2006:211 CIV

MASTER'S THESIS

# Quality Hand Book Joinery Kiln Drying

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2006:211 CIV - ISSN: 1402-1617 - ISRN: LTU-EX--06/211--SE

# Acknowledgements

This Master's Thesis *Quality Hand Book- Joinery Kiln Drying (QHB)* marks the closure of my Master of Science program in Wood Technology, at Luleå University of Technology, LTU.

I would like to thank my supervisor at Barbro EM Svensson at Stora Enso Timber R&D and Professor Tom Morén at LTU for being helpful to me during my work. Thanks to all involved in the QHB project group.

I would also like to thank one person which has been very helpful to me during this thesis; Tomas Ståhl, kiln operator at Stora Enso Ala Sawmill. Thank you for your cooperation and interesting discussions!

Finally I would like to thank my family and especially my girlfriend Linda who has been supporting me throughout my years in school!

Skellefteå, Sweden. 2006-06-06

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# Abstract

To be competitive in wooden industry you need to have well defined quality of your products and processes. This document *Quality Hand Book-Joinery Kiln Drying* (*QHB*) presents definitions of drying quality parameters. The wood drying process is the most important process within sawmilling. If the drying process is not functioning accurate, enormous values will be literally dried away.

A number of actors are producers of timber blanks and semi-finished profiles for non structural uses, such as window frames. Customers need, demand and expectations have to be fulfilled by supplying products which have the correct quality, even if customer is internal or external of the company. To have a high quality further processed product, a successive drying process of the timber is necessary to meet the competition of tomorrow. As high-class drying process is achieved this will separate the performer from its competitors.

The *QHB* shall be base for further quality thinking and identifies quality parameters and definitions of important factors related to drying. The quality parameters have to be taken into consideration in kiln drying production to meet further processing requirements.

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# Abbreviations

| | |
|---|---|
| CEN | The European Committee for Standardization (Comité Européen de Normalisation) |
| EDG | European Drying Group |
| EN | European standard, CEN |
| ENV | European standard, predefined by CEN |
| EMC | Equilibrium moisture content. The moisture content wood adapts due to certain climate conditions |
| FSP | Fiber Saturation Point. Where moisture within wood turns from capillary free water to bound water in wood cells happens ≈ 28 % MC for pine. |
| NTI | Norsk Treteknisk Institutt; Norwegian Institute of Wood Technology |
| MC | Moisture Content |
| ODM | Oven Dry Method |
| prEN | A draft by CEN of pre-standard, open for comments |
| QHB | Quality Hand Book |
| IMPCOPCO | EU project. *Improvement of moisture content measuring systems and testing strategies to enable precise process and quality control of kiln dried timber.* |
| INSTA | INternordic STAndard |
| SET | Stora Enso Timber |
| SPC | Statistical Production Control |
| SP Trätek | SP Swedish National Testing and Research Institute |
| TQM | Total Quality Management |

# 1. Introduction

A QHB will never be finished. What does this statement mean?

*A QHB shall be continuously updated* by reason of areas which this QHB do not cover or have lack of information. It is up to each producer to develop and refine the QHB to meet the needs. Therefore, a QHB will never be finished and has to be updated as revision of this area is made.

## 1.1. Aim of the QHB

The aim for this QHB is to be an introduction to quality thinking and covers timber drying quality parameters which influence production of timber blanks and semi-finished profiles for non structural uses.

The structure is set by following *the main thread of the QHB*. It is the structure of the QHB that shall make the organization to widen their quality thinking. As production differ a lot between units within a company, to point out *how to do* in all possible situations is of cause impossible. Therefore has each user adapt the QHB for their purposes.

This QHB is a guideline to drying quality for the joinery kiln drying production. The QHB is implemented to guide operators and managers in the kiln drying production and related activities, to find a way of work to develop quality to a higher level. However, the handbook is primarily to make key persons within the organization reminded of what drying quality is all about.

## 1.2. Why a QHB?

Even if SET is one of the leading producers of quality joinery products, there is always a way of develop quality, make production effective and reduce costs.

A high level of timber drying quality is a goal. Identified problems such as moisture variation of batches after kiln drying production require a strategy for kiln drying control. The character of the need are more of a developed product quality rather than production quality but although activities in production are affecting. There is a need of routines concerning measuring strategies, follow-up, feedback etc. to meet quality requirements of joinery timber. This will create a situation where company will have better control of product/production and meet customer demands, both internally and externally!

From theory of marketing an expression can be taken;

*Strategy is how to win the war.*
*Tactics is how to win the battle.*

And of cause, it is the war which has to be won…

## 1.3. Structure of the QHB

The structure of the QHB is adapted to meet quality thinking in practical kiln drying production of joinery goods. From empirical benchmarked findings and theory covering the quality area, this QHB has its base as illustrated in *Figure 1.1*.

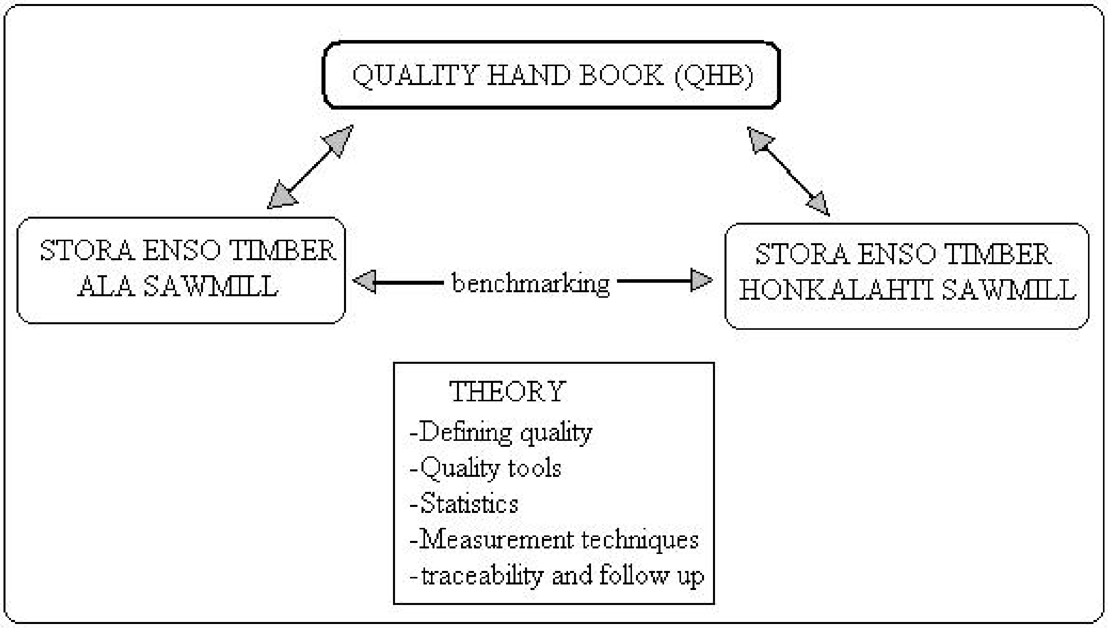



*Figure 1.1 Base of the QHB*

The base of the QHB is partly from benchmarking of joinery production within SET, partly from theory concerning quality development and litterateur of researches covering this area. Benchmarking is made on two SET joinery producers; Honkalahti sawmill in Finland and Ala sawmill in Sweden. Production related information regarding joinery is identified from interviews with operators and managers in the production, internally in SET. Benchmarking is backed up by theory of quality development and with interviews, external from SET, with people who have insight in drying quality. This QHB has its central point based from findings in litterateur.

### *1.3.1. What is "Benchmarking"?*

Benchmarking is a way of study equalities of similar production methods. By systematically explore production processes for differences/similarities, areas for development can be found. The benchmarking of other activities is to evaluate and make use of information which shall be a guideline for the organization to implement improvements in the own production process. Benchmarking is not to copy the one you have been studying!

### *1.3.2. What theory is adapted to fit QHB?*

The theory which acts as foundation of this QHB is mainly well-known litterateur from institutions which have made research within this area. Some investigations have also contributed with some information, such as investigations made by Trätek and IMPCOPCO.

# 2. Quality

On a competing market there has to be a high quality on services and products to be successive. Quality is of importance and large resources are invested to fulfill quality. As the customer set the level for quality, it's up to the seller to meet customer requirements.

## 2.1. What is Quality?

The word *quality* is Latin and means *characteristic properties*. *Quality* is connected to the product and its value which is produced or performed.

### *2.1.1. A general definition of quality*

Quality is hard to define when everyone has different ways of relate to it. But overriding is to "create quality", to draw plans of future work. Some vague definitions are

- Quality for a product is its ability to satisfy and even exceed the customers needs, demands and expectations
- A level of inbuilt properties which fulfill customer demands
- Superior in its kind
- Fitness for use

Quality can also be described as the three words *Need*, *Demand* and *Expectation*, where there is a difference between them. As *demand* is base criteria of the product, the *need* and *expectation* is something which differ the product from its competitors; some value-adding feature which make the customer choose that specific product.

### *2.1.2. Definition of joinery kiln drying quality*

*Joinery kiln drying quality* is dependable by many different factors. These factors are related to the wood material itself and factors within the kiln drying production at the industry. Recently there have been prepared a new international standard for drying quality named *EN14298 Sawn timber - Assessment of drying quality* and is mainly based on the Nordic standard INSTA 141. This standard handles drying quality of the product. Joinery drying quality has its central point based of statistics. By having characteristics and properties of the wood quality described numerically, this can be statistically expressed as a level of quality in the specific case. Wood drying quality is *product related* but it is often *production related* parameters which are influencing it. As production of joinery is integrated with the drying unit, quality thinking due to quality parameters can be implemented throughout the production from log yard to out feed of the joinery production so a high product quality is achieved.

Quality level of dried timber for joinery is presented numerically in statistics. By controlling drying performance by measuring the process and statistically analyze the result, it is possible to define quality level. One so called performance indicator or quality parameter is in wood drying production "variation of the moisture content within a batch". This quality parameter is explained statistically from data and describes how successful the production is due to this. From the quality level of the specific quality parameter, assumptions can be made of what has increased/decreased it and corrections can be made. By comparing sub-processes, for example drying of one single batch with some other batch or two separate kilns with each other, one can find parameters which are influencing kiln drying quality in the specific case and be able to make corrections.

### 2.1.3. *Product related quality of timber blanks and semi-finished profiles for non-structural uses*

Quality parameters are required to be high to meet production requirements of "timber blanks and semi-finished profiles for non-structural uses", as window frames is. Following are parameters which have influence on product quality and with comments.

The standard EN 14298 are handling three *product* related parameters,

1. Moisture variation within a batch
2. Range of average MC from desired target MC of batch
3. Case hardening

but quality can be widened with indicators such as

- Moisture gradient within the cross section of the timber pieces
- Amount of checks
- Amount of micro shakes
- Deformation
- (Mould caused by activities related to drying process)

Drying quality of product can be easily described but are not that easy to display. A control of the production is needed to fulfill the demands which are raised for the product, illustrated in *Figure 2.1*.

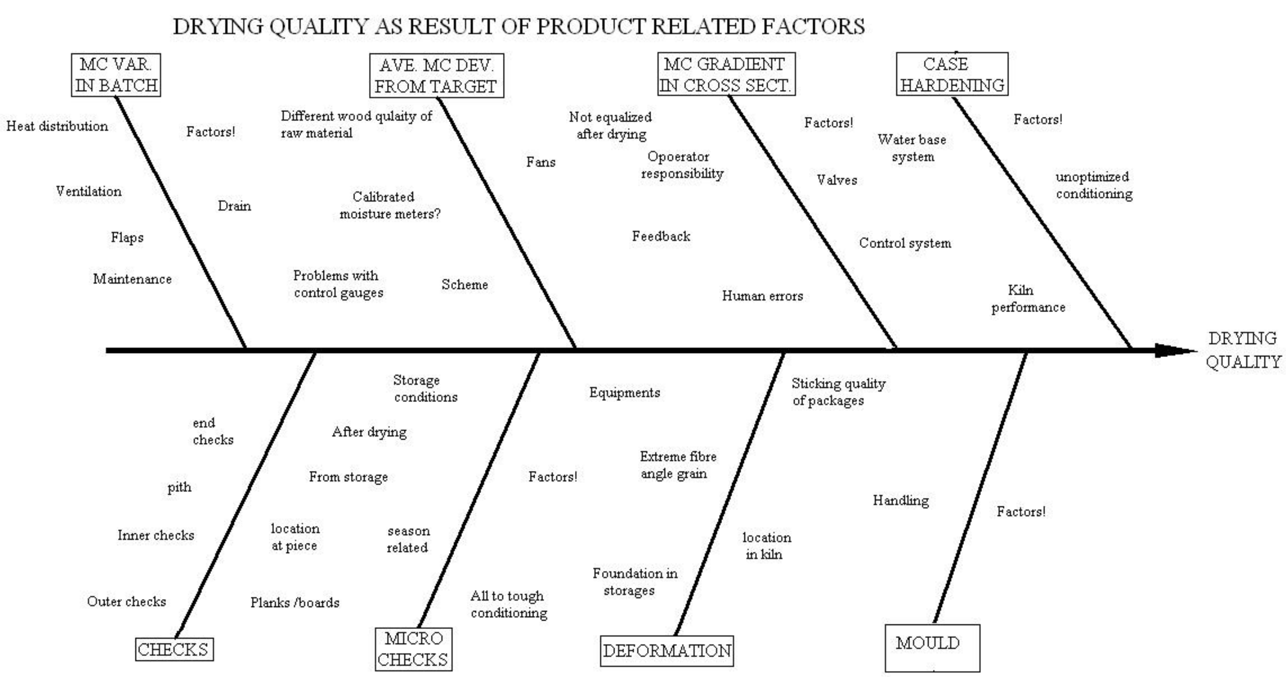



*Figure 2.1 Product related factors which are influencing quality presented in a "fishbone diagram".*

### *2.1.4. Production related quality of the kiln drying process*

To have a high product quality it is necessary to have control of the production. The long term drying quality is affected by the quality of the *production*. The quality of the production can be divided in

a) Personnel related factors
b) Equipment for drying process and related apparatus
c) Environmental related factors
d) Raw material related
e) Feedback and follow up of production

Such factors have to be controlled and planned carefully! By having control of factors in the production it is possible to achieve a stable and capable production. This results in a higher level of product quality and more predictable performance of the production. The production related factors are here explained and widened.

**a) Personnel**

- Instructions of production control
- Education of personnel
- Engagement of personnel
- Skills
- Entrepreneur personnel related factors

Operators, managers and entrepreneurs who have deep knowledge of wood drying process are priceless. By standardizing and optimizing routines, training personnel to wider knowledge about drying quality, a situation arise where activities are performed identically. This eliminates the human error as a factor causing quality variation. This will also increase areas of responsibility for the personnel.

**b) Equipment for drying process and related apparatus**

- Strategy for maintenance and service of drying facilities and related equipment
- Suitable apparatus for process control
- Calibration of equipment for drying control
- Instructions of the equipments
- Drying related factors (design of drying schedules)
  - Temperature
  - Air velocity
  - Ground support
  - Etc.

To keep control of drying equipment will reduce sources of errors, which lead to interruptions in drying processes and misjudgments by incorrectly collected information from process. There is a need to use equipment correctly and equally by using routines. Both “hardware and software” has to be up-to-date, by developing and maintain these thoroughly. Calibration of electrical resistance and capacitance moisture meters, maintenance and service program, heat distribution, inspections, status of equipment etc and other drying related process control are important issues.

**c) Environment**

- Storage of material
- Handling of material

To organize handling of timber, control of timber flow, keep environment in good condition (clean), organize and control storages etc. will reduce handling costs and increase material control. As wood is a hygroscopic material, surrounding air conditions has a huge influence of material properties, which makes it of importance that storage is well arranged to minimize drying quality to be degraded by incorrect storage climate. A well organized environment will also increase personnel satisfaction with a positive synergy effect.

**d) Raw material related**

- Raw material properties, such as
  - Dimension
  - Specie
  - Green timber moisture content
  - Knots
  - Mechanical properties
  - Density
  - Fiber angle and fiber direction
  - Saw pattern
  - Disturbances in wood structure such as juvenile and compression wood
  - Initialized splits of the timber caused by frost, lumbering (felling) or careless storage before kilning

- Season related properties
  - Ice
  - Temperature
  - Outdoor humidity
  - Sun and wind (which can initialize splits of the timber)

To have a high drying quality which suits joinery products and joinery production, it is of importance to gather timber with same properties. E.g. green timber MC differs as heartwood has approximately 30-40% and sapwood 130-150% MC in green condition. In winter time frozen timber will cause heating period to increase. Sorting of timber in green condition must be planned carefully. All raw material related properties has to be taken into consideration, to adapt correct drying and storage strategy for the particular situation.

**e) Feedback and follow up of production**

- Strategy for measurements in production and handling of measurement data
- Utilization of statistical methods for following up
- Documentation strategy
- Communication with customer, sawmill, other units within the organization and key persons will reveal usable information.

To develop quality of both product and production it is necessary to have information. Strategy concerning *what*, *how* and *when* to collect data or other information from the drying process is important, to be able to follow up production. Data should be documented in a structural way so concerned persons easily can have access to it. Knowledge of how to analyze data by e.g. use suitable statistics has to be high to be able to base decisions on facts and make correct analyzes.

## 2.2. Quality control theoretically

Even if it’s hard to define quality in the specific state of affair, it is up to the producer to find a level of quality which receives customer satisfaction. To make this possible the company has to develop their production, by working with quality control. Quality policies and plans of actions which meet visions, the entrepreneurial spirit within the company and individual needs has to be prepared.

Quality control is the ability to find and eliminate sources which create problems. The result of a well working quality control is where a good output is separated from a bad. The basic principle of strategic quality control has to be revised to a higher level concept. This model is using customer actively to give feedback (output) of the product quality. The "old" model is revised by analyzing process and quality earlier in the production. This new type of quality control will minimize the situation where rejects are fed further into the value chain and scrap being delivered to the end-customer. The new, revised quality control has to avoid situations where the customer will act as quality control, illustrated in *Figure 2.2*.

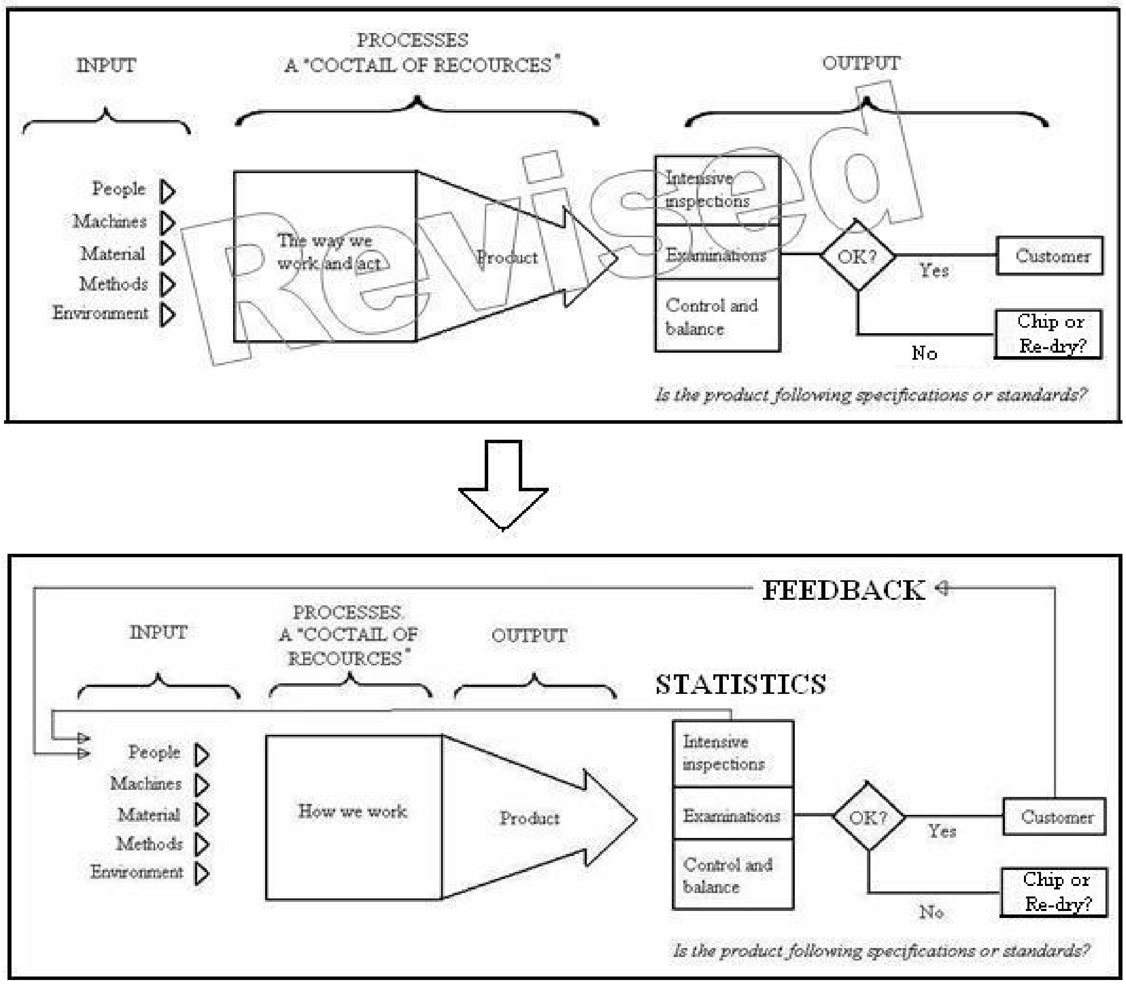



*Figure 2.2 Basic concept of quality control has to be revised and developed further (figure developed from What is quality? by Sveriges Verkstadsindustier, 1996)*

The basic quality control is focusing on the *product* from the process and the developed quality control is focusing on the *process* which produces the product. The "old", basic quality control will create a situation where

- customer is used as quality control
- scrap and rework is tolerated
- production is expensive
- specifications is in focus

- feedback is delayed
- extra work in output will be created
- all defects are handled the same way
- used inspections and control is sensitive to variation and errors

As in the "old", basic quality control where focus where on "product *after* production" the focus in the "new", revised quality control is moved to "product *while* producing". A revised thinking of the basic quality control will secure the process and minimize rejects. This is achieved by using a mix of

- Statistical methods of measure the process and define internal routines and standards
- Use feedback from customers to develop the process, not customers as quality control of the product

This information will act as input for the quality control instead of using the customer as input.

