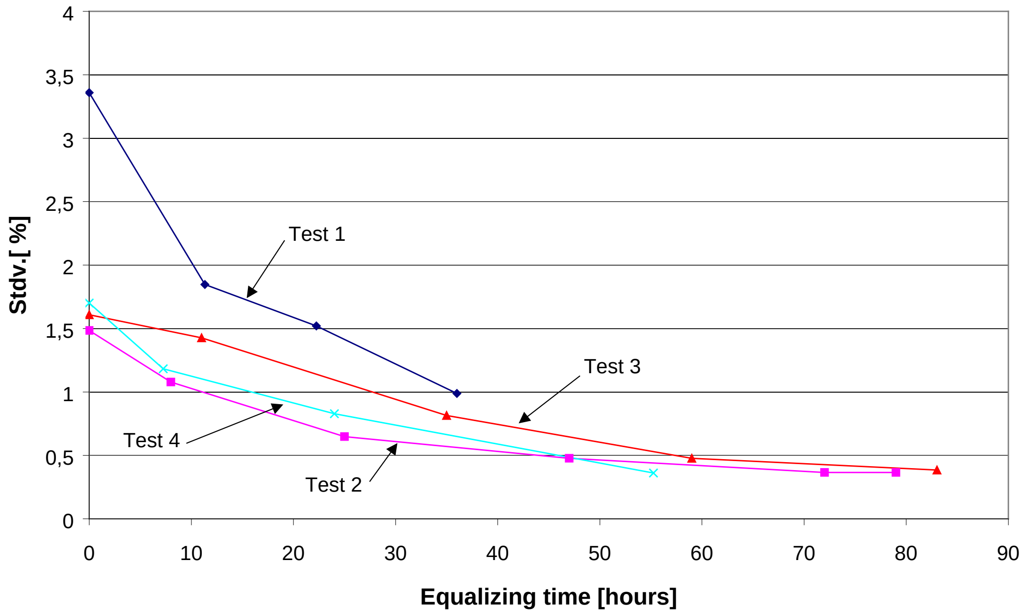


Figure 55. Development in the moisture spread during the equalising process measured by the oven-dry method.

For all tests a marked reduction in the standard deviation of the MC during the equalising process can be observed. The standard deviation is reduced to roughly 1/3 after 48 hours of equalising and to 1/2 after 24 hours. After 60-80 hours of equalising the standard deviation is reduced to a value as low as

0,35 %, which is close to the natural spread in standard deviation caused by the inhomogeneity in the wood itself.

In test no. 4 casehardening tests were taken at intervals during the equalising process. The level of casehardening was tested according to the procedure in the EDG-proposal for drying quality.

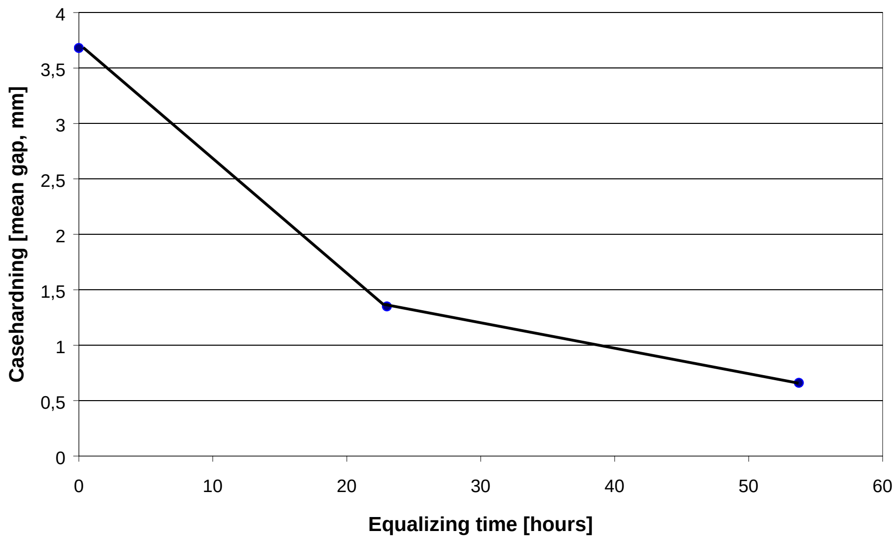


Figure 56. Development in the casehardening during the equalising process in test no. 4

As can be seen from figure 56, the casehardening was also markedly reduced during the equalising period, falling from a mean gap of 3,7 mm to a mean gap of 0,65 mm during the equalising period.

5.8.4. Conclusion

The use of the "equalising principle" has proved to be an effective way of adjusting the final MC towards the target MC. During the tests the deviation from the target MC has been reduced to 1/2 in 24 hours.

Other than being used as an end point correction principle, the equalising has also had a positive influence on the spread in MC and on the casehardening, which have been reduced to 1/2 and 1/3 respectively, in 24 hours.

5.9. Drying models

5.9.1. Material and methods

Two different simulation models for wood drying were tried out during the project. The models were developed and implemented by project partners Trätek and VTT, who also conducted the actual calculations.

For the calculation they received the following information about the kiln set-up:

- Air flow velocity (constant during all tests)
- Blowing depth
- Sticker dimension

In addition they received the following information about each specific drying run:

- Timber dimensions
- Basic density
- Initial MC
- Measured values for dry- and wet bulb temperatures in half-hour intervals during the entire drying run

Both parties then calculated the expected MC at intervals during the drying cycle, including the final MC. The model from VTT also estimated a relative stress level during drying.

5.9.2. Results and discussion

An example of the models' performance is shown in figure 57, using the weight-based MC as a reference.

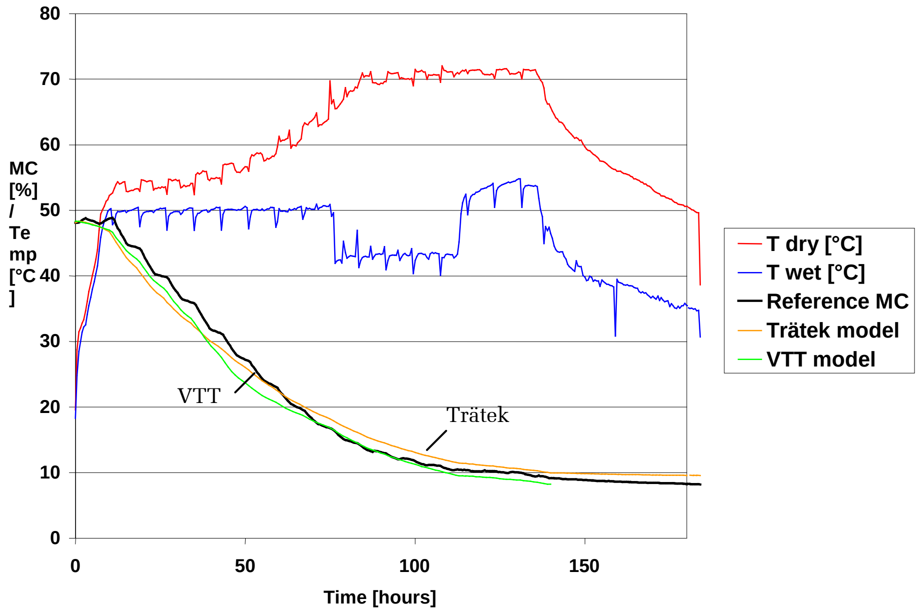


Figure 57. Drying models from Trätek and VTT in comparison to a reference MC based on weighing during test #3 at sawmill 1. The initial MC in the models was set identical to the average MC measured by the oven-dry method.

The calculation with the VTT model was stopped at the time the fans stopped, at 140 hours, while the Trätek model also calculates MC for the prolonged cooling period.