### *2.2.1. Improve processes by working systematic*

To aim towards a higher level of quality and to find causes of variation, demands a structural way of attacking the problem. It is necessary to attack the problem while it has the highest potential for improvements. A method called *Plan-Do-Study-Act (PDSA) cycle* can be applied on every kind of process. By attacking problems this way and continuously improve the process will raise the quality level making it more refined.

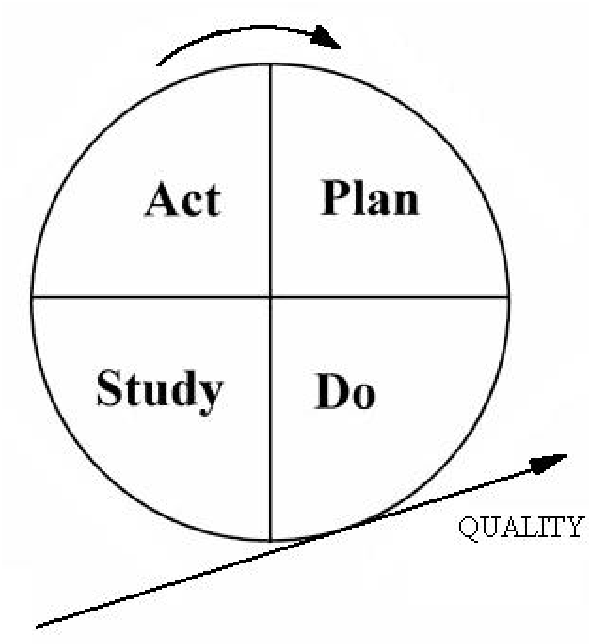



*Figure 2.3. The Deming cycle or PDSA cycle.*

**Plan**
Define and analyze the problem. Define the most important factor of error by grading them. Find information from the process and analyze statistically by using quality tools such as SPC.

**Do**
Tackle the problem.

**Study (control)**
Was the result better/worse? Follow up by collecting facts and use quality tools. Improve the process to become more even than before.

**Act**
Learn from the changes. Repeat the cycle.

When the process is stable and consistent, move to the second most important problem or processes where other problems exist.

## 2.3. Fundamentals of TQM

If total quality management (TQM) should succeed, it is of importance that the management provides the economical resources and time for the organization to advance in quality work. The focus of TQM is to work actively by preventing, changing and improving processes and products instead of "controlling and repairing".

By having a commitment and engagement to develop quality, five cornerstones of TQM is implemented. These shall act as foundation for process-thinking, where the processes are a number of activities which are performed within the company, illustrated in *Figure 2.4*

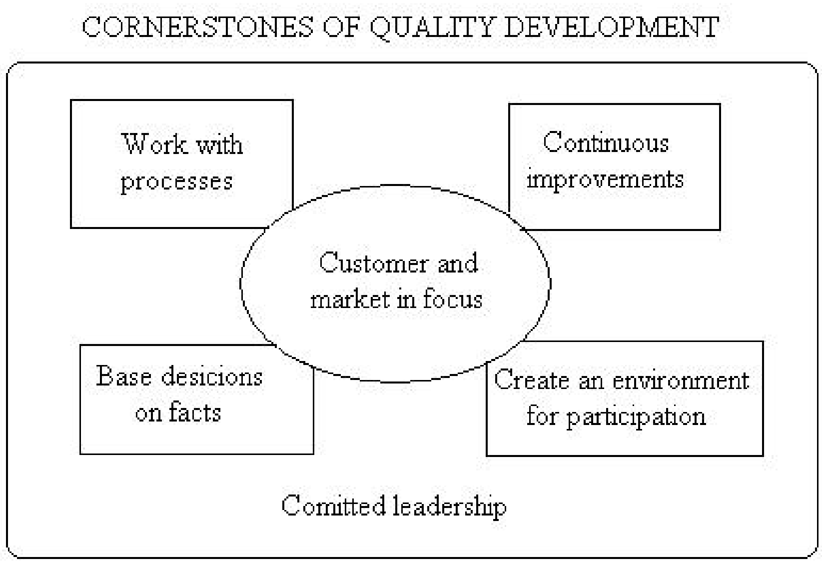



*Figure 2.4 Cornerstones in TQM.*

### *2.3.1. Focus on customer / next step in production flow*

TQM defines that next step in the value adding chain is the customer. The customer can be internal within the company or external on the market. The customers are comparing the actual quality to its competitors and as *quality* is a relative conception, this leads the company to base actual quality from customers' point of view and find a "correct" level of quality. The production has to be adapted to demands, needs and expectations of the customers. If the customer is external, to differ from other competitors it is of importance you offer the core product in combination with some added value. This will make you advance on the market, when customers find your product offer something more.

As kiln dried joinery timber are produced for internal production within SET sawmills, a higher level of communication and information share can be implemented compared to an external customer.

### 2.3.2. Base decisions from facts

All decisions have to be based from facts to meet quality development strategy! All other decision takings are assumptions and will differ from who the observer is. This means that such information which provides basic data for decision taking in the production has to be collected strategic.

**"Tools" for analyze of numerical information**

To be able to base decisions on facts, not randomly, some tools are needed. In the fundamentals of TQM seven quality control tools for development and analysis of numerical information are defined. In this QHB two of these seven quality tools are presented, SPC which handles *control charts* and *histograms*. These tools are powerful statistical tools for control and follow up of wood drying production. (*Fishbone diagram* is also a quality tool and is illustrated in chapter "*Joinery raw material; Product related quality*" but not further described in this QHB.)

### 2.3.3. Work with processes

A process is a happening, activity or a number of these, continuously repeated over and over again. A process transforms resources into result. It is from processes developments can be implemented.

A drying scheme is a production process. Drying of a batch is a process. A standardized way of measuring moisture with electrical resistance moisture meter is a process, etc.

### 2.3.4. Create environment for participation

When strategies for developing quality are formed, an environment for personnel where everyone can participate is important. If everyone does not participate, this will be a source of error and a situation where quality work is not successive.

It is of importance that every operator accepts the situation of how work are going to be performed. This will minimize sources of errors and information from production which is collected manually will be able to be compared and utilized for development of processes.

### 2.3.5. Continuous improvements

There is always a way of accomplish higher quality for less cost! The products and production has to be continuously improved to meet market demands by making production efficacy. The one who stops to improve to become better will soon be degraded.

# 3. Quality control tools in wood drying production

This chapter shall act as an introduction of how statistics can be used as a quality tool. Quality is in drying production expressed statistically. Wood drying quality can be the result of meeting high quality of performance indicators, as described in chapter "*Product related quality of timber blanks and semi-finished profiles for non-structural* uses". A low variation of MC within a batch will reduce rejects further into the production, caused by to low/high MC. As low number of rejects is preferred economically, low variation will also make it possible to have high quality joint of the finger jointed products and low distortion after moisture are equalized between the two neighboring wood pieces. A modern perspective of quality has been implemented, where any deviation form desired target quality is a decrease in overall quality, illustrated in *Figure 3.1*.

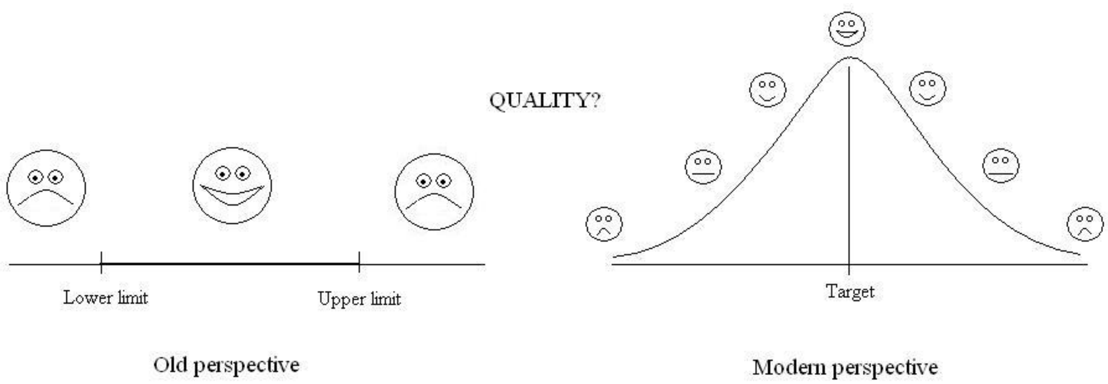



*Figure 3.1 Different ways of looking at quality; old versus modern perspective.*

As production is often using the "old perspective" in controlling the production process, the "modern perspective" has to be deeply rooted in the organization and people in production. Statistics is a central part in defining drying quality. What kind of problem can statistics answer? Examples of such problems are

- Determine if a limited number of measurements can represent the true value of a parameter in a process
- Determine how many measurements are needed to get as exact data which is needed to evaluate a process
- To compare data with specifications or between two processes
- Make a plan to find parameters which are influencing a process

## 3.1. The variation of a process is one important quality indicator

Preliminary, definitions have to be clarified. A *process*, *sub-process* and *population* in wood drying are

- A *population* consists of an entire set of objects, observations, or scores that have something in common. For example, a population might be defined as all pieces within one batch of timber in a kiln, each pieces in a package or each measurement of MC in a in-line capacitive moisture meter
- A main *process* is a use of a specific drying scheme and contains a continuous number of drying operations of several batches

- The main process contains a number of *sub processes*. A sub process can e.g. be drying of one specific batch

Every process will vary depending on condition. Processes differ in some small degree from each other. Differences are referred to as variation, no matter how small they are. In wood drying variation is also changing from time to time between each produced batch by mere accident, even if quite same conditions are held in each sub-process (wood drying schedule, type of raw material, kiln number, time of year etc...). To find target MC in a sub-process is not possible for every piece in a batch. Each individual piece within a batch will differ from the desired target MC, more or less. This will make each sub-process vary from another sub-process. Illustrated in *Figure 3.2*, the process to the right is more predictable than the process to the left as each sub-process is behaving quite similar to each other.

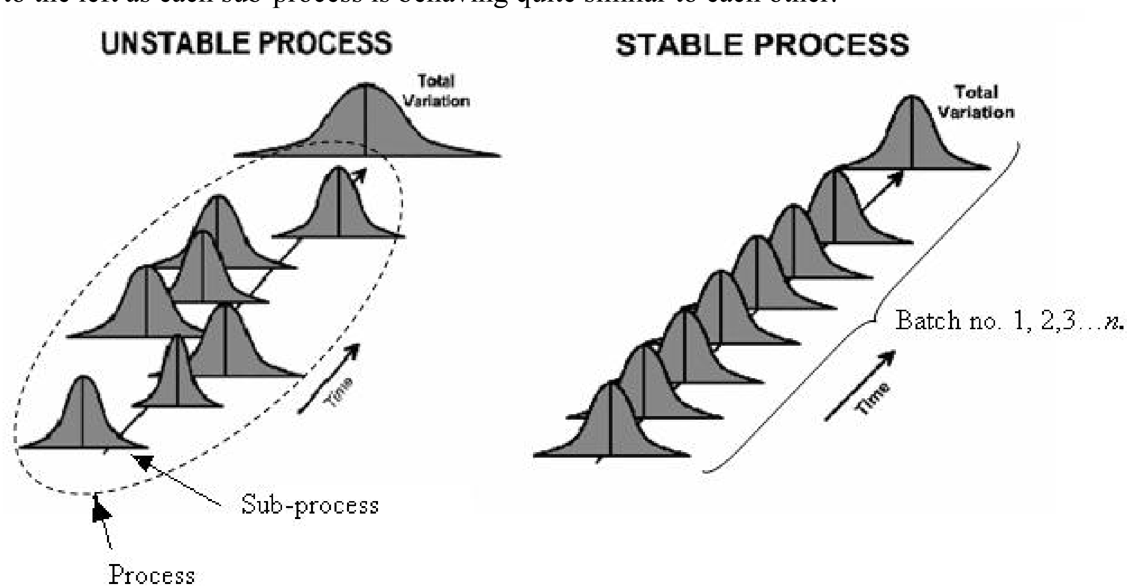



*Figure 3.2 A process will vary over time. To the left is an unstable process where every sub-process is changing constantly. To the right is a stable process. Notice the larger span of total variance in left figure compared to the total variance in the right figure.*

For the left process, the average value shifts up and down and the variation increases and decreases for every sub process. The process to the right is stable as the average value and variation for every sub-process are held constant, which makes the process have a consistent level of performance. There are many factors affecting a process and to find such factors and improve the process can make it possible to reduce the total variation, which lead to an improved quality.

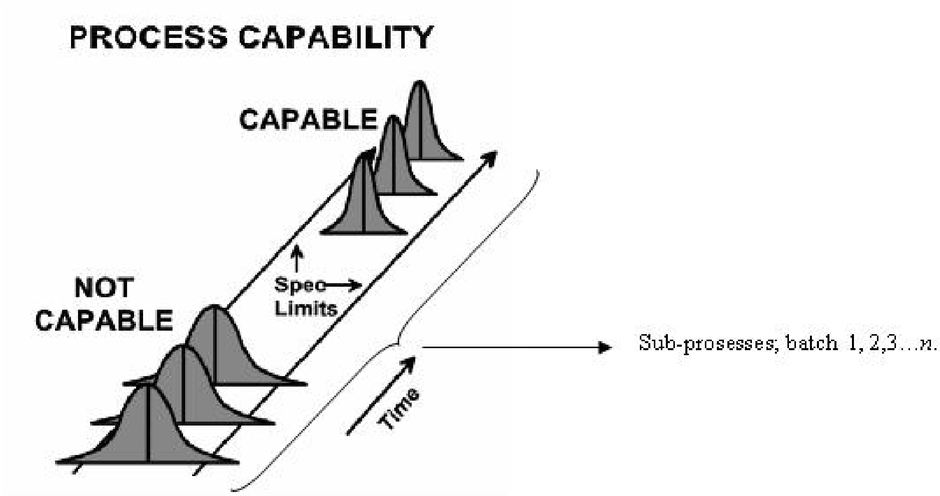



*Figure 3.3 Process which have become tighter in its variation, from being "not capable" to "capable".*

*"Predictable within certain limits"* is an expression for a stable process. With a reduction of variation with as low amount of rejects as possible (e.g. pieces outside of specified moisture limits) an increase of the yield in the following further processing will be produced. *Figure 3.3* can describe a situation where a certain process has been developed to producing low variation. A process which consistently finds target value and low variation is said to be stable and capable and will have a predictable performance. This theory is base for the new drying quality *EN 14298:2004, Sawn timber – Assessment of drying quality.*

## 3.2. Short explanation of "normal distribution"

In wood drying of a batch it is impossible to find target MC for every timber piece. There will always be a variation within a batch or even within a timber piece from the desired target MC. In statistics a statement which is called *the empirical rule*, claims that for a distribution such as a normal distribution which is "bell-shaped", all observations will conform in a certain way. When observations are plotted in a normal distribution diagram, the distribution will always be uniform in its shape but will vary in span and height. In wood drying the variation of MC for a whole batch is assumed to conform in a normal distribution and a batch dried to 12% is (approximately) normal distributed. The area under the normal distribution curve represents the total number of observations, *Figure 3.4*.

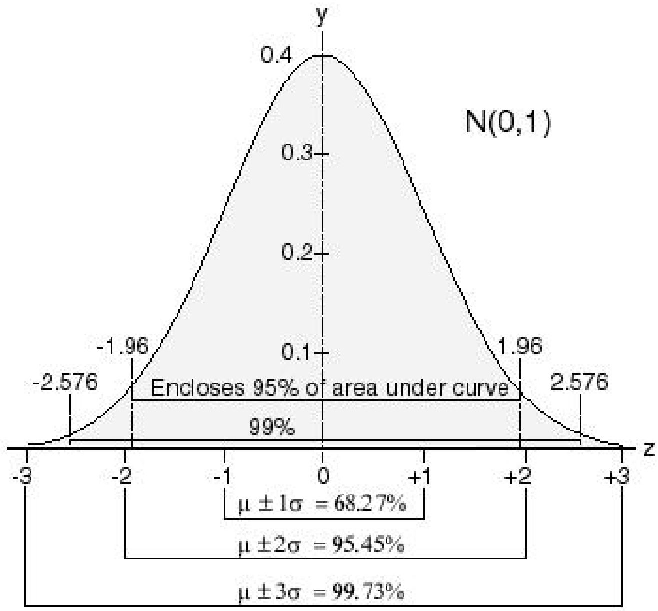



*Figure 3.4 A "bell-shaped" normal distribution curve. The curve illustrates how many observations (%) which are included in deviation from average value (μ=0; average value, σ=std.dev.).*

The span will always follow

- deviation ±1 *S* contains 68.27% of all observations
- deviation ±2 *S* contains 95.45% of all observations
- deviation ±3 *S* contains 99.73% of all observations
- deviation ±1.96 *S* contains 95% of all observations

A normal distribution consist of two values

- The center of the curve is the average ( $\bar{x}$ ) of the population

  $$\bar{x} = \frac{x_1 + x_2 + ... + x_n}{n}$$

- The deviation for all units from the average value ( $\bar{x}$ ) of the population, expressed as standard deviation ($\sigma = S$)

  $$S = \sqrt{\frac{(x_1 - \bar{x})^2 + (x_2 - \bar{x})^2 + ... + (x_n - \bar{x})^2}{n-1}}$$ , where

  - $\bar{x}$ *=average for population*
  - *n=number of observations*
  - *index 1,2,…,n= specific observation*

And this will make it possible to express the MC variation for one batch, as standard deviation. Moisture variation will decrease as drying are made toward lower target MC, this will make the normal distribution tighter and higher.

*Example 1 "Mean value and standard deviation"*

*Followed are an example of a calculation of mean and standard deviation of twenty measurements of moisture content (%) of a dried batch.*

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 10,3 | 11 | 11,8 | 10,5 | 12,6 | 14,5 | 12,1 | 12,3 | 12,9 | 13,8 |
| 11,8 | 12,6 | 11 | 10,5 | 12,6 | 14,4 | 12,1 | 13,8 | 12,3 | 11,8 |
| Mean | 12,2 | % | | | | | | | |
| Std. Dev (S) | 1,2 | % | | n=20 | | | | | |

*Table 1 Calculation of average moisture content and standard deviation.*

### 3.2.1. T-distribution of collected data

The t-distribution is designed as the normal distribution. But the t-distribution is not as accurate as the normal distribution as the t-distribution is based on the whole population and the t-distribution is based on a number of samples from the population.

In wood drying production there can be infinitely many measurements made with a electrical moisture meter! Every each piece in the batch will contain a unique MC level, caused by local variations of the woods natural properties or caused by different conditions during drying (location in package, kiln etc.). To measure MC for every single piece within the batch is of cause not possible in practice. Every piece will vary in MC throughout its length and traditionally one measurement at a local point of the sample shall reveal the "true" MC of a whole piece. There is no exact answer of how many measurements are enough to find out whole batch average and variation MC, as every other drying process will differ from another.

T-distribution is an approximation of the normal distribution. If the number of observations in a t-distribution is approaching the number of observations which totally can be made, the t-distribution turns to normal distribution. The t-distribution is creating an interval for the mean value, based on a few observations. "With 95% confidence" is an often used level for the interval and can be estimated as "a standard" in statistics. The calculation of the interval is based on mean value and standard deviation form observations in a batch, the number of samples and a "t-value".

An example of t-distribution is presented in *Example 2,* below.

The interval for the average value is calculated based on each measurement or observation from the collected set of data.

Lower limit: $\bar{x} - t_{\alpha/2}(n-1)\frac{S}{\sqrt{n}}$ Upper limit: $\bar{x} + t_{\alpha/2}(n-1)\frac{S}{\sqrt{n}}$

- *$\bar{x}$ =average value for the observations (measurements)*
- *n=number of observations (measurements) within the whole population (batch)*
- *S= standard deviation of the observations when just a selection of the population is contained in the analysis (e.g. 20 measurements from a batch in a kiln with >1500 pieces.)*
- *The t-value $t_{\alpha/2}(n-1)$ is a statistical defined value which depends on number of measurements and desired accuracy of the interval (e.g. 95% accuracy). In Table 2 t-values for 95 and 98% accuracy of the interval are presented. The value is based for n-1 samples, e.g. for 20 measurements value is based on 19 which is 2.093*

| *Number of measure - ments* | *10* | *11* | *12* | *13* | *14* | *15* | *16* | *17* | *18* | *19* | *20* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Value Conf: 95%* | 2.228 | 2.201 | 2.179 | 2.160 | 2.145 | 2.131 | 2.120 | 2.110 | 2.101 | 2.093 | 2.086 |
| *Value Conf: 98%* | 2.76 | 2.72 | 2.68 | 2.65 | 2.62 | 2.60 | 2.58 | 2.57 | 2.55 | 2.54 | 2.53 |

*Table 2 T-value for specified number of 10-20 measurements, with a 95 and 98% confidence interval (Vännman K, Matematisk Statistik)*

*Example 2*

*"Samples from batch will describe an interval with 95% confidence for the average moisture content within the batch"*

*(Values are taken from Example 1.) 20 samples are measured with electrical moisture meter in a kiln and show average moisture content of 12.2 with a standard deviation of 1.2%. T-value from Table 2 for n=20 measurements (n-1=19 → t-value=2.093) is 2.093. Inserted in formulas*

*Lower* limit: $\bar{x} - t_{\alpha/2}(n-1)\frac{S}{\sqrt{n}}$ Upper limit: $\bar{x} + t_{\alpha/2}(n-1)\frac{S}{\sqrt{n}}$

*Lower and upper limits respectively are calculated and the interval is 11.6 and 12.8%. This means that with 95% confidence that average moisture content can be found within these limits if every piece in the whole batch is checked.*

*Comment to Example 2:*
*Example 2 shows the inaccuracy which is present when measuring MC of samples within a batch contained in a kiln. Therefore it is of importance that measurements are made in a position which is uniform for the true average MC within the batch to have a high accuracy of the calculated interval (tighter interval). See chapter "Where in a compartment kiln is the climate representative".*

For further information about t-distribution, see statistical litterateur about "t-distribution where the standard deviation is not known".

## 3.3. Statistical Process Control as a "quality control tool"

This is an introduction of Statistical Process Control (SPC) as "quality control tool" of numerical data.

Variations are present in all kind of production, especially in drying of wood. By working structural as *PDSA-cycle* and make adjustments within processes it is possible to find a more stable production. The purpose of SPC is to show trends which influence on drying quality.

### *3.3.1. Control charts*

Control charts detect changes in a process during a time period. A control chart handles variation and performance from several sub processes which have been running in equal conditions, collected over a period of time and is illustrating trends for the whole process. Control charts make it possible to modify processes by making it possible for operators to do changes based on facts. To determine if a process is stable and capable, control charts can be a statistical tool. Control charts are studied parallel with a so-called X bar chart and an R bar chart. The X bar chart is developed from the average of each subgroup data. The R chart is developed from the ranges of each sub-process data. The R bar chart handles variation within every sub process, e.g. in wood drying by calculating the difference between the lowest and the highest measured value by the electrical resistance moisture meter.

*"Appendix 2 Control chart"* is an example of handling and use of numerical data to follow up a specific process over a period of time, by using MS Excel.

- **Histogram**

Variation can be characterized by measure each object and sort observations in intervals. It is a variation of a bar chart, in which data values are grouped together and put into different classes. The grouping allows the observer to see how frequently data in each class occurs in the data set. The higher bars represent more data values in that class, while lower bars represent fewer data values in a certain class. From a histogram the observer can tell relative frequency of occurrence for certain data values e.g. moisture deviation in a batch. In line capacitance moisture meters are logging every measurement this way. In a timber batch the majority of the pieces are focused to the mean MC but there will be "tails" with individuals which vary from the mean MC. A histogram shows how groups are formed and a normal distribution curve can be adapted from the average value and variation of the population, exemplified in *Figure 3.5*. The histogram can e.g. represent data from a sub-process or a specific package or batch of timber.

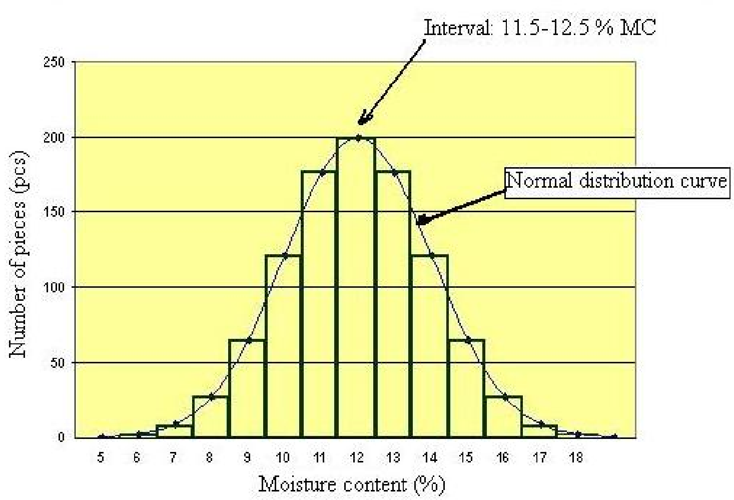



*Figure 3.5. Histogram where each stack contains a number of observations creating a normal distribution (Each interval is in this figure set to 1% MC).*

- **Design and calculation of control chart**

There is a relation between the histogram and the control chart. If characteristics of the sub-process are compared to each other in a histogram, it is possible to develop a control chart where every sub-process illustrates the process as time dependable. SPC makes it possible to analyze how sub-processes are varying during time, illustrated in *Figure 3.6*.

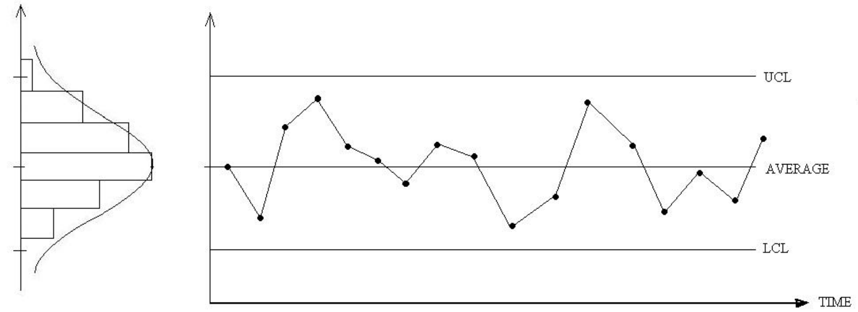



*Figure 3.6 The variation of the process is based on a number of sub-processes. (Figure can e.g. show how average MC for each 17 batches is varying; X-bar control chart). The normal distribution to the left is developed from the 17 sub-processes to the right. The "tails" of the normal distribution is outside of the UCL and LCL; the process is "not capable".*

A control chart consists of two (or more) diagram

- $\overline{X}$–bar diagram: Displays all *average value* $\bar{x}$ of each sub-process, plotted in a comparing diagram for the process during a time period.
- *R*-bar diagram: Displays the *span of variation R* of each sub-process, plotted in a comparing diagram for the process during a time period.

The average values and deviations are plotted over time to determine if the result of a process is running within acceptable limits. The upper and lower control limits can be set manually by a observer with knowledge of the process or calculated based on measurement data from the process. An "ideal" level called center line is also set or calculated, e.g. the target MC 12% or likely. If samples of each batch conform in their average and, joined within specific limits and fulfill the rules for analyze control charts, the process is stable and consistent.

For both diagrams a center line, control limits have to be calculated and eventually warning limits,

- Center line (CL), often average value from processes
- Upper Control Limit (*UCL*)
- Lower Control Limit (*LCL*)
- Upper Warning Limit (*UWL*), placed between UCL and CL
- Lower Warning Limit (LWL), placed between LCL and CL

CL, UCL and LCL, UWL and LWL for those diagrams are calculated by the $\overline{X}$ - *R*-method. Notice that $\overline{X}$ – and *R*-diagram should be studied parallel.

- **A comment to R-diagram, application in wood drying**

Variations can be found in a process due to many different causes. A control chart may indicate an out-of-control condition either when one or more points fall beyond the control limits or when the plotted points display some systematic error or other "process behavior". Variation can be affected by

- Natural causes, e.g. as time at year
- Specific to a certain operator, kiln, batch of material, raw material etc.
- Other estimated abnormalities

Analysis of the process and removal of variations due to such causes is the solution to process development. The R-diagram is calculated based on the variation of many processes. In wood drying there can be useful to eliminate extreme values which can occur in measurement of MC (specifically with incorrect electrical resistance moisture meter readings). Some pieces with extremely different MC than target will occur in dried batch and can cause errors in moisture readings. Therefore it can be useful to systematically eliminate the highest and lowest measured value when control limits are calculated, see *Example 3*.

*Example 3 "Eliminate extreme values from measurements when calculation of R-diagram"*

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| *10,3* | 11 | 11,8 | 10,5 | 12,6 | *14,5* | 12,1 | 12,3 | 12,9 | 13,8 |
| 11,8 | 12,6 | 11 | 10,5 | 12,6 | 14,4 | 12,1 | 13,8 | 12,3 | 11,8 |
| Mean | 12,2 % | | | | | | | | |
| Std. Dev (S) | 1,1 % | | | *n=18* | | | | | |

*Table 3 Calculation of average moisture content and standard deviation. Extreme values are not included (10.3 and 14.5%), compare with Example 1.*

- **Control chart demands**

To get control charts reliable, these have to fulfill specific demands. Some demands are

- To translate and use a control chart has to be easy
- Systematical errors or abnormalities has to be detected quickly
- "False alarm" should not be flagged without a reason (curve outside of control limits)
- The actual time in the control chart must be able to be estimated
- The control chart should act as a "receipt" if the process is stable and consistent
- The control chart should act as a "receipt" if changes of the process has succeed or not

- **Rules of analyzing control charts**

When do the control chart show if process is correct or incorrect?

There are "rules" or recommendations of how to translate the information which the control charts illustrates. A point outside defined control limits indicates that the process has changed. When a change is illustrated by the control chart, an investigation should be made to find the cause of the change and make corrections. Control charts can help to identify key input variables which cause the process to shift. The rules are as followed

- One point is beyond upper (UCL) or lower (LCL) control limits
- Two following points lying over or under a warning limit
- Seven or more following points lying on one side of the center line (CL)
- Five or six following points going in the same direction, which indicates a trend of the process
- Four out of five observations more than one standard deviation from center line (CL)
- Own rules based from experiences by operators

*For further information about calculation methods of e.g. control limits, see statistical litterateur about "X-R Control charts".*

# 4. Standards concerning Joinery Kiln Drying

Followed is a short description of standards concerning joinery kiln drying and backed up in a later chapter where recommendations for a daily usage are presented.

Standards are implemented so production fulfils required demands. Standards are technical regulations and rules where these are drafted as general demands with purpose to find optimal technical solutions of continuously returning problems. E.g. standards are implemented to define specific properties, methods and reduction of alternatives. This is to make it possible to ensure quality of the production and products. European standards are defined by The European Committee for Standardization (CEN) and approved standards are given identification by the abbreviation "EN" followed by a number.

There are three European standards which are main methods for determination or estimation of MC in wood. Measurements are made to act as information for follow up drying performance and shall describe a situation of level of timber quality. These are

1. EN 13183-1:2002. MC of a piece of timber.
   Part 1: Determination by oven dry method
2. EN 13183-2:2002. MC of a piece of timber.
   Part 2: Determination by electrical resistance method
3. EN 13183-3:2005. MC of a piece of timber.
   Part 3: Determination by capacitance method

Because of a low industrially usage of hand held capacitance moisture meters, this QHB only makes comments of prEN 13183-3:2005, in-line capacitive measurement technique.

Additional, summarized standards which concern quality of joinery products is

- ENV 14464 Sawn timber - Method for assessment of case-hardening
- EN 14298 Sawn timber - Assessment of drying quality
- prEN 13307-1&2 Timber blanks and semi-finished profiles for non-structural uses, part 1: Requirements and 2: Process control
  (Where part 2 probably will be degraded to TS status)

## 4.1. EN 13183-1:2002, Oven Dry Method (ODM)

This method bases the MC on weight loss in a sample (or samples) and is destructive. The ODM shall act as a reference method to other MC measuring techniques and calibrations of equipment used for determining MC. This method is also acting as reference method in case of a dispute regarding moisture level.

### *4.1.1. Description of the standard EN 13183-1:2002*

This is a summary of the standard, to what is of interest in QHB

- **Calculation and presentation**

The amount of moisture in wood is expressed as "moisture content" (MC). MC or $\omega$ is presented as moisture fraction of absolutely dry wood, and unit for MC expression is percent (%).

$$MC\ (\%),\ \omega = \frac{(green\_weight)-(dry\_weight)}{(dry\_weight)}\cdot 100$$

The fraction of moisture in wood is calculated and round off to nearest 0.1 percentage point.

- **Equipment needed**
  - Chain saw/circular saw with high sharpness, so friction will not have an effect of moisture being eliminated. (pertain to larger dimensions of samples)
  - Weight scale
    - Accuracy of 0.1g if test slice weight are greater than 100g in oven dry state
    - Accuracy of 0.01g if test slice weight are less than 100g in oven dry state
  - Oven capable of maintaining 103±2 ºC

- **Procedure of the standard**

This description follows the definition of the standard.

- Select area of wood carefully and cut sample at minimum 20mm wide (in the direction of the piece), at least 300mm from edge of board. No knots, resin wood, resin pockets or bark are allowed. If location of the sample has one of these features, relocate the cut toward center of the piece where clear wood are found. (*Figure 5.9*)
- Number the sample(s) for identification
- Weigh sample directly after they are cut. If weighing will be delayed, contain samples in a slim plastic bag for maximum two hours until measurements are made.
- 12-24 hours depending on MC and dimension. Contain sample in oven until difference in mass are less than 0.1% between two weighing separated by an interval of two hours
- Weigh sample directly after oven drying
- Calculate MC

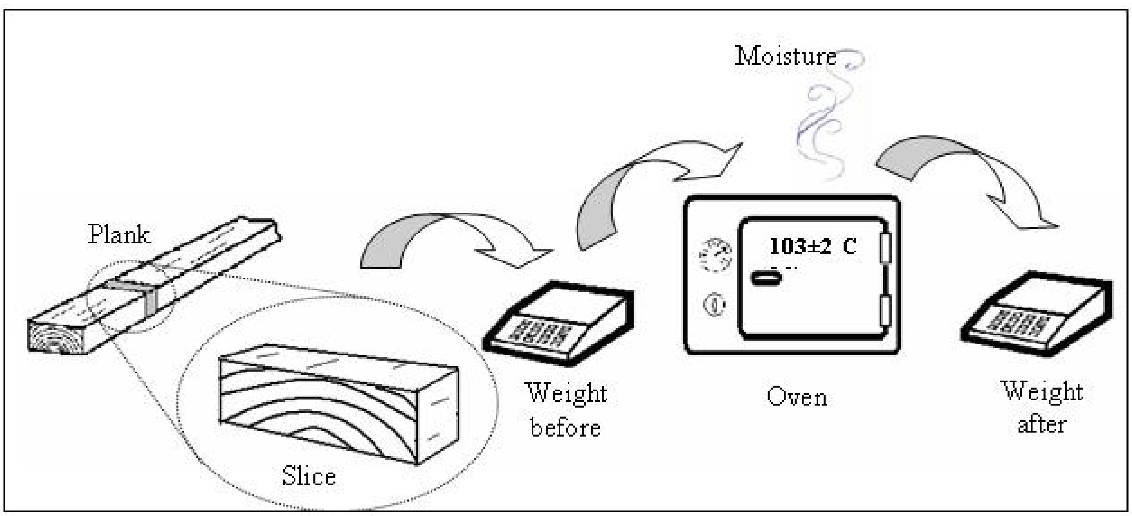



*Figure 4.1 Method of ODM.*

## 4.2. EN 13183-2:2002, Electrical resistance method

This method is the most common in industry today of measuring moisture in wood. This non-destructive technique measures the resistance between two electrodes. The contact resistance between each electrode and wood is mainly what is measured. The electrical resistance moisture meter measures the wettest wood that contacts both electrodes.

### *4.2.1. Description of the standard EN 13183-2:2002*

This is a translation of the standard, to what is of interest in a QHB

- **Calculation and presentation**

Estimated reading and automatically calculations from electrical resistance moisture meter as standard shall be expressed in nearest whole percentage point. Though, it can be useful to present readings by one decimal (0.1).

- **Equipment needed**
  - Electrical resistance moisture meter

- **Procedure of the standard**

This description follows the instruction of the standard, illustrated in *Figure 4.2.*

- Pikes shall be in the direction of the grain (or as instructions from manufacturer of the electrical resistance moisture meter)
- Wood shall not contain features as knots, resin wood, resin pockets or bark. If location of the sample has one of these features, relocate the measurement toward nearest area in the centered direction of the board, where clear wood is found.
- Collect reading from electrical resistance moisture meter after 2-3 seconds

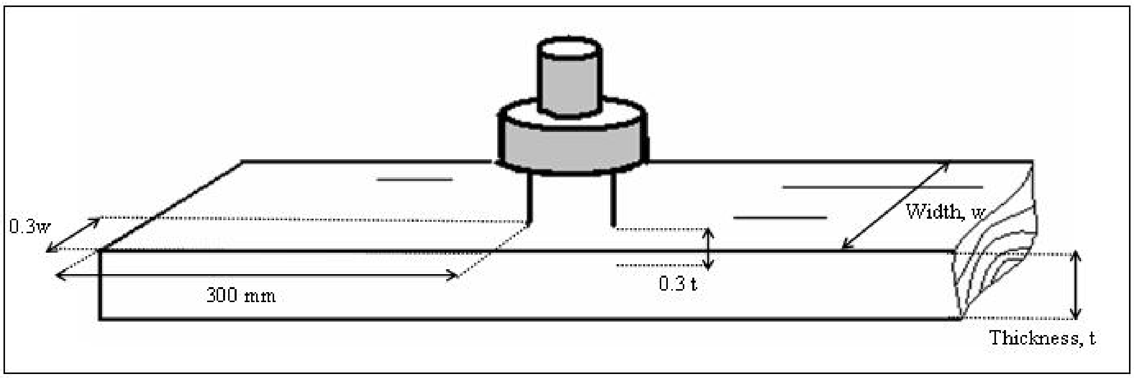



*Figure 4.2. Place of measurement from the end of a single board. 300mm are always excluded.*

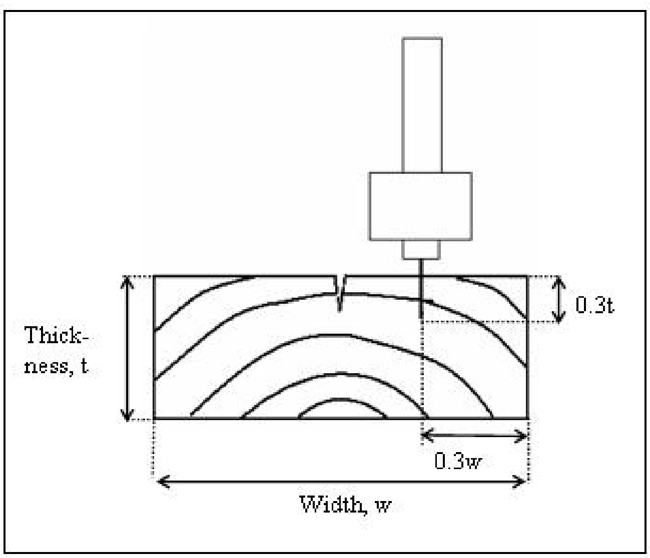


*Figure 4.3. The points of the electrodes shall be driven to a depth of 0.3t and 0.3w for a correct measurement of the average MC of the cross section.*

- **Number of measurements of a lot, due to the standard**

As accuracy will decrease if low number of measurements is made on few pieces, there have to be a lower limit of the number of measurements per pieces. In kiln drying production where the number of pieces are greater than >5, will approve one measurement per piece. See *Table 4*.

| *Number of tested pieces* | *Number of measurements per test piece(*)* |
|---|---|
| *1* | *3* |
| *2* | *3* |
| *3* | *2* |
| *4* | *2* |
| *5* | *2* |
| *>5* | *1* |
| ** Measurements should be taken at random along the length excluding 300mm at each end (or at mid point of pieces less then 600mm long. All results of measurements should be noted.* | |

*Table 4. Number of MC measurements of a lot. One measurement per piece are enough as timber in production is stored >5 pieces per batch.*

## 4.3. EN 13183-3:2005, Capacitance method (in-line), comments.

The standard is more of general recommendations in daily use of the equipment and calibration of it. Chapter *Capacitive moisture meter (in-line)* refers to wider discussion of the equipment. The standard is not covering exact how measurements shall be made, as the installations differ between users. Though, there are issues covered by the standard which can be described. According to the standard;

- Recommended overall interval of the equipment is 7-30% MC
- Pressing device is recommended to keep distance between sensors and sample constant
- Eliminate vibrations of the equipment
- Keep cables and sensors shielded to avoid electromagnetic interference
- Keep equipment clean from dust and other dirt
- Make calibration with ODM and sensor reading within the same area on the actual sample
- Make calibration on an eventual used density measuring unit separately in the calibration
- To have high accuracy of the calibration, exclude samples in the calibration where density ($\rho$) of an oven dry sample (ODM) is varying more than 40 kg/m$^3$ from mean density ($\rho_{mean}$) of the timber batch in the calibration set.
- Calibrate using samples with a fix MC interval, recommended as *class B*; 10-18% MC

And finally,

- Calibrate equipment according to instructions by manufacturer.