Looking at the situation at 140 hours, the Trätek and VTT models have a deviation from the reference MC of 0,8 % and 1,0 %, respectively. Considering the standard deviation of the final MC, which is 1,5 %, both models predict MC values well within one standard deviation from the reference MC during the drying run that is shown in the figure.

Table 14 shows the results from all tests performed. Precise timber dimensions and basic density were not measured during the tests at sawmill 2 and sawmill 3 (except during test #1 at sawmill 3). In these cases nominal values were used.

Table 14. Results from simulation models during all tests.

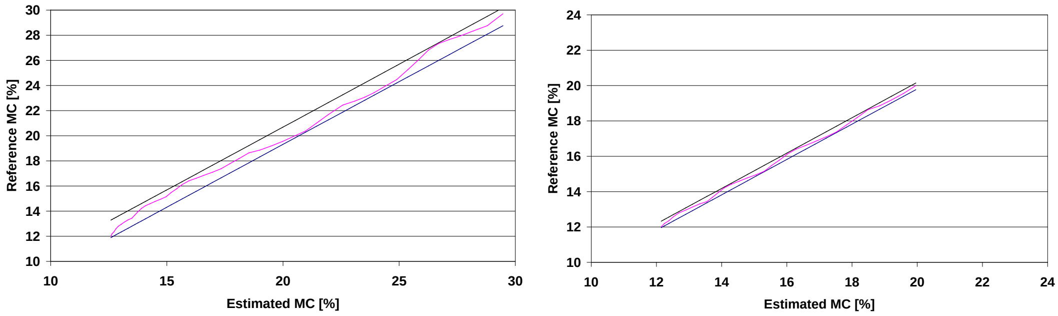
	Drying test no.	Wood species	Dimension		Density		Initial MC		Final MC		Trätek model		VTT modell	
			Thickness [mm]	Width [mm]	Average [kg/m³]	Std.dev. [kg/m³]	Average [%]	Std.dev. [%]	Average [%]	Std.dev. [%]	Calc. [%]	Dev. [%]	Calc. [%]	Dev. [%]
Sawmill 1	Fossum 1	Picea abies	52,7	104,6	394,5	39	60,1	32,2	11	1,2	11,8	0,8	12,9	1,9
	Fossum 2	Pinus sylv.	53	115,3	404,4	55	62,4	28,8	9,8	1,7	10,7	0,9	10,7	0,9
	Fossum 3	Pinus sylv.	52,8	105	401,8	52,7	48,1	28,2	8,2	1,5	9,8	1,6	8,2	0
	Fossum 4	Picea abies	52,5	105,4	390,4	39,1	50,9	23,9	8,9	0,8	7,7	-1,2	9,7	0,8
Sawmill 2	Bruvoll 1	Picea abies	(50)	(150)	-	-	35,2	12,7	12,9	1		-	-	-
	Bruvoll 2	Picea abies	(50)	(150)	-	-	51,5	24,3	19,9	6,6	17,8	-2,1	18,9	-1
	Bruvoll 3	Picea abies	(50)	(150)	-	-	50,2	25	16,6	1,7	16,6	0	19,2	2,6
	Bruvoll 4	Picea abies	(50)	(150)	-	-	48,8	24	16,6	1,6	16,6	0	18,9	2,3
Sawmill 3	Sokna 1	Pinus sylv.	67,1	80,2	450,6	54,4	61,2	22,6	9	0,9	10,3	1,3	8,9	-0,1
	Sokna 2	Pinus sylv.	(63)	(100)	-	-	64,7	21,7	11,9	1,8	12,1	0,2	11,5	-0,4
	Sokna 3	Pinus sylv.	(63)	(100)	-	-	55,6	21,8	10,8	1,5	11,2	0,4	10,3	-0,5
	Sokna 4	Pinus sylv.	(63)	(100)	-	-	50,6	18,3	10,3	1,2	11	0,7	9,4	-0,9