*Further information can be found in the standard and are not further described in the QHB.*

## 4.4. ENV 14464, Sawn timber- Method for assessment of case hardening

This method is the standardized method for measuring case hardening in wood. This is a destructive technique and measures how developed tensions are within the wood after drying. This is a summary of the standard, to what is of interest in QHB.

A common definition of case hardening is;

*Case hardening is the tendency of dried wood to deform after re-sawing and equalizing of the MC within the wood sample.*

### *4.4.1. Description of the standard ENV 14464*

According to the standard, the slicing test is an analysis of the performance of conditioning phase during drying.

- **Presentation of result**

Expression of case hardening is presented in millimeters of gap. Calculation can be positive/negative depending on tensions within the wood sample. Measurements have to be presented with 0.1mm accuracy. (Remember to withdraw the width of jig test pins; 10mm.)

Is the width of the sample <100mm the shorter distance (75mm) between the pins of the test jig can be used. The result from this test are recalculated by multiplying the value with 1.78, which then will be comparable with samples >100mm.

- **Equipment needed**
  - o Chain saw/ circular saw, knife/band saw to divide sample in half
  - o Calibrated measuring device graded in at least 0.1mm steps.
  - o Plastic bags (one for every test sample)
  - o Standardized jig, designed as *Figure 4.4* (which can be bought from e.g. SP Trätek or manufactured by a mechanical workshop).

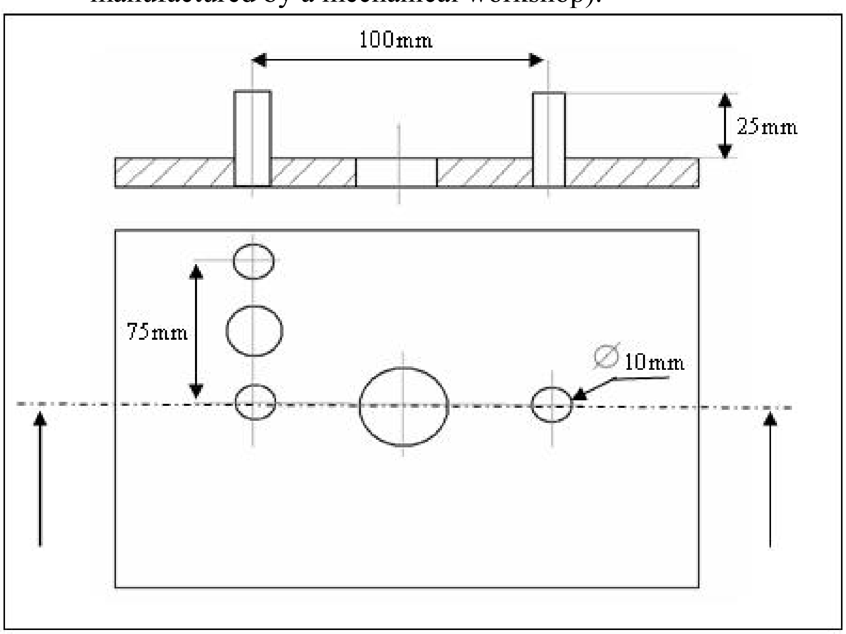



*Figure 4.4 Jig for slicing test, standardized according to ENV 14464.*

- **Procedure of the standard**

This description follows the instruction of the standard. See *Figure 4.5*.

1. Select area of wood carefully and cut sample at minimum 15mm wide (in the direction of the piece), at least 300mm from edge of board. No knots, resin wood, resin pockets or bark are allowed. If location of the sample has one of these features, relocate the cut toward center of the piece where clear wood is found, illustrated in *Figure 5.9*
2. Number the sample(s) for identification. Slice sample in half with knife. Keep both halves gathered
3. Store sample 24 hours in plastic bag in room temperature for moisture equalization
4. Use test jig to measure width of gap

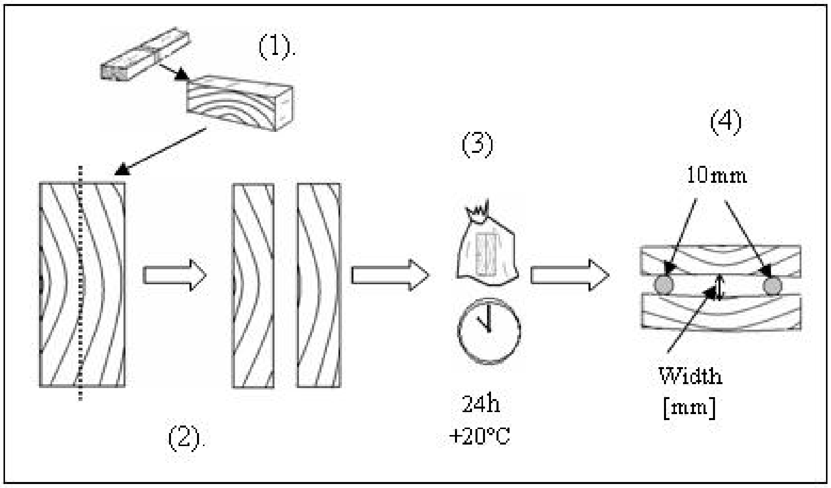



*Figure 4.5. Procedure of making two piece slicing test of one sample.*

## 4.5. prEN 13307-1&2- Timber blanks and semi-finished profiles for non-structural uses

The standard is divided into two parts.

1. Requirements
2. Process control

These preliminary standards are base for production of "timber blanks and semi-finished profiles for non-structural uses", such as doors, windows, stairs etc. These standards are a drafts distributed by Technical Committee to CEN members for review and comments. Tendencies of not letting Part 2 become an official EN standard are discussed.

### *4.5.1. Summary of findings, of interest due to joinery kiln drying*

Interesting findings from the two parts of the standards are

- Cup of produced joinery shall be limited to 0.5% of the width of the piece for planed pieces or 1.0% of the width of the piece for non-planed pieces

- The difference in MC of any lamella within the same profile to be glued together shall not exceed 2%

- Equipment shall be available
  - to continuously monitor and record the temperature and relative humidity in storage, production and curing areas
  - to measure the wood MC

- MC in service for external doors, windows etc. are within the range of 12±3% (according to EN 335 class E2 or E3)

- The manufacturer shall keep a record of the tests carried out and the results against the batch identification for a minimum of 10 years

- Acceptable moisture variation between any two neighboring lamellae in the same profile shall not be greater than 2% when glued together

## 4.6. EN 14298:2004, Sawn timber – Assessment of drying quality

This standard is recently implemented due to production of timber blanks and semi-finished profiles for non-structural uses, such as window components.

### *4.6.1. Description of the standard EN 14298:2004*

The base of the standard is by using statistics to define quality. Parameters which the standard are handling are

- Maximum deviation of average MC in relation to target MC
- Maximum range of moisture variation within a batch
- Maximum percentage of pieces outside of specified moisture limits
- Permitted case hardening (included in some cases)

- **Different quality levels**

The standard is based on two drying qualities

1. Standard drying
2. Specific end use drying

Followed are shorter descriptions of the two drying qualities.

1. Standard drying quality handles target MC range from 7-18% and a maximum allowable range of average MC in relation to moisture target. The range of MC of individual pieces within a batch shall be between $0.7\omega_{target}$ and $1.3\omega_{target}$ for 93.5 % of the all pieces in batch. An interpretation of these demands for different moisture levels is presented in
2. *Table* 5.

| Target MC | Allowable range of average MC around target MC | 93,5% of individual pieces should be within these MC limits | | Maximum allowable std.dev. when average MC=target MC | Maximum allowable std.dev. when average MC=lower allowable average MC (*) | Maximum allowable std.dev. when average MC=upper allowable average MC (*) |
|---|---|---|---|---|---|---|
| (%) | (%) | min (%) | max (%) | (%) | (%) | (%) |
| 7 | -1/+1 | 4.9 | 9.1 | 1.1 | 0.7 | 0.7 |
| 8 | -1/+1 | 5.6 | 10.4 | 1.2 | 0.8 | 0.8 |
| 9 | -1/+1 | 6.3 | 11.7 | 1 | 1.1 | 1.1 |
| 10 | -1.5/+1.5 | 7.0 | 13.0 | 1.5 | 1.0 | 1.0 |
| 11 | -1.5/+1.5 | 7.7 | 14.3 | 1.8 | 1.2 | 1.2 |
| 12 | -1.5/+1.5 | 8.4 | 15.6 | 2 | 1.4 | 1.4 |
| 13 | -2.0/+1.5 | 9.1 | 16.9 | 2.1 | 1.3 | 1.9 |
| 14 | -2.5/+1.5 | 9.8 | 18.2 | 2.3 | 1.5 | 2.1 |
| 15 | -2.5/+1.5 | 10.5 | 19.5 | 2.4 | 1.7 | 2.3 |
| 16 | -2.5/+2.0 | 11.2 | 20.8 | 2.6 | 1.6 | 1.9 |
| 17 | -2.5/+2.0 | 11.9 | 22.1 | 2.8 | 1.7 | 2.0 |
| 18 | -2.5/+2.0 | 12.6 | 23.4 | 2.9 | 1.8 | 2.2 |

* As larger deviation of average MC from target MC, to have 93.5% of batch within MC limits the maximum allowable standard deviation will be lower than if average MC=target MC. (E.g. when target MC=12% maximum std.dev. will drop 0.6% from 2.0% to 1.4%)

*Table 5 Translation of the standard due to allowable deviations in moisture levels*

The demands from *Table 5* for “standard drying, 12% target MC” are illustrated in *Figure 4.6*.

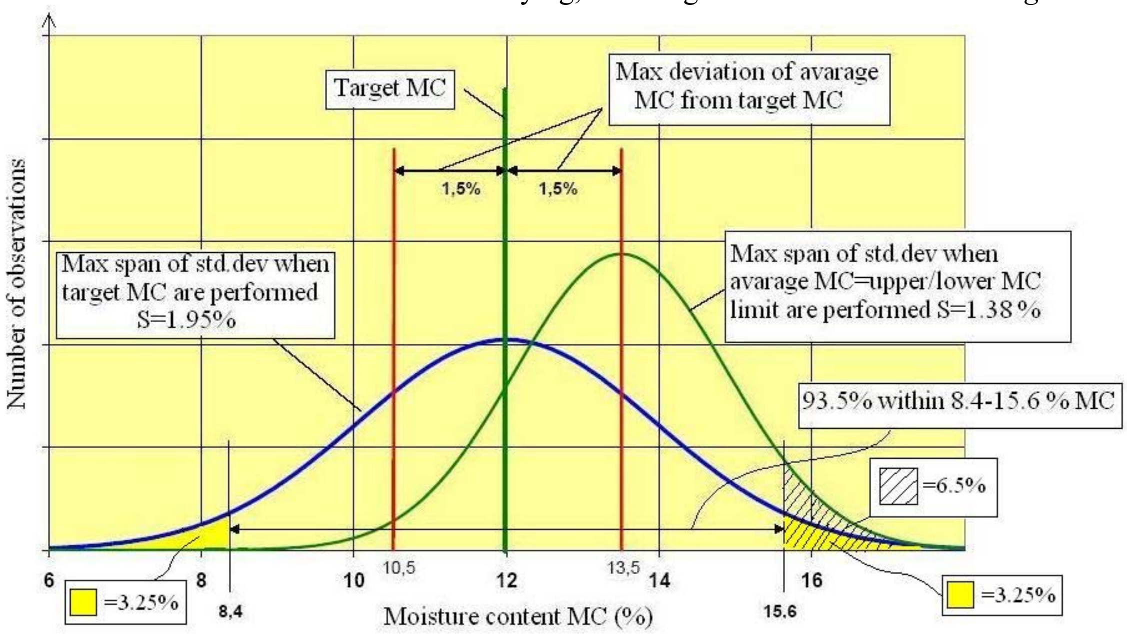



*Figure 4.6 Allowable variation of MC due to the standard for 12 % target MC. Area under curve contains 93.5% of all observations; maximum allowed rejects are 6.5% even if average MC is above or below target MC.*

3. Specific end use drying quality is different from standard drying quality, when features do not follow pre-set levels. Joinery drying quality can be defined as “Specific end use drying quality” as requirements of moisture variation of dried joinery raw material is 10-14%. Features which has to be clarified is

   - Target MC
   - Allowable range of average MC in relation to target MC
   - Allowable moisture limits for individual pieces within a batch
   - Allowable case hardening
   - (Defined acceptable quality level AQL, suitable for the product. See standard “EN 12169, Criteria for the assessment of conformity of a lot of sawn timber”)

- **Collection of samples and testing routines**

The batch meets requirements if it fulfils standard EN14298 in combination with EN 12169 “Criteria for the assessment of conformity of a lot of timber”. Selection of samples shall be according to the standard “EN 12169, which describe acceptable quality limit (AQL). Testing routines are made according to standards ENV 14464, EN 13183-2 (or in case of dispute EN 13183-1).

*The standard EN 12169 “Criteria for the assessment of conformity of a lot of timber” is not further described in the QHB.*

### 4.6.2. Comments of standard EN14298 and a comparison to prEN 13307-1&2

The standard is focusing on moisture variation within a package and as supplement in some cases (between seller/customer in specific situation) a defined level of case hardening. This standard is comparable to *prEN 13307-1&2,* Timber blanks and semi-finished profiles for non-structural uses, part 1 & 2. Here recommendation is 10-14% MC for the timber when it is used for window production.

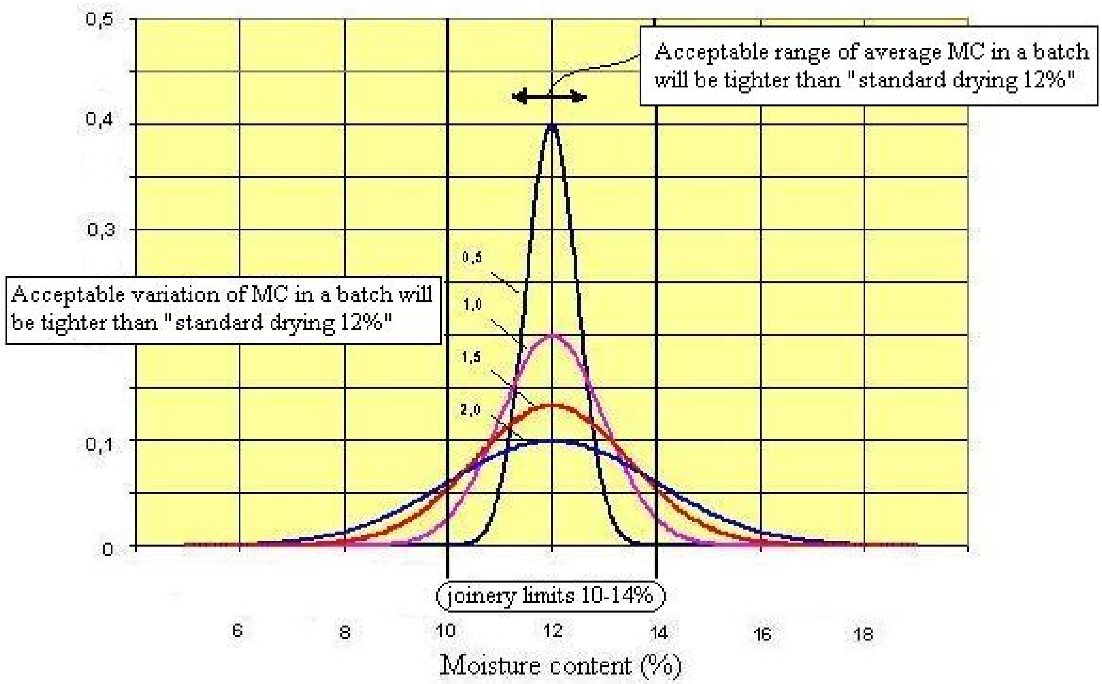



*Figure 4.7 From figure an interpretation can be made, that an acceptable moisture variation is 0.7-0.8 % MC to meet joinery production requirements (standard EN 13307).*

The recommendation is that pieces with lower/higher MC than 10-14% are not acceptable in production and shall be rejected. A recommendation by SP Trätek is that 2% rejects are an acceptable limit. This means that recommended is that 98% of all pieces should be within 10-14% MC-limits. From *Figure 4.7* can be seen, that to fulfill this recommendation an acceptable standard deviation (S) will be S≈ 0.7-0.8, if average MC for the batch is found to be 12%.

# 5. Recommendations to increase drying quality

## 5.1. Influence of kiln drying quality

Wood drying is quite complex as wood is an anisotropic material and not uniform in its properties. Parts of the batches of wood and even parts within a timber piece can differ from the main wood quality. Therefore there will be small differences of the drying quality.

### *5.1.1. Decrease deviation from MC target and MC variation of a batch*

Wood drying result will always be varying, more or less as many factors are influencing. It is the raw material properties combined with production parameters which result in different moisture variation. In the drying production factors which can increase the MC variation has to be eliminated.

To reduce moisture variation drying can be performed as followed.

- o Sorting of green timber in the log yard and in the green sorting has to be planned thoroughly. Wood material related factors which influence moisture variation within a batch are e.g.
  - *Variation of the density within a package or batch which is going to be fed into the drying process has to be minimized. Low-dense wood dries faster than high-dense, the drying time ratio is circa 2:1*
  - *Initial MC of timber has to be as uniform as possible*
  - *Dimensions of timber has to be as uniform as possible*
  - *Ratio of heartwood/sapwood content has to be as uniform as possible as sapwood dries faster than heartwood*
- o Timber packages are drawn equal in the green sorting (sve: "jämndragna paket"). Every second timber piece is adjusted toward the maximum length of the package. This will make airflow become uniform throughout the batch as it is in the drying kiln.
- o MC variation will decrease for timber with low target MC, in a situation where no equalizing of the timber are made in the end of the drying process, illustrated in *Figure 5.1*. In this situation average MC will decrease (moisture is dried out and removed from the timber).

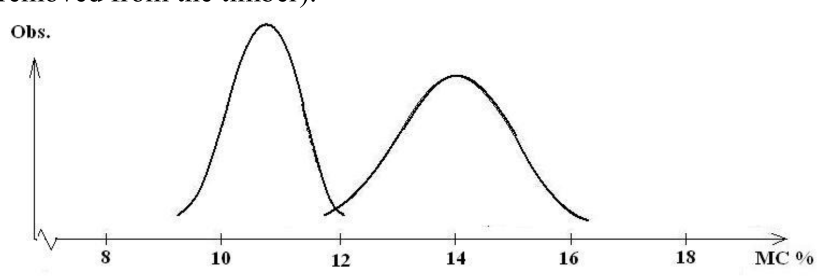



*Figure 5.1 Drying to lower $MC_{target}$ will reduce MC variation within a batch.*

- o MC variation within the batch will decrease if the timber in a conditioning phase is equalized in the end of the drying process, illustrated in *Figure 5.2*. Though, average MC will increase (moisture is added to the timber as it is re-wetted or conditioned).