Bracketed values are nominal

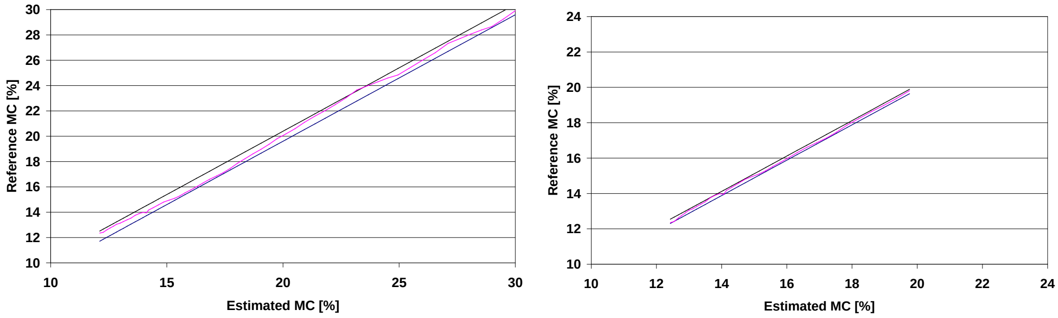
Both models were originally designed for Pine (*Pinus sylvestris*), but are being developed to include spruce as well.

The average absolute deviation from the reference MC was 0,85 % and 0,47 % for the Trätek model and the VTT model, respectively. For spruce the Trätek model showed a similar performance, 0,82 %, while the VTT model had an average deviation of 1,72 %.

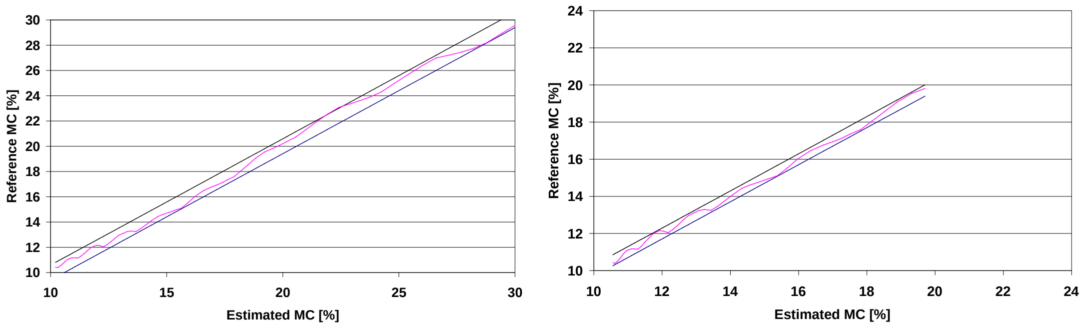
A second-degree polynomial curve was fitted to the curve that represents the coherence between calculated and references MC. The 95 % confidence interval for the individual points then represents the accuracy of the MC-measuring system. Figure 58 and 59 show the results for both systems during the tests at sawmill 1 in the MC range below 30 % and below 20 %.