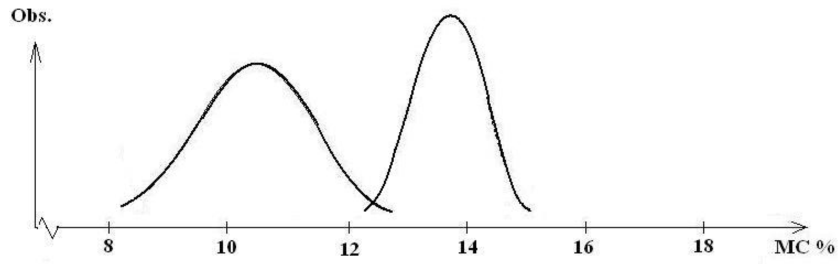



*Figure 5.2 Moisture variation of timber batch will be reduced if a conditioning phase is used in the end of the drying process.*

Production related factors are

- *Uneven air velocity through the stickered packages*. Caused by design and condition of flaps, air flow direction, if not having timber every other layer even toward flaps making air velocity differ throughout packages, etc.
- *Uneven basing* causing outer layers being more/less moist than the majority of the batch, which can depend on design and maintenance of basing system, etc.
- *Depth of the kiln*. Longer kilns produces higher moisture variation than shorter ones
- *Drying schedule*.
- *Maintenance of kiln*.
- *No equalizing/conditioning phase after drying.* Investigations by IMPCOPCO have shown that an equalizing period with suitable climate for the actual timber reduces deviation from average MC toward target MC and moisture variation of batch to the half.

### 5.1.2. Case hardening and moisture gradient

Case hardening is a problem which is caused by fast drying and rapid development of moisture gradient between core and surface. Case hardening can be more or less severe as result of drying when surface of timber is shrinking as it comes below FSP and core of the timber still is in its swelled state. Storage of un-equalized and without stress relaxation will build up severe stress as the moisture gradient is even out by time. Drying schedules which allows high amount of tensile stress of timber surface without causing timber to check, will produce timber with a ”compressed surface” when moisture gradients are even out. “Seasoned” or conditioned timber is preferred to reduce this problem as timber is used for joinery. Case hardening can be reduced to one third if an effective conditioning is performed.

- **Development of case hardening**

Case gardening is an area which is not that investigated. Somewhat we have a hint of what is happening with the wood but here more knowledge is needed. Theoretically the phenomenon can be described by describing how stress is developed throughout the ongoing drying and conditioning phases. Following is a short description of how stress is developed during the drying process and how timber is reacting as MC gradient is even out within the cross section by time. A non-stressed material after moisture gradient has been reduced is of cause desirable.

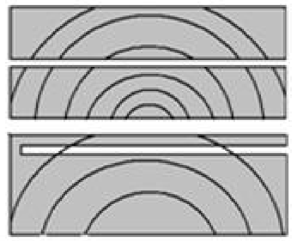
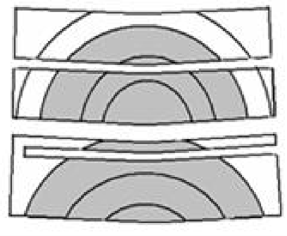
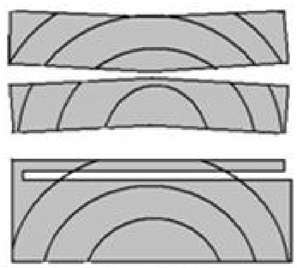
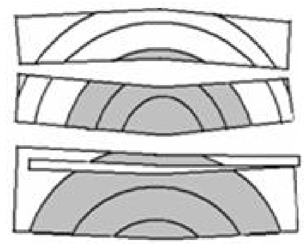
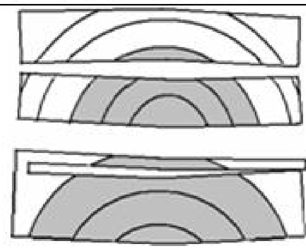
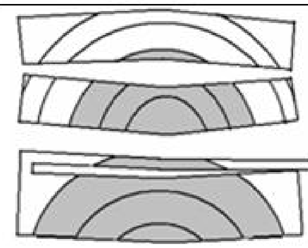
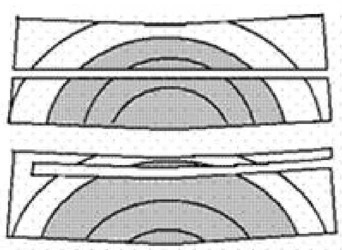
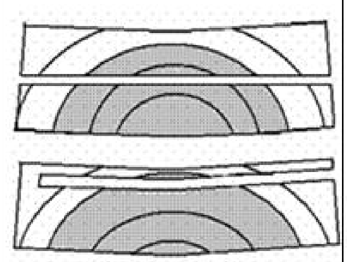
| *Stage of drying process* | *Appearance of sample directly after collecting it* | *Condition of timber during drying stage* | *Appearance of sample after gradient has been reduced. (time >few days)* |
|---|---|---|---|
| Ideal heating without surface drying |  | No tensions |  |
| Early stage of drying. Surface <FSP but core >FSP |  | Tensile stress in surface results in mechano sorptive tension of surface and compressive stress in core |  |
| Late in drying. Whole cross section <FSP |  | Tensions are now reversed. Compression stress in surface and tensile in core. This happen 18-22% MC. |  |
| During conditioning moisture are added to surface and the plastic tension are pressed back in same time moisture gradient are even out |  | Result after conditioning will be timber even out in case of stress and a reduced moisture gradient |  |

*Figure 5.3 Theoretically of how case hardening is developed and how to reduce it (follows discussion by Sehlstedt-Persson M, LTU)*

This is practically illustrated if a slicing test is made from timber pieces which have been conditioned. A slicing test reveals the amount of case hardening and gap >3mm is said to be severe. An acceptable level of gap is by SP Trätek recommended to be <1mm and is reachable with the conditioning technique of today. From the discussion made in *Figure 5.3* can be found that for timber which has tensions even out, has also moisture gradient even out. There have been no or negligible moisture movement in the cross section of the sample, if a well performed conditioning has been made. In wooden industry case hardening is a huge problem when timber is resawn along the timber piece, as deformations will occur. A conditioning phase which reduces this phenomenon can be utilized.

- **How can case hardening be reduced?**

Generally equalization of the MC gradient is made during the conditioning phase, as a climate which is >EMC of the timber is applied. A high performance basing system raises humidity in the kiln climate rapidly, without decrease dry temperature too much. A high dry temperature is necessary to keep the timber formable and plastic in its behavior. Moisture can be added differently to the kiln climate and due to moisture adding technique, timber will react differently. E.g., as steam is sprayed into kiln, both the wet and dry bulb temperature is increasing very fast. Today also high temperature water basing (HTWB) sprayed into kiln with high pressure has quite similar performance as steam, as this technique has been further developed.

A use of different moisture adding techniques will result in differently distributed gradients after the conditioning phase is performed. If timber has moisture gradient and timber surface is re-wetted with steam or water, this will make the surface to "re-swell" and make the initialized tensions to be reversed. When using steam the surface will make outer layers become re-wetted rapidly and hereby will the MC gradient be very steep; large difference in surface MC compared to the MC some millimeter into the cross section of the timber. With other moisture adding technique such as HTWB and LTWB this gradient is not as steep as when steam basing is used, illustrated in *Figure 5.4*.

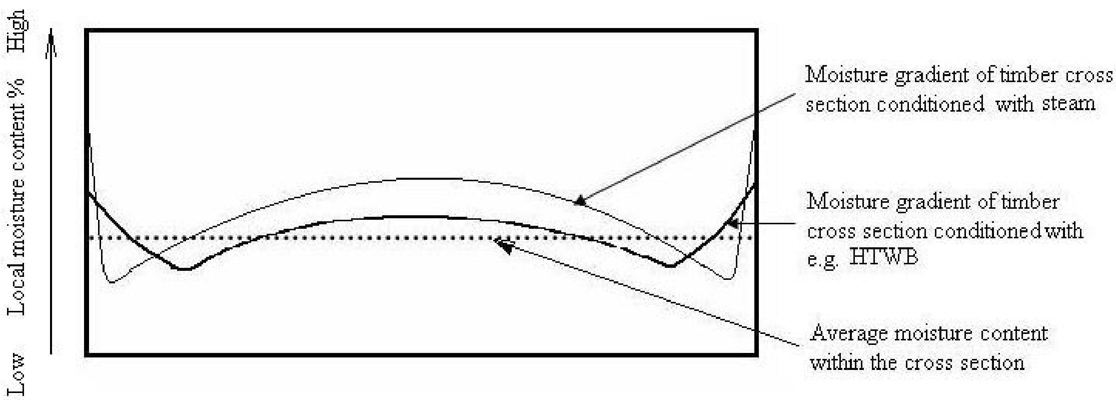



*Figure 5.4 Moisture gradient is distributed differently depending on moisture adding technique used. Surface wood is moister (higher MC) than wood a few millimeters into the timber.*

Following three different basing techniques is described.

a) **Basing with low pressure and low temperature of the water (LTWB)**
Moisture is added to the kiln climate by using a number of sprayers fed with cold water and low pressure and located on strategic places within the kiln. An aerosol with water is produced which adds moisture to the kiln climate. A problem with this technique is that as cold water is sprayed into kiln, moisture which is contained and carried by the air in the kiln may condensate on the basing water (cold and "big" water particles of the aerosol), fall to the floor and be lead away by the drain outlet. This leads to RH may be reduced in the kiln instead of being increased. It can be difficult to rapidly increase the RH in the kiln and reach a low psychometric difference by using LTWB. Therefore this technique is not recommended to use in production of high quality timber today as better basing techniques are developed. HTWB and steam has become methods for basing and these have to be implemented to have a high drying quality.

b) **Basing with high pressure and high temperature of the water (HTWB)**

This technique is quite similar to LTWB but here water is pre-heated and fed into kiln with high pressure. This makes the water to be a finer aerosol than using LTWB which is more easily added to the kiln climate. An investigation by Trätek has shown that heating and conditioning time are reduced when using HTWB instead of LTWB. A water temperature of 70-90 ºC is found to be very effective in combination with suitable water pressure, size and location of sprayers.

**c) Basing with saturated steam**

Saturated steam is an excellent medium to add moisture to kiln climate and has many advantages. As steam is warm and highly humid, this will have an excellent effect when it is sprayed into kiln as temperature can be held at a high level even if moisture is added. Investigations have showed that conditioning with steam will restrain temperature at high temperature causing timber to obtain plastic behavior which is preferable. A low psychometric difference ($\Delta T \approx 3$ºC) is easily held as steam is used for heating. Industrially it have been shown that it can be difficult to raise temperature to higher levels than the maximum temperature during drying, as machinery of the kilns are not suitable for being exposed all too high temperatures. High temperatures can also affect the wood material as resin flow and discoloration of timber then will increase. To control dry temperature when saturated steam is used, a combination with HTWB can hold dry temperature within reasonable limits, allowing RH to rise quite fast anyway. Investigations have also shown, by using steam instead of only HTWB, moisture variation within the batch and heating/conditioning phases will be reduced.

Choice of conditioning technique has an effect of how rapidly equalization phase and reduction of case hardening are performed. A desired effective basing should make heating and conditioning phases short to not be costly for the producer as kilns are occupied with timber for long periods. Most suitable is to combine conditioning phase with drying process in a controlled climate, as reduction of case hardening and initialized tensions are not possible to perform good enough in storages after timber is taken out from kiln.

When measuring gradient in production by electrical resistance moisture meter the moisture gradient have to be kept in mind. Depending on type of conditioning technique which is used in the specific case, distribution of the moisture gradient within the cross section will vary due to conditioning technique, illustrated in *Figure 5.44*.

- **Comparison of storage of conditioned/unconditioned timber**

If unconditioned timber is stored a couple of month, tensions and deformation will increase (most severe is cupping as a timber piece is split sawn). If unconditioned timber is stored for a long period (years), there will be a slight decrease of tensions but far from enough.

*Figure 5.5* and its attached table shows that a well performed conditioning phase will eliminate problems with gradients, case hardening and tensions.

| **Kiln dried timber. Pine 75*150, 8% ave** | Not conditioned in kiln or conditioning storage | Not conditioned in kiln but stored in conditioning storage | | Timber conditioned in kiln |
|---|---|---|---|---|
| Time in storage, month | 0 | 1 | 3 | 0-3 No difference |
| Moisture content, min/max % | 4-12 | 8-11 | 8-10 | 8-9 |
| Deformation (gap), mm | 3.0 | 3.5 | 3.2 | 0-0,1 |

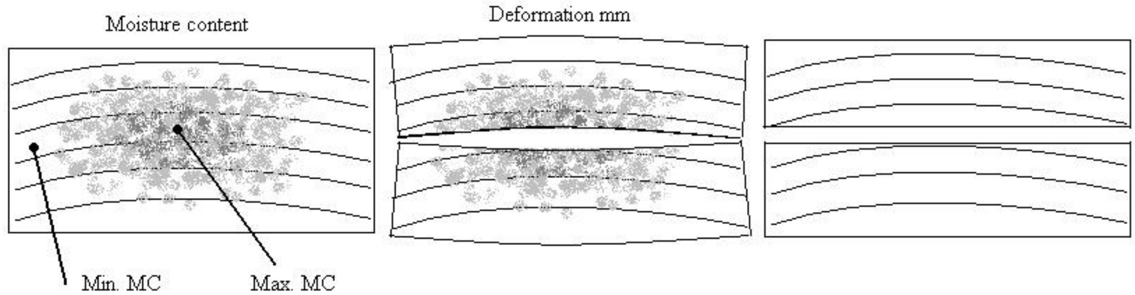



*Figure 5.5 Conditioned timber is recommended as deformation will decrease (Investigation by SP Trätek).*

- **A controlled cooling period is important**

In wintertime it is necessary to have controlled cooling period after drying process and a conditioning/equalization phase. As timber is produced to a high-class quality during the drying process within the kiln, an incorrect cooling period can decrease this instantly. As the wood has a high temperature and is taken out to winter climate, this can cause severe surface drying making timber check and develop steep gradients. These gradients which are eliminated in the conditioning/equalization phase can be re-developed if warm timber is taken out in cold outdoor air. In wintertime as outdoor temperature is low, a gradient will not be equalized in storage as moisture movement at low temperatures is small. Hereby, it's especially in wintertime important to have a cooling period to make timber temperature drop as much as possible to meet outdoor climate. Then this phenomenon will be reduced.

### *5.1.3. Deformation caused by drying process*

Deformation can act as warping, cupping, twist or bow. Timber with extreme fiber grain angle or other disoriented wood structure will have problems with deformation as wood shifts in shape when moisture is dried out from the wood. Shrinkage is generating deformations as the rate of shrinkage is different in each direction (tangential, longitudinal and radial) of the wood from FSP-0% moisture content. Deformation can be generated as a result of case hardening, as tensions are built up during drying.

Suggestible actions to reduce deformation are

- Avoid production timber of all too low moisture content. (< than target MC)
- Reduce moisture gradient in the cross sections of the timber after drying process are finished, by use water basing technique in the conditioning stage (equalizing of MC and reduction of case hardening).
- Position timber carefully in kiln supports or on timber carriage and use many stickers. Timber without support will deform more easily than timber with support. A sticker-stacker recently delivered by Renholmen had 11 stickers/6 meters. This shows that supports are in focus today to have low deformations as a result of the drying process. (Renholmen: Producer of high-quality handling equipments of timber. www.renholmen.se)

- Organize support on ground (floor) or carriages due to sticker locations and be levered at same height
- As high temperatures as possible in drying process and conditioning phase will make timber more plastic with a better end result. (≈75-90°C depending on how resinous the timber is and what the allowable level of resin flow and discoloration for the specific customer is)
- Use pressure frames, this will reduce deformations to about half for 5-8 top layers of packages
- Include a controlled cooling period after drying/conditioning. This will reduce deformation, moisture gradient within timber cross section and, in wintertime, checking

A reduction of deformation is important to not reduce

- *End quality of the product*. The timber should not deform during further processing or after delivery to customer
- *Accuracy of in-line moisture determination by capacitance method*. Distance form sensing unit in in-line capacitance moisture meters to wood sample is affecting accuracy of moisture reading. Deformations of the timber will make distance between those to vary

### 5.1.4. Fissure

Rupture of the timber structure, such as checking is one main quality parameter which is easily identified. Ruptures are caused by the wood anisotropy as wood shrink differently in tangential, radial and longitudinal direction. Pine shrinks about nineteen times more in tangential direction than along the fibers (longitudinal direction) and twice as much in tangential direction compared to radial direction. This will make timber sawn from different locations of the log (planks, boards) to deform differently as directions of annual rings are changing within timber cross cut when the timber is shrinking as MC is decreasing, illustrated in *Figure 5.6*.


*Figure 5.6, Ratio of shrinkage is different and will deform sawn timber due to location in log.*

During drying, when surface is passing below FSP, the anisotropy will make some surfaces rupture more easily than others. As tensions are built up by the shrinkage and the wood is less durable in different directions, wood will rupture. Rupture can be of different character, such as end checks, micro shakes, surface checks etc. To reduce tendencies of rupture during the drying process, temperatures > 50ºC for pine is recommended. When core MC is still above FSP (28-30% MC) and surface of the timber pieces are below FSP and a climate with low temperature, where the wood material is non-plastic can produce severe shakes, splits and chakes.

Density is one parameter which has big influence if timber is going to rupture during drying. High-dense wood has a higher ability to rupture than low-dense wood, if "tough" drying schemes are used which produces steep gradients and tensions within the wood. Often schemes are designed for average density of the batch, creating a higher number of high-dens pieces to rupture as the scheme is not adapted to this kind of timber. One possible way to reduce this phenomenon is to place high-dense wood at strategic locations within the chamber kiln where climate is more "mild".

Fissures can also be generated in the end of the drying process as high temperature timber is taken from kiln out in cold outdoor climate. Here surface will dry uncontrolled and steam will be generated inside the wood cells making wood rupture as the steam is pressed toward the surface.

- **End shakes**

End shakes (in different forms) are mostly initialized by uncontrolled storage before drying process. As wood dries faster in the longitudinal direction this will in unfavorable situations make end of timber start shrink before other parts of the piece, with end shakes as result. One other factor for the problem can come from leakages caused by bad flaps in kilns forming high air velocity and making ends dry faster than other parts of timber.

- **Surface checking**

Main problem is an all too steep moisture gradient from dry surface toward wet core. Surface checking are formed early in the drying process. This also follows the situation where case hardening is developed. Wood anatomy with its rays located from pith perpendicular toward log surface in combination with ratio of shrinking properties in radial/tangential direction will make center of planks to easily check. Heartwood has low moisture content (30-40%) and is near FSP and sapwood is highly moist (130-150%). This make flat side perpendicular to pith with visible heartwood start shrink quite instantly in the drying process as the center parts of the flat side surface gets <FSP, illustrated in *Figure 5.7*.

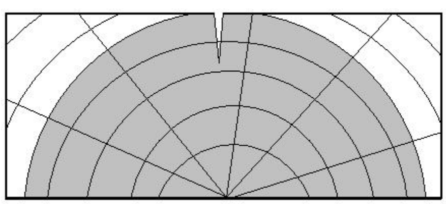


*Figure 5.7 Surface checking is mostly perpendicular toward pith for planks. Gray area illustrates heartwood, white sapwood.*

- **Micro shakes**

Micro shakes are defined as a few mm short openings, fissures on the flat surface which are not visible for the human eye, as they are not wider than 1mm. When a surface containing micro shakes are planed and surface is coated with stain, these will be visual as the color is contained into the shakes and then will be eye-catching.

Three main areas of what is causing micro shakes are

- Careless storage of timber before drying. This will produce all kinds of fissures, including micro shakes.

- Un-optimized conditioning drying phase. A theory is that extremely wet surfaces and steep moisture gradients will make surface be put at risk of having extreme compressed tensions, which make surface crinkle and wood cells collapse. As timber then is equalized, surface can not unfold the wood cells to original shape and micro shakes are formed.
- Unloading hot timber from kiln in unfavorable climate, as in wintertime. In winter time, if cold air meets hot wood surface this will make extreme surface drying to occur and fissures being initialized.