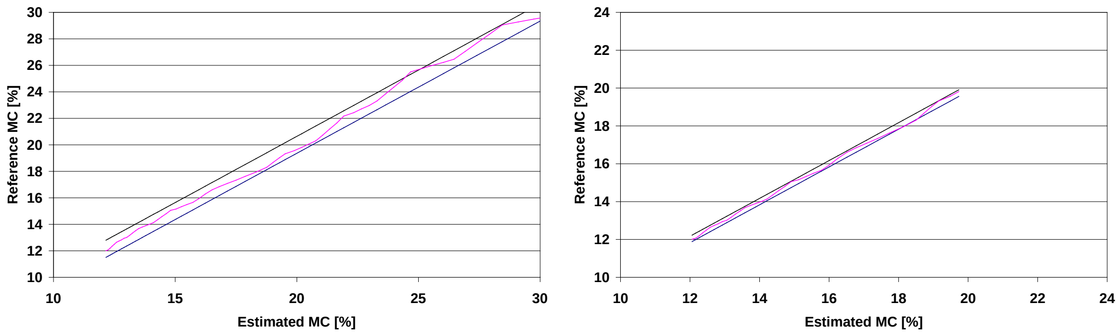
Test #1



Test #2

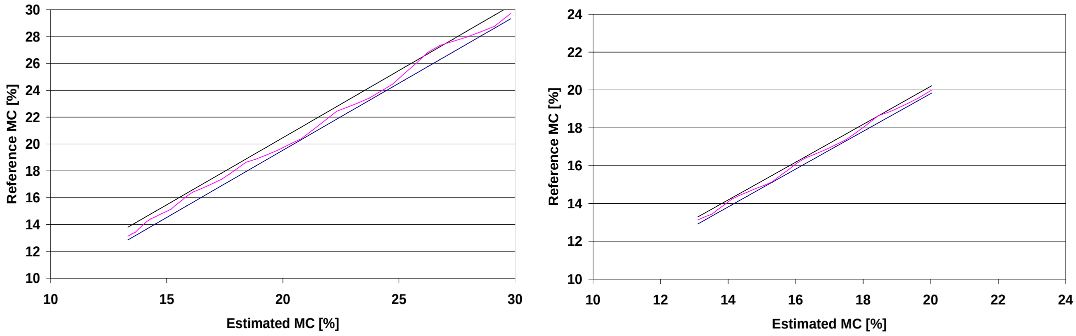


Test #3

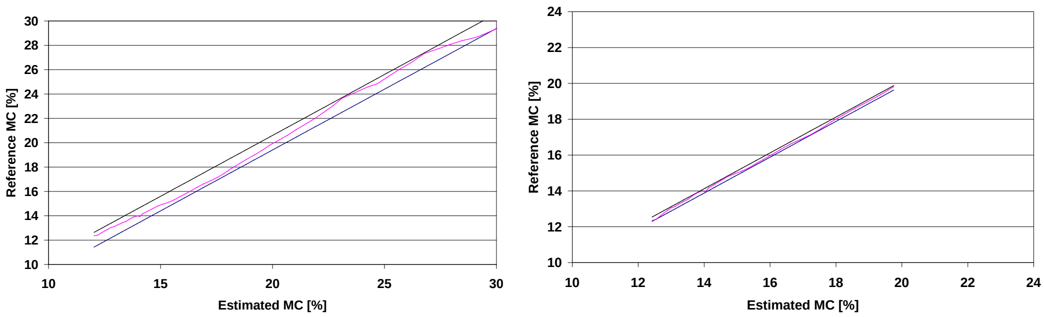


Test #4

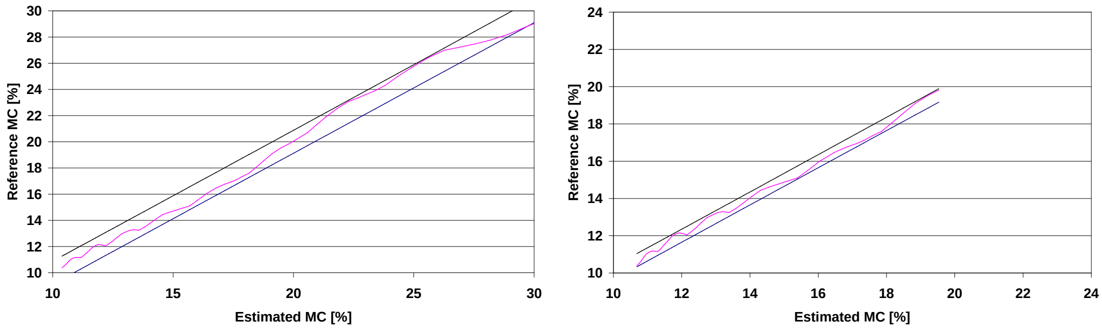
Figure 58. Potential accuracy of Trätek Simulation model during tests at sawmill 1.



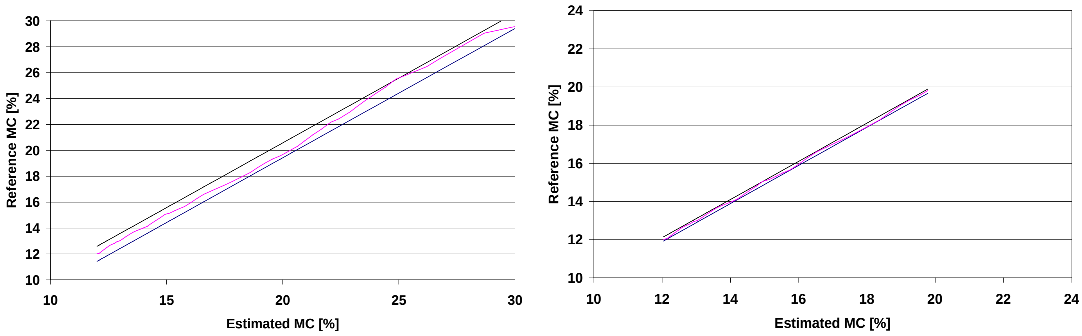
Test #1



Test #2



Test #3



Test #4

Figure 59. Potential accuracy of VTT Simulation model during tests at sawmill 1.

The relatively narrow confidence intervals indicate that the simulation models correspond well with the actual wood MC over the entire MC range below 30 %, and especially good below 20 % MC. Table 15 gives the maximum width of the confidence intervals during the sawmill 1 tests (figure 58 and 59).

Table 15. Width of the 95 % confidence interval at sawmill 1 for the MC estimates for the simulation models in the MC range below 30 % and below 20 % by optimal calibration.

	Width of confidence interval			
	Below 30 % MC		**Below 20 % MC**	
Test number	**Trätek**	**VTT**	**Trätek**	**VTT**
1	1,43	0,98	0,38	0,39
2	0,82	1,24	0,25	0,25
3	1,22	1,83	0,61	0,73
4	1,32	1,19	0,35	0,22

For spruce (test #1 and test #4) the maximum inaccuracy below 30 % MC was recorded at 1,4 % and 1,2 % for the Trätek model and the VTT model, respectively. For pine the corresponding values are 1,2 % and 1,8 %. In the range below 20 % MC the potential accuracy for spruce are 0,4 % for both models, and 0,6 % and 0,7 % for pine.

The results clearly indicate that the drying models can be of great help in predicting the wood MC during drying.

5.9.3. Conclusion

With detailed input data for initial MC, density and kiln climate the results for the simulation models were very promising, showing a maximum deviation between measured and calculated final MC of 1,9 %. The average deviation was approximately 1,0 %. Without density input data (only initial MC and actual climate)the deviation was at 2,9 % as a maximum and at 0,9 % as a very good average.

In everyday use, however, it is not practical to determine initial MC and density with the same accuracy as were done in the tests, and the results will certainly suffer from that. To what extent is not verified in this test. Still, the principle show promising results and has a great potential both to monitor MC during drying, and to assist in determining when to stop the drying cycle.

6. Summary and conclusion

The eight different principles for in-kiln MC monitoring and end-point determination tested in this project show a great difference in accuracy due to the limitation in the principle itself, poor calibration and due to different degrees of development.

The comparison is therefore focused on the potential accuracy of each of the systems, given their calibration curve (relation between meter reading and actual MC) is ideal. As a measure on the potential accuracy, a 95 % confidence interval for the curve describing the relationship between meter reading and actual MC is used for the different principles.

The *weighing principle* measures the amount of water removed from the drying batch or a part thereof, with good accuracy. To use the system for practical end point determination the initial moisture content must, however, be determined with a high degree of accuracy. This requires a great number of samples to be taken from each batch, which is not realistic in every-day operation. The standard deviation for green wood MC is so high (20 %-40 %) that even with 100 samples taken from a normal kiln load, the accuracy in determining the average initial MC will be in the range of ± 6-7 % (95 % confidence interval). This again produces inaccuracy in predicting the final moisture content in the range of ± 4-5 %. Even lower accuracy is obtained by calculating the dry weight based on measured volume and estimated density. During the tests such calculations produced deviation between measured and calculated values of up to 15 % MC.