### *5.1.5. Maintenance*

Primarily, maintenance shall be performed as instructions from manufacturer and keep documentation of performed and planned maintenance!

This chapter recommends actions to an implementation of a maintenance program. Maintenance is a fundamental factor for having a quality product. Without maintenance and a planned way for maintenance, situations will arise when production has to be shut down for long times. Maintenance can be separated into

- *Repairing* maintenance
- *Preventing* maintenance

Preventing maintenance has to be planned in a structural way. In wood drying the hardware, or drying machinery, is of importance to be maintained as wear affected by the extreme climate inside of kilns is huge. Though materials of hardware are adapted to its use, parts inside of kilns have an unfavorable working climate. Exemplified wear as result of bad maintenance follows.

Preventing maintenance is advantageous to repairing, though a balance of these is of cause the reality due to economical matters. To achieve an acceptable level of maintenance is related to the accessibility of the kilns in the production. The level of maintenance shall be set according to acceptable kiln performance, drying quality and production disturbance.

Areas of maintenance are

a) Equipment related to drying production control
b) Drying machinery; “hardware”
c) (Software of drying control system)

**a) Equipment related to drying production control**
Followed are areas where maintenance of equipment which is related to controlling the drying process.

- **Climate control sensors**

Knowing sensors are delivering correct information is important. These are revealing actual situation of climate and are the base in a control system for the system to make corrections and adjustments. There are a few common types of sensors used to control climate today. The most popular sensors are controlling wet and dry temperature or relative humidity within the kiln.

Sensors have to be calibrated regularly. When psychometric temperature difference is used to control climate it is extremely important that this is correct. Wet bulb rags have to be changed in fixed intervals for proper performance. Also check proper water feeding to these senders.

Today there are adaptive control systems in use which are controlling drying process by controlling the drop of temperature across the packages in the length of the kiln. Key factor of this system is correct signal of temperature on the two sides of the batch. Obviously maintenance of these senders/sensors is of importance.

- **Air velocity and air flow direction**

Controlling air velocity regularly and fans are synchronized all together due to direction of flow is checkpoints to not overlook. These can be factors which are not recognized directly and can cause severe degrade of drying quality. Also reversing intervals has to be checked in compartment kilns to be 1-1.5 hours. This makes moisture variation within the batch to be reduced. Often when stoppages (measurements or other interruptions) are made manually within the kiln and production is restarted, an incorrect direction of air flow can be adapted as the system is not correctly programmed. This can lead to all too long time of air flow in one direction with deviating moisture variation, low average MC, checking of timber and drier timber in one side of the timber batch. Check with your manufacturer about this issue or control it.

- **Electrical resistance moisture meters**

See chapter "*calibration of electrical resistance moisture meters*"

**b) Drying machinery**

Followed are areas where maintenance of "hardware" is of importance.

- **Flaps and related parts**

Flaps have to be in a good condition, so these are tight to timber making air flow through timber packages instead of at the side of these, this to have as uniform air flow as possible. Rubber has to be flexible and has to be changed once in a while as these are degraded by the climate and torn down by timber as these are moved/ transported inside of kiln. Moving parts has to be in a shape so flaps are moving easily and correctly. Yearly intervals of maintenance is not good enough, these have to be switched regularly when flaps are damaged.

- **Fans and related parts**

Motors are often not suited for the working conditions. This makes it importance that greasing and inspection of these are made according to the manufacturer. Vibrations in these can be devastating, as length of life for motor bearings and related construction in the region of fans are decreased instantly leading to failures with interruptions in production as result.

- **Pressure frames and related parts**

Pressure frames shall be pressing uniform at timber packages. When pressure frames are used, these are often not well maintained. Cylinders which are controlling pressure frames are often controlled hydraulic or pneumatic. Bosses mounted in cylinders are often living a tough life and when these are broken leakages of air/oil into kiln compartment can come up. Also rubber flaps will be stiff during time, making controlling of the frames troublesome.

- **Floor**

Without cleaning floor the drain will be jammed, making it impossible to evacuate water which is condensed. Jammed drains will make energy (heat) needed to evaporate the water into moisture again to be able to evacuate it through the ventilation system.

Deformation problems on timber are often led to simple things such as supports on floor (if not carriages are used). During long term usage these supports are often bent, buckled and unorganized which leads to timber deformation when these not meet locations of stickers in packages.

- **Leakages of kiln compartment**

Doors and walls which are not sealed can influence climate inside the specific kiln but also the kilns “next door”. This can make climate difficult to control and a reduction of kiln performance. It is also a safety reason to not allow leakage, when humid air which is leaking out in wintertime will build up ice in areas around door and edges of roof. Accidents can happen when these fall to the ground.

- **Steam distribution**

Steam from boiler which is distributed irregularly is important to be minimized. As preliminary heating and conditioning phases in drying production are using steam more frequently nowadays, schedules are adapted to steam instead of other basing systems. Drying quality due to fissures, gradients, case hardening and mould are dependable of the performance of correct distribution of steam.

- **Heat distribution**

To dry wood, the climate has to be controlled precisely. By having good heat distribution climate can be controlled more rapidly. This makes it importance to maintain equipment which is controlling temperature, such as keeping heating cores clean, checking that valves and shunts are working properly. By cleaning heating cores intervallic and control shunt operate correctly the heat distribution and production will not be interrupted.

- **Basing equipment**

Basing equipment is a big source of error for drying quality! Water sprayers have to be checked for not being blocked, this is often caused by basing water quality. Also to check tubing inside kiln as fasteners often are broken, making tubes incorrectly fastened toward the walls or/and roof of the kiln structure. This can lead to tubes are split and all too big amount of water is distributed into kiln when sprayers are pointing in an incorrect direction.

- **In feeding equipment**

When kilns are automatically loaded/unloaded, related parts for this is of importance to be maintained. As doors are open during this occurrence, interruption of this can be devastating as climate is interrupted every time doors are opened.

- **Ventilation**

Ventilation shutters and evacuation fans/motors have to be working properly. Leakages, vibrations, correct positions of shutters etc. has to be checked. Heat exchanger within the ventilation system also has to be inspected for abnormalities. One phenomenon which can cause damage to ventilation shutters is when timber is loaded into a compartment kiln in wintertime. As extreme cold timber is placed in a chamber which has its floor, walls, and other equipment already warmed up from prior drying process and the port is shut, the warm air inside the kiln will decrease its volume as the temperature is reduced caused by the massive cold timber volume which is loaded. The lower air pressure (due to outdoor air pressure) which will be generated can cause damage to hardware inside the kiln severely! This phenomenon can be eliminated by having the ventilation slightly open as the port is closed and timber is warmed up.

## 5.2. Follow up kiln drying production

As the new standard EN 14298, *Sawn timber - Assessment of drying quality* has been implemented, it is of importance that control of drying production are made in a proper way to have a defined high class dried timber quality. The standard *EN14298* is *not* directly applicable on drying production, as the measuring strategy in the standard differs from the strategy used in drying production.

To have good *product quality* of the drying processes means that one are forced to advance in *production quality*. By control key factors in production which have influence on product quality, you need methods and strategies to come to the position where a stabile process control is established. There are many different strategies of how to control and develop a drying process. By collecting data which give accurate information of the production, this can be basis for future decision taking.

This chapter shall act as recommendation based on know-how from litterateur, investigations and interviews with highly qualified kiln operators and are describing one way of utilize measuring techniques in drying production. Due to different arrangements of timber in kilns, designs of kilns, performance of kilns, etc., etc. maybe this strategy can not be utilized in a specific production unit. Though, this chapter shall act as a guideline to how it can be performed and local variations will redesign the usage of the following suggestions to suit their production and purposes.

Discuss with kiln manufacturer where suitable positions are for making measurements within the kiln.

### 5.2.1. Where in a compartment kiln is the climate representative?

To make measurements of MC in kilns, planning is essential! In industrial wood drying, the importance is to select a number of representative samples from the process, which can be as reference of a whole batch. To reduce number of samples to a minimum and keep the low number of measurements representative for the whole batch a strategy adapted to specific kiln has to be defined and implemented.

Followed are a couple of strategies to measure MC in compartment kiln drying, illustrated in *Figure 5.8*.

a) One strategy to find representative pieces due to MC of batches is to collect samples from each row, in a diagonal from lowest package in the first row, to the top in the innermost package along the length of the pieces. This will show the most correct moisture variation within the batch. This will unfortunately produce all too high number of samples and be complicated in practice of everyday production.
b) The most easy and suitable position to collect samples from in compartment kilns is the second row (also second inmost row are suitable for this purposes), this because the most representative climate of the drying climate is in this position when a interval of revving of air flow is used in the drying process.

These two strategies will result in quite similar detection of average moisture content within the batch. But in the strategy with collecting samples diagonally in kiln (1.) will show a higher variation of the moisture content within the batch compared to measure on one position (2.). By focus on target moisture content, the average moisture content of the batch is of interest. By adapting an equalization phase for a certain time in the drying scheme and optimizing the uniformity of the drying climate within the kiln, the variation can be reduced to meet the requirements of the standard *EN14298* and *prEN 13307-1&2*.

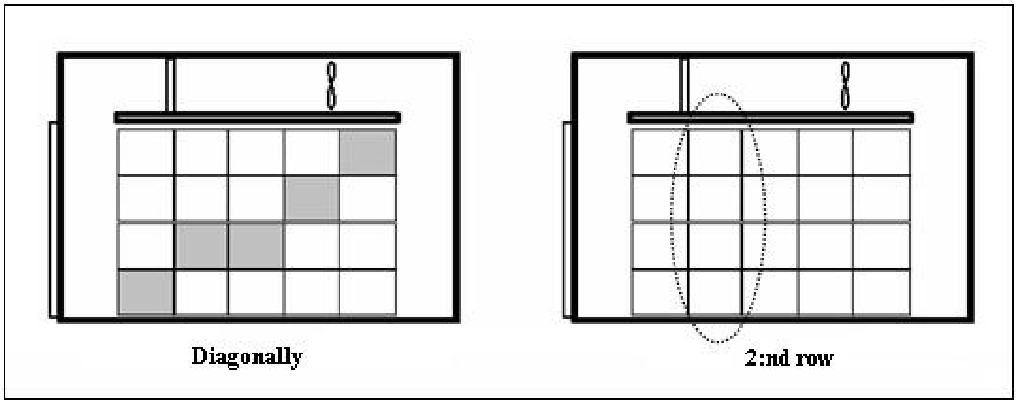



*Figure 5.8 Compartment kiln. Left: Most representative pieces due to moisture content of a batch; will produce all too high number of samples. Right: Second row is representative for the batch regarding average moisture content; fewer samples required.*

In progressive kilns this strategy is of cause not possible to use and in this case measurements will be done at a recently out fed package or use of climate or MC-resistance loggers which follows packages throughout the drying process from in feed side to out feed side.

### 5.2.2. Procedure of the ODM in kiln drying production

This method of estimating MC is the most reliable and the most powerful to use in follow up of drying quality regarding moisture level. As the method is slightly time consuming, this has to be well organized. By arrange equipment and area to analyze samples, this will lead to efficiency in production.

This procedure is describing the procedure in determination of the MC in a batch from a compartment kiln drying process. SP Trätek recommendation is at least 20 samples within a batch.

- Select package from second row, calculated from the port side of the compartment.
- Split top package in half and select a number of timber pieces (10 recommended). Do not select pieces located in outer layers of package, when these do not represent the majority of drying performance within the batch
- Cut samples, one sample from root and one sample from top of each selected piece*(20 recommended)*, illustrated in *Figure 5.9*
- Procedure of the standard *EN 13183-1:2002, Oven Dry Method (ODM)* described earlier in the QHB
- Document usable information, such as calculated MC for all samples, average and standard deviation of the *n* samples
- Document and archive information in drying report

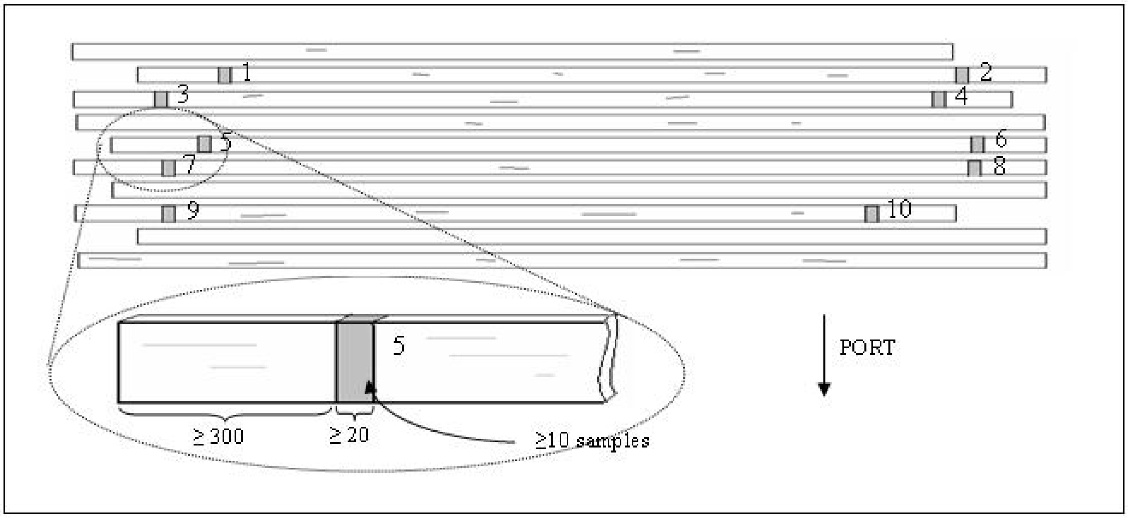



*Figure 5.9. Location of samples 1-10 for ODM. Second row, seen from above. 20 samples are recommended by SP Trätek.*

- **Accelerated ODM**

Same method is used as in standard ODM, except of temperature level. An investigation has shown that sufficient accuracy of ODM with raised temperature to 130ºC can be achieved.

- For non-resinous samples of pine with dimensions from 25x150 to 50x150 drying rate has been found to be ended in 15-25 minutes!
- For high resinous samples of pine with a dimension of 50x150, the drying rate was found to be greatly reduced after 30-50 minutes but a negligible amount of moisture evaporation continued after this point.

- Accelerated ODM shows an accuracy of ±0.5% in MC determination, which is slightly better than electrical resistance method. A recommended drying time of 1.5-2.5 hours are found for resinous/non-resinous wood samples with 15mm thickness (in grain direction). The method is concluded to be suitable for industrial use. Though, this method is not standardized and has many influencing factors which can reduce its reliability of results, compared to the standard method (102ºC).

### 5.2.3. Procedure of the Electrical Resistance Method in kiln drying production

In daily kiln drying production the most common method is to use he resistance method to determine MC of a batch. Herby some recommendations can be implied, to reduce different factors which can lead to misjudgments.

The electrical resistance meter measure MC due to resistance within the wood. The resistance is depending on how water is distributed within the wood. Free water is distributed within the wood cells above fiber saturation point (FSP) ≈30% MC. Problems above this moisture level will create situation where resistance between electrodes are measured of water, not moist wood. Higher resistance will decrease reading of moisture reading. Type of brand will also result in different moisture readings. Resistance in wood (<FSP) follow

- High resistance => Low MC reading and vice versa
- High wood temperature => Increased MC reading and vice versa

- **Location of samples within the kiln**

As it in daily production is just possible to make a few measurements due to a time consuming method and other practical factors, it is of importance that these are made at positions which are representative for the batch. The discussion in chapter "*where in a compartment kiln is the climate representative*", about correct location within the kiln can be implemented in measuring with electrical resistance meter.

To have comparable results from ODM and electrical resistance meter, measurements should be performed on the same location of package within the kiln as other measuring techniques. This will make it possible to evaluate different types of measuring techniques of the batch (e.g. oven dry to resistance method) to each other. If this is not possible, one should know that disturbances caused by mechanical reasons during the drying (e.g. steam loss), may not be detectable if measurements with electrical resistance meter are performed in the outer layers of the first package of batch. Though, readings of the outmost package will show a trend of drying quality. Recommended positions on packages in second row are illustrated in *Figure 5.10.*

- **Example of procedure**

To measure average MC for a whole batch, at least 20 measurements are recommended to be acceptable statistically and practically. Measurements shall be spread from top end, middle toward root end of boards, and in the height of the packages, illustrated in *Figure* 5.10. All too gathered measurements in the middle of one package will result in slightly too high reading of the average MC and also reduce the range of moisture variation, showing too good drying result within the batch.

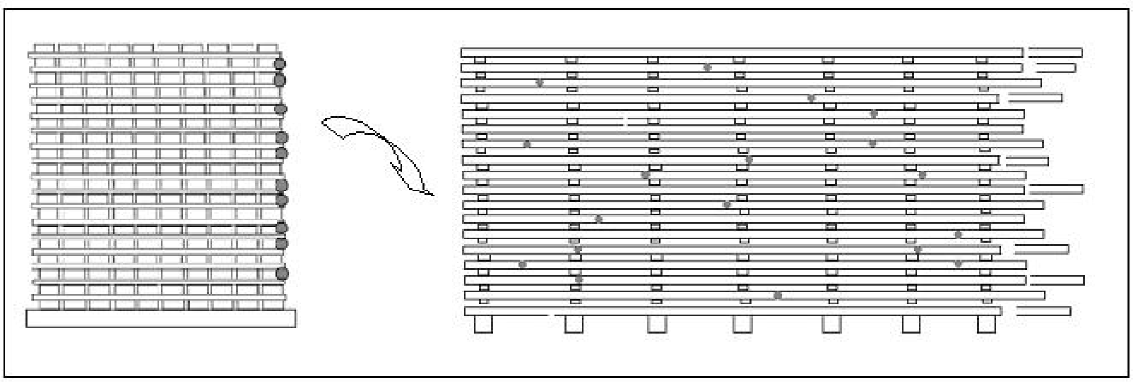


*Figure 5.10, 20 samples (marked in figure) for every batch, equally divided top/middle/root of the package. Spread measurements will reflect average MC of batch. Middle of package has highest moisture content lengthwise the timber.*

The standard EN 13183-2:2002, electrical resistance method, recommends that measurements should be made from the flat side of the piece. In practice this will create problems due to timber piling, because it is just possible to reach the edges of the pieces when these are stacked. The best location to measure average MC within one sample, is to place the points of the insulated electrodes 0.3*thickness and 0.3*width of the piece, illustrated in *Figure 5.11*

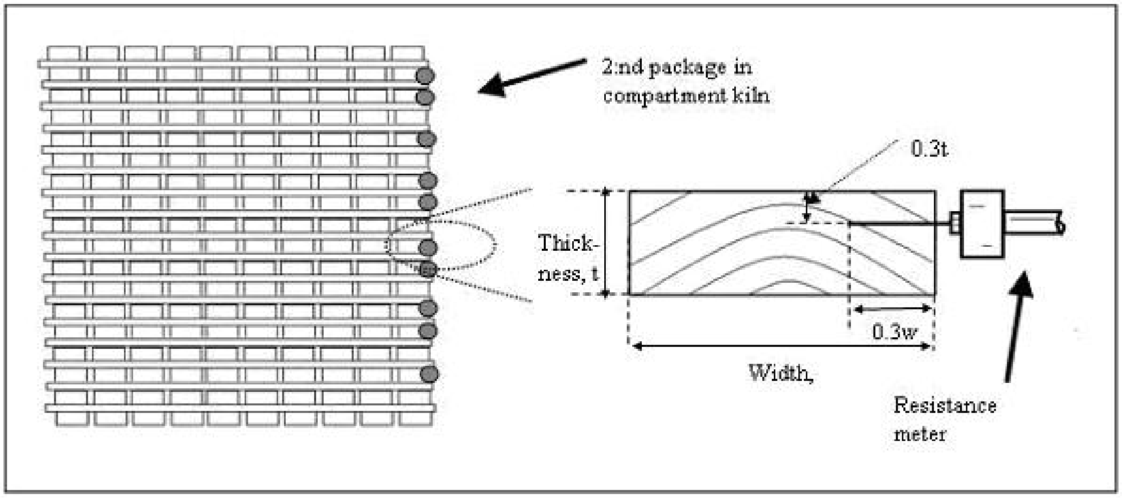



*Figure 5.11, 20 samples for every batch, with the location of the electrodes as figure are recommended. This is the best location of peaks to determine average MC within a cross section of a piece.*

- **Presentation of electrical resistance meter reading**

1. The result of the test can be referred to standard *EN 14298, Sawn timber - Assessment of drying quality* which is a document composed to act as define drying quality between seller/customer.
2. The result of the test can be referred to internal established limits for the particular timber quality. For statistical presentation of the result, check chapter "*t-distribution of collected data*".

### *5.2.4. Calibration of electrical resistance moisture meters*

Primary, calibration should be made according to instructions from manufacturer of the moisture meter. As resistance in wood changes due to different factors, it is of importance that the moisture meter is calibrated and used properly to the specific conditions.

- **Time intervals for calibration**

Calibration should at least be made twice a year or according to manufacturer or when there are hesitations of the performance of the moisture meter. A check toward calibration block can be made rapidly and reveal errors in software settings.

- **Software and certified calibration block**

The software of the moisture meter has to be adapted to what specie which is going to be measured. Every other brand of moisture meters have their individual pre designed resistance curve developed for specific type of wood specie. It is shown in investigations that many pre designed software from manufacturers of moisture meters are more or less unrelated toward Nordic pine and spruce. Therefore each SET manufacturer has to calibrate their moisture meters due to same conditions! Pre designed software has to be controlled toward the specific wood specie, in the Finnish and Swedish production by using certified calibration block for northern pine which has an accurate range from 8.9%-26.3% MC (in Sweden contact SP Trätek). In Nordic countries a developed calibration block is based on a large representative number of pine timber. IMPCOPCO investigation shows that Finnish and Swedish pine is quite equal in resistance properties which make it possible to use same type of calibration block. Corrections of software are made from this and logged in calibration documents for each resistance meter. Illustration of block is presented in *Figure 5.12*.

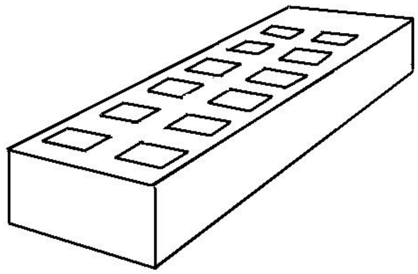


*Figure 5.12 Use a certified calibration block for pine to achieve better moisture meter performance. Figure illustrate calibration block with six moisture levels forming a correction curve for pine developed by Trätek.*

If readings differs more than 0.3% between moisture meter and noted MC level on the block when calibration is performed, adjustments of the software has to be made. Recommended is to not use pine wood in calibration, this because using wood will need all too many wood samples when calibrating! To find one specific wood sample which is representative for the whole timber in production is more or less impossible.

- **Temperature important when calibrating**

As moisture meters are dependable on conditions of the temperature, it is of importance that these are calibrated correctly. Air temperature has to be 20ºC when calibration is carried out. Place the resistance meter and calibration block in 20ºC room climate for some time before calibration is performed.

- **Temperature of wood important when measurement is performed**

Temperature calibration when measuring is performed has to be according to core temperature. Surface temperature in not good enough as the outmost points of the electrodes can be within an area where the local temperature differs from surface!

Recommendations from IMPCOPCO is to use the electrical resistance technique at moisture levels 8-20%, where temperature are taken into consideration. There are implemented recommendations for temperature corrections; a rule of thumb for MCs 8-20% when moisture meter calibration is fixed to 20ºC

⇒ Every 10ºC increase from 20ºC, decrease (subtract) moisture reading by 1%
⇒ Every 6ºC decrease from 20ºC, increase (add) moisture reading by 1%

Recommended temperature intervals where accuracy is acceptable are presented in *Table 6*.

| Temp (ºC) | Rec. interval (%MC) |
|---|---|
| -10 | 10-28 |
| 0 | 9-27 |
| +20 | 7-25 |
| +30 | 5,5-25 |

*Table 6 Recommended intervals where resistance method is acceptable, due to outdoor wood temperature (SP Trätek).*

- **Temperature of air**

Be careful to expose the moisture meter to extreme temperatures. Every moisture meter is functioning best at normal outdoor temperatures. Check with manufacturer what temperature interval the moisture meter can work in.

- **The influence of moisture gradient**

There will more or less be a *moisture gradient* in the cross section of the wood directly after drying process, and mistakes in the measurement procedure can lead to misjudgments of the MC. *Temperature* gradient is also a factor of error. Resistance is dependable of local moisture and temperature level and therefore it is of importance that measurements are made properly.

The moisture gradient makes the surface and core more dry and moist, respectively, compared with average MC in the cross section. Therefore it's of importance that electrodes measure the MC in the cross section where this is representative, illustrated in *Figure 4.3* and *Figure 5.11*. Moisture meter with electrodes which are insulated except of the outmost point of the electrodes are recommended. The use of such electrodes will not affect misjudgments of moisture level caused by disturbance of moist surface or moisture gradient within the sample. It can be useful to use insulated electrodes which are suited for the dimension and specie, to come around this source of error. Length of electrodes shall be according to timber dimension. Also is surface of the wood pieces extremely moist after a conditioning phase in the end of the drying process, making moisture gradient to distribute differently according to conditioning technique, illustrated in *Figure 5.4*.

- **The influence of temperature gradient**

There can also be a *temperature gradient*. The temperature of the surface is some cases not same as the core. The temperature calibration shall suit the temperature where the points of the electrodes are located within the wood piece. Just to measure surface temperature of the wood can in some cases not be good enough when e.g. storage temperature differ from core temperature. The other way around is that wood which has been outside for several days in wintertime will have a much colder core than surface even if the piece have been indoors for several hours.

- **Other comments of resistance moisture meter reading**

The standard EN 13183-2 does not state which *flat side is* meant. IMPCOPCO have investigated differences between moisture readings made in heartwood or sapwood. Heartwood showed slightly lower resistance than sapwood which shows moisture reading of heartwood to be moister (follows correlation of resistance and MC). MC <15% showed a difference of 0.5% when conditioned wood samples where measured. Sapwood dries faster than heartwood and is often more dry. After equalizing in storage, the cross section of the pieces should be quite uniform in moisture distribution. Illustrations from websites of wood related institutions shows that measurement with resistance meter should be made from sapwood side. In joinery production measurements should be made suitable for the production which side can be of importance in the specific situation (how pieces are going to be assembled), illustrated in *Figure 5.13*.


*Figure 5.13. Point indicates location of the outmost points of the electrodes in cross section of piece. Figure left/right respectively: Measurement made from sapwood/heartwood side. About 0.5% difference in reading of MC can occur.*

In batch production where pieces are randomly located sapwood side up/down, a high number of measurements have to be performed to be able to reduce the sapwood/heartwood correlated error of the measurements. Recommendation is to make at least 20 measurements (often made from edge) to have a stable result where measurements (points of electrodes) are located randomly in sapwood/heartwood.

Further, beware of free water or moisture on electrodes before the measuring is performed! Use a rag to clean electrodes and fasteners for electrodes. Investigations made by IMPCOPCO have proved that distance between electrodes is not influence moisture reading. Recommended is to use original electrodes of the moisture meter.

### *5.2.5. Procedure of the "Case hardening test" in kiln drying production*

Two piece slicing test is acting as quality check of case hardening (tensions within the wood). The procedure is according to *ENV 14464, Sawn timber- Method for assessment of case hardening.* This test is also act as quality test of moisture gradient (difference in MC from core to surface) as other methods are time consuming, e.g. five piece slicing test backed up with ODM.

As these measurements are carried through, it can be practical to make the slicing test parallel to the ODM, even if this will require a slightly more work, illustrated in *Figure 5.14*. The test samples for those two tests are then cut next to each other when these are collected from the batch. Collecting samples and make these two tests parallel will not be that time consuming, if apparatus are arranged and standardized routines for the working methods are defined.

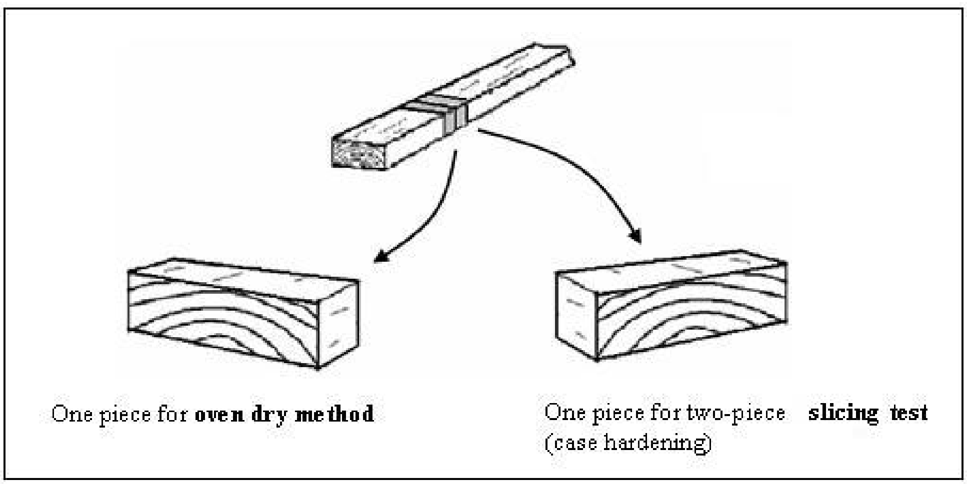



*Figure 5.14. Slicing test and ODM can be made parallel.*

As this QHB aim toward Joinery Kiln Drying, a rule of thumb is to produce a product which not exceed 1mm slice gap. Will a greater gap be generated, this can be of problem in the further processing production. This test is describing how tensions are built up within the wood and it is of importance to develop schedules according to the results from this test.

- **Presentation of slicing test quality**
  - The result of the slicing test can be referred to standard *EN 14298, Sawn timber - Assessment of drying quality* which is a document composed to act as define drying quality between seller/customer.
  - The result of the test can be referred to internal established limits. For statistical presentation of the result, check chapter "*t-distribution of collected data*".
  - Documentation are made in the drying report of the specific batch

### 5.2.6. Quality control due to checks

Measuring checks on timber can reveal how drying process has been adapted to suit the timber. All too powerful drying with great moisture gradients in the capillary regime of the drying process will make shrinkage in the outer layers which has MC <FSP produce tensile tension which is more than timber can hold and visible checks will be created. Procedure of controlling checks can be made as followed.

- Collect a number of samples from batch located in different locations in kiln. To have 20 samples are statistically and practically recommended.
- All sides shall be measured on samples
- Checks which are located within 30cm from ends are not included in measurements IF the check starts from the end of piece. Otherwise if they are starting within 30cm and not from end of piece, they are included.
- Parallel, overlapping checks are measured lengthwise sample as one check, illustrated in *Figure 5.15*

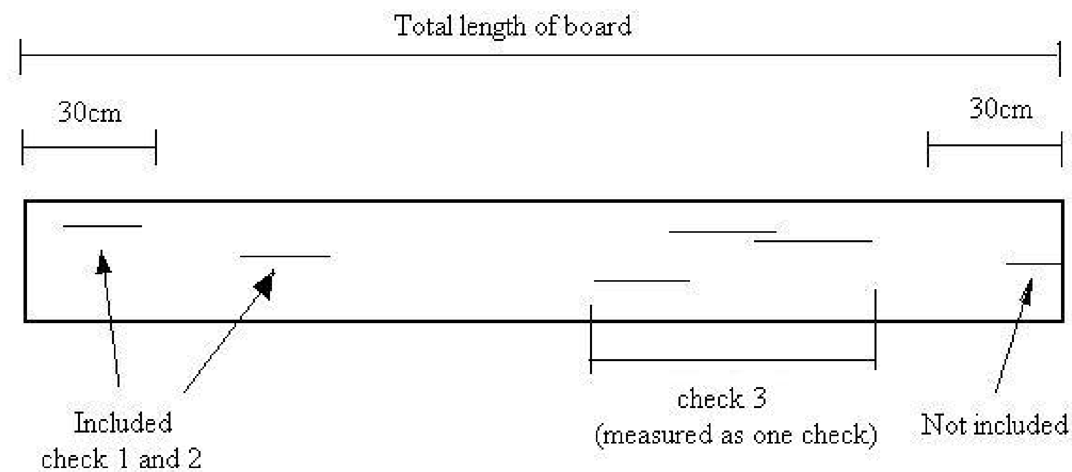



*Figure 5.15 Measure checks on sample.*

- Micro shakes are 1mm wide and short. Presence of micro shakes and side of timber (heartwood/sapwood) are noted in drying report
- The ratio of checks are calculated

$$\text{Checks \%} = \frac{\text{Total length of checks along the board (in figure represented by check no. 1, 2 and 3)}}{\text{Total length of the board}}$$

- Presentation of the result is documented in drying report by calculating average ratio and standard deviation of total amount of checks of the samples.

- **Comment**

The location of samples in packages close to door (and innermost package if reversing air flow are used) in a compartment kiln will have the most powerful drying. Herby is this location where most severe checking probably will occur.

What an acceptable level of checking is shall be defined due to timber quality (2 ex log, 4 ex log, dimension etc.). Generally in industry 2-3% checking is acceptable but a comment from SP Trätek is that checking can be almost eliminated by using updated drying technique of today.

### 5.2.7. Measuring MC gradient of timber cross section

The best way, traditionally, of measuring moisture gradient is to make a 5- or 10-slicing test (depending on timber dimension) combined with ODM. Samples should represent average wood quality. This will reveal the developed gradient with precision, illustrated in *Figure 5.16*.

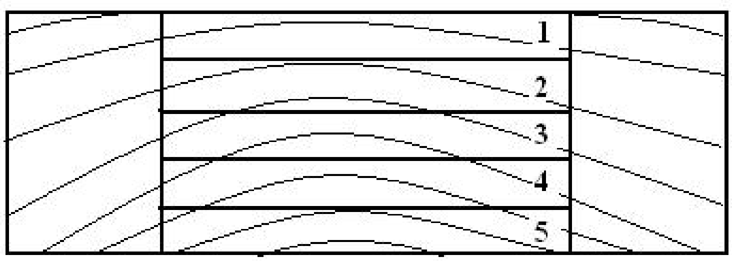



*Figure 5.16 Measuring gradient can be performed by making, as illustrated, 5-sample test and detect MC in each slice by using ODM.*

To measure moisture gradient with a resistance meter will set demands on the equipment, making it necessary to have temperature correction automatically or correction lists due to temperature when moisture meters have a fixed temperature setting. The information you get from measuring a gradient using electrical resistance moisture meter is if there is a difference in moisture between the core and surface or not. Electrical resistance moisture meters have an accuracy of ±1% MC of one specific measurement and hereby this technique is not suitable to reveal a numerical value of a gradient. The information from measuring a gradient using electrical resistance moisture meter is best used to be base for decision taking, if timber is going to be equalized further or not. Contact moisture meter manufacturer or retailer to get information due to performance of the equipment.

There are other technology developed for laboratory use to determine moisture gradient, e.g. NMR is one way. But nowadays industrially an acceptable gradient and deviation between each slice in the five piece slicing test should be according to result in two piece slicing test, standard *EN 14464*.

### 5.2.8. Follow up by using simulation software and reference pieces

Beyond traditional measurements mentioned in previous chapter, follow up can be made by using other techniques. Traditionally by analyzing and evaluate reference pieces within the drying process, these together with drying trends and other manually measurements has been the way of develop drying performance. These methods are not to neglect but nowadays as research and knowledge in wood drying has increased, simulation software has been developed and adapted for kiln drying personnel to use practically. A new "*quality tool"* has been introduced in wood drying!

- **Simulation of drying process by using computer software**

Use of simulation computer software has been in many cases been successful. Several different simulation software which handles wood drying is on the market today. The performance of the software varies as the algorithms are calculated differently. Some software is calculating geometrically in one direction, some in two directions and there are today even those which are calculating three dimensionally. The software of today is more or less advanced but as they are further developed and introduced industrially, these are being more user-friendly. The correctness between the different software on the market differs though

The software TORKSIM is one of many today at the market which can be used for analyzing drying performance and developing drying schedules. By identify parameters to feed into the software, a simulation of these can retrieve critical positions and actions of the drying strategy. Such parameters are

- Wood specie
- Nominal dimension (green) of timber
- Green moisture content (before drying process, detected by ODM)
- Final moisture content
- Initial timber temperature
- Heartwood/sapwood ratio
- Instant air velocity during drying process
- Drying time and design of scheme in a specific case

Three main areas where simulation software together with other information of timber properties and other measurement techniques can be utilized are

a) *Drying process is generating fissures*. Here, by noting drying parameters and feeding these into the software, the development of stress within the timber can be analyzed, making it possible to make adjustments of the drying schedules. This situation has been noticed, being an area where this tool have contributed positively
b) *Reduction of drying time*. By adapting drying schemes which not generates tensions within the wood, can be checked theoretically with the software making it possible to make corrections of the scheme to increase drying power when possible
c) *To control and develop already stable and capable schemes*. By constantly analyzing process adjustments which are made, performance of schedules can be increased

- **Reference pieces in the kiln, within the timber batch**

By using a number of reference pieces during the drying process it is possible to follow how it is proceeding. By using cut pieces with a specific dimension which represent average timber quality, it is possible to calculate e.g. timber density. By sealing ends at the pieces drying will be performed as the actual timber within the batch. Different locations within a kiln will slightly differ in between, therefore these reference pieces has to be strategically locate within the kiln. Location should be so operators continuously during the drying process can go inside kiln and weigh samples. By making measurements at certain intervals one can follow how drying is developed, e.g. how moisture content are dropping and how checking are generated etc.

## 5.3. Establish plan to determine drying quality

It is expressed that making incorrect measurements within process will create a situation where decisions are taken based on false premises or false information. It is much worse to base decisions on incorrect information, than make decisions based on chance. Correct information is a cornerstone for quality development; *base decisions on facts*.

### *5.3.1. Monitoring and follow up of drying production*

Drying wood has to be followed up by collecting information from processes which will be the base in decision taking processes. A strategy shall be adapted to suit the production, product and personnel to eliminate factors which can lead to that error are created in the collection of information and data from the drying process.

Standards which cover methods and regulations in how to control and collect information of drying processes are implemented. The standards are implemented to give correct and easy analyzed feedback of the drying process to kiln operators. The feedback can also be data for communication with customers. Information and data which is going to be utilized and evaluated has to be collected and measured in a uniform way to be valid and useful.

### *5.3.2. Establish limits for each quality parameter*

By define an interval and limits of each quality parameter and adapt these to suitable measuring technique, it is possible to correct level of drying quality. Limits have to be conferred by drying- and joinery personnel/managers to fit the specific situation and product.

Acceptable limits for the certain process has to be defined to determine in which situation the process is in. Due to kiln drying of joinery raw material, the joinery production uses several different types of timber qualities. The demands and limits which are set for each quality parameter has to be according to the accuracy of known measurement technique.

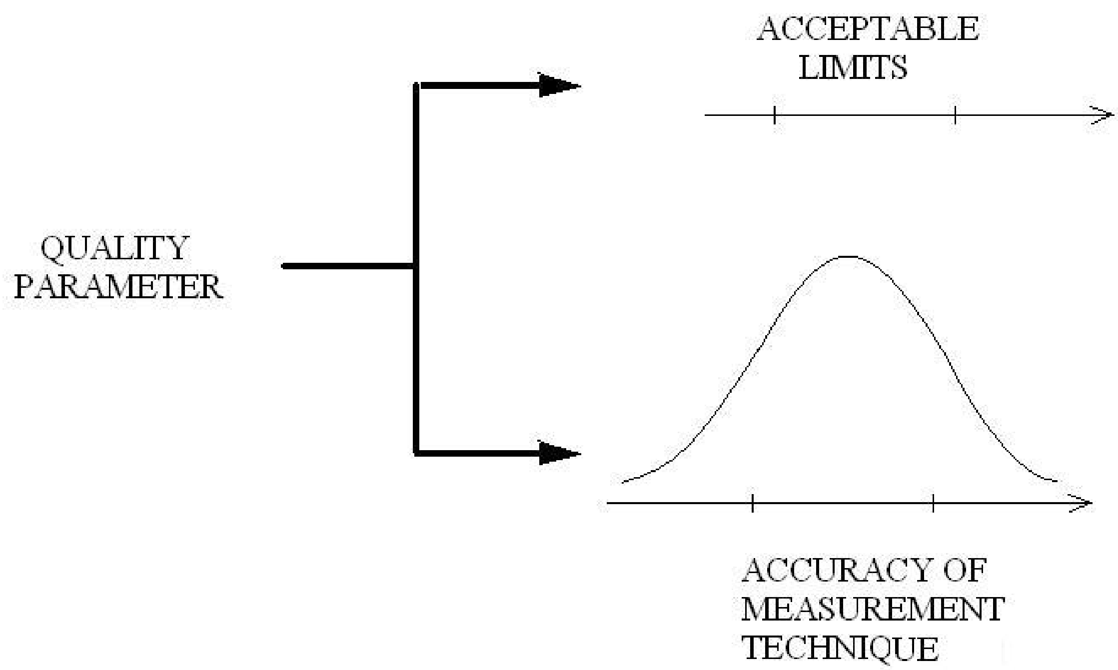



*Figure 5.17 For each quality parameter, acceptable limits should be according to the accuracy of the measurement technique.*

Limits shall follow the requirements which the joinery production line (the customer demands) has set. Acceptable limits for drying quality factors and routines for controlling them have to be implemented by each SET joinery producer, for each type of product. Acceptable limits for following quality parameters have to be set.

| Quality parameter | According to |
|---|---|
| 1. Acceptable range of average MC from desired target MC of batch<br>2. Acceptable moisture variation within a batch<br>3. Acceptable case hardening<br>4. Acceptable gradient | a. Timber properties<br>▪ Dimension<br>▪ Specie<br>▪ Density<br>b. Measurement technique<br>c. Size on population within the batch; |

| | |
|---|---|
| 5. Acceptable amount of checking<br>6. Acceptable deformation<br>7. Other factors regarding kilning quality | acceptable statistical accuracy<br>d. Measure samples or total population within the batch?<br>e. Acceptable number of rejects<br>f. Performance of drying technique |

- **Comment to establish limits based on recommendations**

The standard *prEN 13307-1&2 Timber blanks and semi-finished profiles for non-structural uses* sets desired requirement for timber for window production. The recommendation is that all timber should be within 10-14% MC limits. This is of cause not possible, therefore is a recommendation EDG implemented to meet the requirements and the drying production. The recommendation is that

- $MC_{average}$ should be within 12 %± 1.2S. This means that standard deviation S can span S=1.2 from [$MC_{average}$] → Statistically this means that 95% of timber should be within [$MC_{average}$] ±1.2*1.96= [$MC_{average}$] ± 2.4% → Hereby acceptable limits for 95% of the timber will be 9.6-14.4%
- 95% of timber should have case hardening gap <1mm

## 5.4. Documentation of measurements

Identification and handling of documents shall be made according to SET standards. Documentation in drying production is needed to be able to statistically follow up kiln drying performance.