By use of a few sample boards for weighing it's possible to predict the MC development of the sample boards with very good accuracy as the MC of the sample boards may be determined with a high degree of accuracy without to much work.,. How representative the sample boards are in MC content and properties , with regard to the entire kiln batch, will however be highly dependent on the number of samples. By use of 12 samples the deviation between predicted and measured final MC was in this test in average ±6,6 %.

Of the eight principles tested the *electric resistance* principle is by far the most developed and widespread. During the tests, the accuracy of the system was mainly influenced by the MC level measured and the calibration curve used. After the initial heat-up period, when the MC was still above the FSP, an accuracy (deviation between meter reading and oven-dry value) in the range of ± 5-8 % was reached. In the range below 20 % MC, the accuracy increased, resulting in an accuracy in the range of 2,0-2,5 %.

However, the tested system used the same calibration curve for both pine and spruce. This introduced inaccuracy into the measurement, since the two species do show a different behaviour regarding electrical resistance. If an "ideal" calibration curve is used for each species, the system has a potential of determining the MC below 20 % with inaccuracy of ± 0,6 % by use of the average value from 10 electrodes.

The electrical resistance system is therefore a suitable system for in-kiln moisture control and will be even more practical in use with the development of wireless signal transmission.

The *dielectric principle* as tested with the capacitance meter indicated that the system itself has a potential as an easy and non-destructive method for monitoring the in-kiln MC. It has the advantage of measuring a great number of planks in each of the monitored packages, increasing the accuracy in determining average MC.

The actual output signal from the tested instrument was a voltage signal, proportional to the wood MC. The manufacturer supplied no calibration curve for the relationship between the voltage signal and the MC, but if a calibration curve ideally fitted for each test were used, a potential accuracy level of approximately ± 2,5 % was calculated.

The repeatability of the *shrinkage measurements* was poor in the higher MC range, but proved to be very good in the range below 20 % MC, when measuring shrinkage over a great number of layers. The most likely reason for the poor repeatability in the initial drying phase is that the timber stack “sets” during the first phases of the drying cycle, correspondingly causing unpredictable shrinkage of the stack. In the range below 20 % almost all “setting” has completed, and the potential accuracy was approx. ± 0,6 % at 95 % confidence interval.

One possible way to reduce the effect of setting is by the use of top load on the timber stack. This will also have a positive effect on the deformation of the timber. Another strategy for shrinkage measurement is to monitor individual pieces of timber, but then the problem of selection appears. The annual ring orientation will also have to be carefully considered when measuring individual pieces.

The *nuclear moisture meter* showed promising results and repeatability in the lower MC range, especially below 20 % MC. A potential accuracy of ± 0,7 % was calculated in this range, provided an ideal calibration curve. Above 30 % the test results were not as good, with differences between calculated and measured MC values of up to 7-10 %. The relatively poor accuracy in the higher MC ranges can partly be explained by a change that was made in the system set-up during the tests, as the distance between the instrument and the bottom package was increased by 10-15 mm.

This demonstrates that the accuracy of the system is very much depending on the geometrical configuration of the package directly above the instrument, which have to be given great concern in further development of the instrument.

The system does, however, have the advantages of non-destructive measuring and minimal labour consumption in everyday use, and should therefore be very interesting for further development. The instrument should also be suitable for use in continuous kilns, as it is lowered into the ground and not in direct contact with the wood.

The principle of *Temperature Drop Across the Load* (TDAL) is easy to use, and requires no additional labour in everyday use. However, it did not show convincing results during the tests. The output signal was severely disturbed by fan reversal, and the system will face additional problems if using variable fan speed, which is now common.

The system reached a potential of ± 7,5 % below 30 % and ± 3 % below 20 %, under constant climate and air velocity. Varying climate and air velocity will worsen the results.

The use of the *equalising principle* has proved to be an effective way of adjusting the final MC towards the target MC. During the tests the deviation from the target MC has been reduced to 1/2 in 24 hours.

In addition to being used as an end point correction principle, the equalising has also had a positive influence on the spread in MC and on the casehardening, which have been reduced to 1/2 and 1/3 respectively, in 24 hours.

With detailed input data for initial MC, density and kiln climate the results for the *simulation models* were very promising, showing a maximum deviation between measured and calculated final MC of 1,9 %. The average deviation was approximately 1,0 %. Without density input data (only initial MC and actual climate) the deviation was at 2,9 % as a maximum and at 0,9 % as a very good average.

In everyday use, however, it is not practical to determine initial MC and density with the same accuracy as was done in the tests, and the results would suffer from that. Still, the principle has a great potential both to monitor MC during drying, and to assist in determining when to stop the drying cycle.

Only the electrical resistance system, the capacitance system and the drying models are commercially available for use at the moment. Most of the other systems are presently either being further developed or upgraded.

In spite of varying performance of the different principles during the comparative testing, most principles have a potential for being further developed into a level of accuracy and applicability which is acceptable as a means for improved MC monitoring during drying and end-point MC determination.

7. References

[i] EN 13183-1 Method of measurement of moisture content, Part 1: Method of determining moisture content of a piece of timber, Oven dry method.

[ii] Karlsson, M., Nordin, A.,Vågsystem för virkestork. Luleå University, Sweden 1995 (in Swedish).

[iii]Lin, R., T., 1965. A Study on the Electrical Conduction in Wood. For. Prod. J. 506-514

[iv]1994, EDG-recommendation, Assessment of Drying Quality of Timber, Pilot edition

[v] James, W., L., Electric Moisture Meters for Wood. Gen. Tech. Rep. FPL-GTR-6. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory; 1988.

[vi] Quarles, S., L., Breiner, T., A., 1992. Operational characteristics of a capacitive-admittance type in-kiln moisture meter. Forest Prod. J. 42(3): 15-22.

[vii] Quarles, S., L., Breiner, T., A., 1989. Effect of density on in-line and hand-held moisture meters. Forest Prod. J. 39(5):51-54.

[viii] Breiner, T., A., Quarles, S., L., 1990. Performance of an in-kiln moisture meter - preliminary results-. Proc. Western Dry Kiln Assoc., Oregon State Univ., Corvallis, Oreg. pp. 104-109.

[ix] Dennis, J., R., Beall, F., C., 1977. Evaluation of a New Portable Radiofrequency Moisture Meter on Timber With Drying Gradients. Forest Prod. J. 27(8): 24-29.

[x] Skaar, C., *Wood-Water Relations*. New York: Springer-Verlag, 1988.

[xi] Engøy, T., Fuktighetsmåling av trevirke med nøytroner. Institutt for energiteknikk, 1992 (in Norwegian).

[xii] Taylor, F., W., Landoch, D., 1990. TDAL profiles of southern pine timber during drying. Forest Prod. J. 40(10):47-50.

[xiii] Weichert, L.: Untersuchungen über das Sorptions- und Quellungsverhalten von Fichte, Buche und Buchen-Pressvollholz bei Temperaturen zwischen 20°C und 100°C. Holz als Roh- und Werkstoff, Bd. 21 (1963).

[xiv] Cloutier, A., Fortin, Y., Gosselin, R., "Quality Wood Drying Through Process Modelling and Novell Technologies." Proceedings from 5th International IUFRO Wood Drying Conference, Quebec, Canada (1996).

[xv] Hukka, A., A Simulation Program for Optimisation of Medium Temperature Drying on an Industrial Scale. 5th International IUFRO Wood Drying Conference, Quebec, Canada (1996).

[xvi] Hukka, A., A Simulation Program for Optimisation of Medium Temperature Drying on an Industrial Scale. 5th International IUFRO Wood Drying Conference, Quebec, Canada (1996).