- **Manually in paper form**

By manually record measurements in pre-designed forms from each dried batch will make it easier to transfer information within the organization

- Attached manually to *drying report* out of the ordinary information from the drying report included by manufacturer of the drying control system are
  - Package identities (for follow up by using information from intake in joinery production)
  - Measurements from electrical resistance moisture meter; average MC std. dev.
  - All single measurements from ODM
  - All single measurements from cleavage test
  - Result from measured amount of checks

This makes it possible to further analyze the drying performance, instead of just interpret trends from the actual drying process.

- **MS Excel**

The information which is documented manually in drying report can be transferred into computer software, such as Excel. This will make it possible to handle the data in an easy way, making it possible to analyze information from the production by using statistics like SPC.

From in line capacitive moisture meters, the collected data can easily be transferred into Excel automatically. (A vision is that) This can be utilized for every batch or even on package level, to use data to transfer feedback to kiln operators of e.g. mean MC of a package.

An example of handling and use data is *Appendix 2*- Control chart, where Excel is used to follow up a specific product from measurements made in kiln drying production, over a period of time.

- **Intranet**

Almost every sawmill has an intranet today. To use Intranet information is transferred within in the company easily. Utilize the intranet to supply information, both ways, between kiln drying production and joinery production e.g. by using databases.

From joinery production information of average MC on package level is useful. By knowing average MC on every package from in-line capacitance moisture meter, information from these packages can be combined by kiln drying personnel to adapt to where the packages where positioned in drying process (kiln number, what other packages was included in the drying process etc.).

## 5.5. New technology in wood drying production

Today there are other techniques developed to determining moisture levels during drying than the traditional measuring techniques. Though, various new techniques have not industrially been successively implemented yet, beside moisture loggers used during drying and adaptive control systems. Traditionally methods like ODM, electrical resistance moisture meters and cleavage tests have been those tools which the industry has, and is using.

Investigation made by IMPCOPCO has made researches on drying control equipments. Developed in-kiln moisture control can achieve satisfying accuracy of moisture determination <20% MC by using electrical resistance method from a number of positions within the kiln during drying process, combined with wireless signal transmission (on-line) from these to the control system. Other equipments such as nuclear- and dielectric moisture meters, control systems working with principles such as weighing, shrinking, drying modeling (based on parameters of kiln performance and timber properties) and temperature drop of the load principle (TDL) are nowadays investigated and developed. Although, the investigation has found that best accuracy is achieved by using traditional resistance meter, weighing of reference pieces within the batch and ODM to determine actual MC.

### *5.5.1. Adaptive control system*

Adaptive control systems are today at the market and used industrially. Primarily the main purpose of using this control system is for reducing drying time. Investigations made by *manufacturers* have found that these control systems are used with satisfying results.

Adaptive control systems are using factors which describe the present situation of the wood drying process. Traditional wood drying schedules are developed by the skills and experiences of drying operators, who have developed schedules suitable for specific occasion. By utilize traditional measuring techniques, such as ODM, electrical resistance method, reference pieces, simulation software etc. to collect information and make adjustments according to these, traditional drying schedules are developed. Adaptive control systems are measuring the status of kiln process at a certain time by different parameters, like temperature drop across the load (TDL), controlling efficiency of the power input of the kiln or other parameters. Traditional schedules do not take into account variations which can occur due to green timber quality, season and so on, which the developed adaptive control systems are intended to do.

The advantage which adaptive controlling of the drying process is offering, is that finding the point where drying turns from capillary to diffusion regime. This allows the drying process to speed up, letting the drying phase get more powerful when the system gets information that FSP is reached. This will reduce drying time. Further, if traditional control of drying goes into diffusion stage to early (FSP is not reached) this will have impact on drying quality. In such situations adaptive controlling can lengthen the capillary phase of the drying process.

As a problem with traditional wood drying, to know green timber MC, amount of heartwood/sapwood in timber etc, of every batch the adaptive controlling is one step forward to increase drying quality as this system is developed to handle such variations.

# 6. A storage strategy after the drying process is important

Wood is dependable on surrounding air conditions because wood is a hygroscopic material. Equilibrium moisture content (EMC) is the MC which the timber will accommodate to when it is balance between the wood and surrounding air. There is always a certain amount of moisture within the air which is influencing the wood characteristics. As product quality will decrease of careless handling, it of is important that storages suits the material behavior. Outdoor temperature, wood temperature, moisture gradient after drying, relative humidity, sunlight and time are factors which have an impact on moisture distribution within the batch and within individual wood pieces, especially when packages are stickered.

A closed storage with climate control of RH combined with in-kiln equalized moisture gradient of the timber is recommended. Timber shall not be exposed to ground moisture; therefore timber should be placed some decimeter above ground (asphalt?) due to this. Following part of the chapter shall try to describe why.

## 6.1. Moisture in air and EMC

Dry air can be mixed with moisture and the amount of moisture in a certain volume is abbreviated υ and has unit [kg/m$^3$]. Maximum amount of moisture which can be contained within air are dependable on air temperature and air pressure. The dew point is when the maximum amount of moisture which can be contained within the air. At this point is RH 100%. If this point is exceeded and more water than can be held by the air at 100% RH is tried to be added to the air, fog will be developed as the air can not hold more than a specific amount of water. This depends on the temperature and pressure of the air. The relation is that warm air can contain more moisture (water) within a specific volume than colder air.

Relative humidity is an expression of the ratio between actual vapor pressure and saturated vapor pressure for the specific temperature. RH is calculated

$$RH\% = \frac{v}{v_{dewp.}}$$

Dew point as function of air temperature is illustrated in *Figure 6.1*.

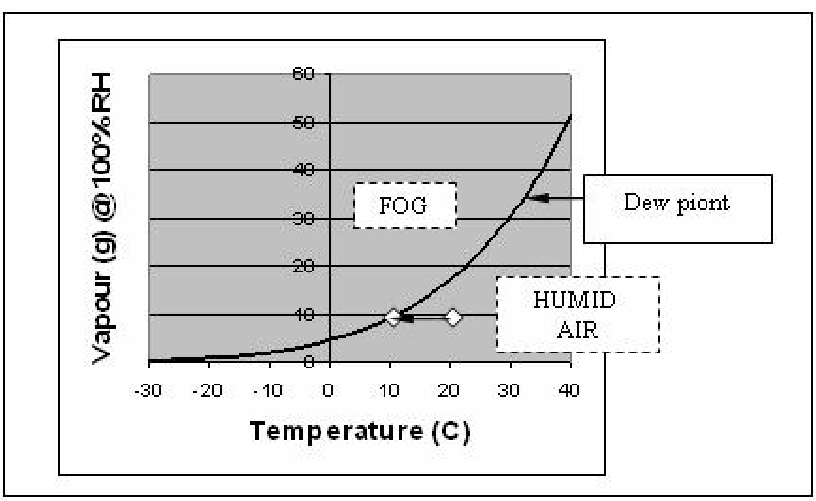



*Figure 6.1 As temperature vary and the amount of water in the air is held constant, relative humidity will change. For example air conditions in the figure is +20ºC and RH at 66%*

*(EMC=12%) will as temperature drop to +11ºC become fully saturated; the dew point is reached and the EMC of wood will increase.*

## 6.2. Storage can affect drying quality

The requirements which are needed to be fulfilled to produce high quality joinery products are found in the standard *prEN 13307 Basic requirements for finger jointed products.* The drying process is one process where quality has to be high but there is also an importance of using correct designed and correct climate in storages, after the drying is finished. The storage strategy will not then jeopardize the quality which is the result of the drying process.

The storage is of cause a buffer of material at the factory but storage of timber is also important in other purposes. Storage of timber after the drying process is in a quality point of view preliminary for letting the timber temperature to decrease to meet required temperature for the adhesive in joinery production. An important factor which is constantly changing is that it in closed storages the relative humidity of the air is season dependable. A constant climate is recommended to not jeopardize drying quality of timber, if storage is made for longer periods. A demand of the storage is that it is well arranged, maintained and the climate being controlled to be able to increase/decrease RH of the storage climate.

To have high quality timber for joinery production it is desirable to have timber with as low moisture gradient as possible within the cross section of wood (equalized). In winter time, when huge differences between outdoor and wood temperature exist as timber is unloaded from kilns, uncontrolled drying can occur as timber is taken out and as a result from this, steep MC gradients being developed and never be equalized until timber is taken indoors and further processed. Therefore a controlled cooling of the dried timber is recommended before timber is transported to storage. Especially in wintertime the ability to equalize a moisture gradient in a cold outdoor storage is reduced significantly, as timber temperature will decrease the MC equalization process.

### *6.2.1. Relative humidity is season dependable*

Climate is changing due to time of year and this will have influence on EMC of the timber. RH is influencing EMC in wood. The relation of RH and EMC can be found in Appendix 4. This has to be taken into consideration in storage strategy of the timber as increasing/decreasing of RH of the storage climate may be necessary, illustrated in *Figure 6.2*.

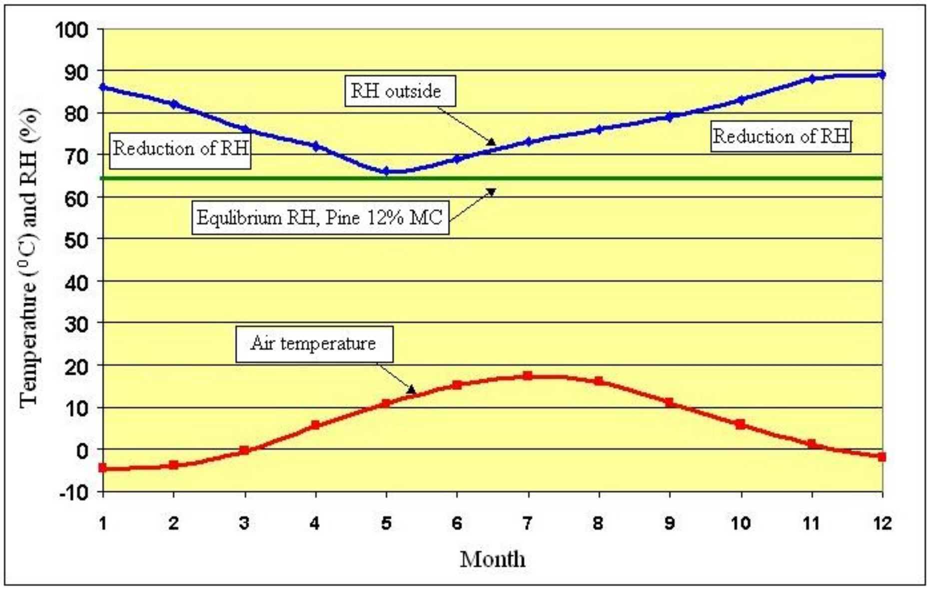



*Figure 6.2 Relative humidity and temperature are changing due to season.*

Variations within a day when there are differences between day/night temperatures do not have that big influence on moisture variations within the wood. If the timber is of thin dimensions the time to reach EMC will be shorter than for thicker dimensions which will need a considerably longer time period. The ability for wood to add/reduce MC caused of surrounding air condition is depending on many material parameters. Depending on time of year, timber properties and number of days in storage the recommendation is to control the climate to meet the required EMC at 12%. The EMC a piece of wood will adapt to for a RH at 65% and a certain temperature is illustrated in *Figure 6.3* .

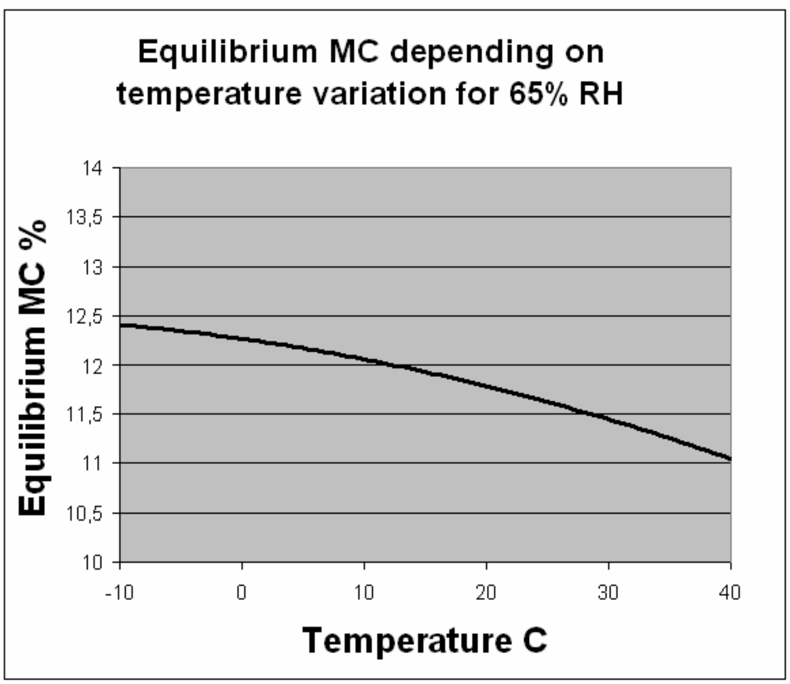



*Figure 6.3 EMC will vary in some small degree, if temperature varies and RH is kept constant at 65% (interpolated from table, Appendix 4).*

Proper equipment for climate control is well known, though, controlling of climate with a hand held psycrometer shall be made continuously and in different areas of storage (far away from ventilation or near ports).

## 6.3. Storage time for dried timber

A season dependable strategy of climate controlled storage has to be implemented to reduce storage time and increase timber quality. Storage time is also of an economical matter, when all too large loads for timber in storages will be expensive for the company.

Wood adapt to EMC influenced by different parameters. A strategy which handles product related factors due to season dependable factors has to follow

Timber properties → Storage climate→ Required timber quality for joinery production→ Acceptable storage time

- **Timber quality**
  - Dimension and density
  - Conditioned/unconditioned
  - Distribution of gradient related to dimension
  - Timber temperature when in feed to storage (caused by temperature of the kiln climate)

- **Storage climate**
  - Season
    - RH
    - Temperature
  - Open/closed storage (sun and wind)
  - Arrangement and design of the storage

- **Required timber quality for joinery production**
  - Acceptable timber temperature shall meet requirements of the adhesive in joinery production
  - Acceptable moisture gradient for joinery production; time for equalization (preliminary in summertime)

- **Acceptable storage time**
  - Minimum/maximum acceptable storage time (of an economical matter)
  - Package flow within the storage. The elapsed time for each timber package to be stored shall be as equal as possible
  - To meet "Required timber quality for joinery production" presented above

Storage shall not be seen as and used as an equalization process. High temperature of the timber is increasing the rate of moisture diffusion in the wood therefore can storage time be reduced in summertime. Timber which is conditioned in kiln will have a surface MC above target MC. The surface MC of conditioned timber is often higher than the EMC of the storage climate and for unconditioned timber below EMC. However, moisture gradient of conditioned timber is often steeper compared to timber which is unconditioned. This means that recommended storage strategy requires that timber is equalized as far as possible in the kiln drying process before timber is taken into storage, as the equalization process will decrease as temperature drops.

Ala sawmill has a strategy that timber is stored *at least five days* within a closed climate controlled storage. This is implemented to reduce timber temperature to an acceptable level and try to reduce MC gradient as far as possible without having all too large volumes of timber within the storage. At Ala, the climate can be controlled by reducing RH. Increase of RH by having water sprayers is not used at the moment. A recommendation is that a system which can increase RH may be necessary. In summertime EMC levels where found to be as low as 6% (30% RH) when an EMC of 12% (66% RH) is desirable. This can have an affect of the EMC of timber which are held in storage for longer periods (months) and taken into joinery production.

## 6.4. Other comments of store dried timber

Load/unload of timber in storages can affect storage climate. When having climate controlled storages it is of importance that ports are kept closed whenever trucks or tractors are not passing in or out of the storage. Factors which can influence storage climate may be season dependable, such as outdoor temperature, outdoor humidity, wind, rain and so on. Such factors can get climate off balance quite rapidly and decrease timber quality due to moisture related factors.

If storage of dried timber is made in open air under screens where wind and uncontrolled climate are present, one should know that such factors in unfavorable situations can degrade drying quality due to uncontrolled drying/wetting in just a number of hours! Wood adapts its EMC to surrounding climate as illustrated in *Figure 6.4*.

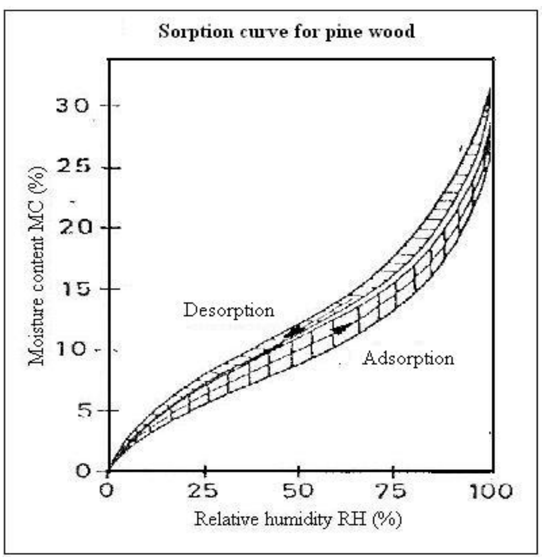



*Figure 6.4 Sorption curve for pine wood. Lower/upper edge of each area respectively, relates to a higher/lower temperature of desorption/adsorption.*

A comment to sorption curves is that as timber properties are differing, adsorption and desorption is unique. Though, it is the relation of the timber behavior which is of interest in the sorption curve.

# 7. From *sample* to *total* quality control

The difference of how to define quality in *kiln drying production* compared to *joinery production* is of another nature. From handle timber large-scale; batch- and package-wise and define quality due to this, timber will split up in the timber flow and quality are described in a more focused way, piece-wise related. The quality thinking turns from sample to total quality control.

In kiln drying production, factors related to the process and product quality are well defined. Kiln drying quality is described roughly with statistics because of its macro level of production (a few samples shall describe a population). All individual pieces are sorted and dried big-scale to specific quality targets to suit joinery production. Though, small differences of timber properties and production can vary slightly within the level of timber quality class, batch in drying process, package and even within the same piece. This will set demands of uniformity of these properties to meet a high class drying quality of the timber based on joinery timber requirements. Joinery timber requirements are set by defining quality level of the raw material and how kiln drying are performed. Quality thinking has to start in log sorting to accommodate to the following production and achieve a high quality end product. And by working structural in the value chain prior joinery production will increase timber quality for its customer and minimize problems in the joinery production. In other words,

*A high class quality of the timber is needed to meet a high class joinery product!*

## 7.1. The way of looking at quality changes with timber flow

Even if a high class timber product is produced in kiln drying production, there still will be small differences within the timber which are fed into joinery production. Hence, here will a new quality thinking take over. Quality has to be focused to find individual pieces or areas at these which can cause decrease of the end product quality.

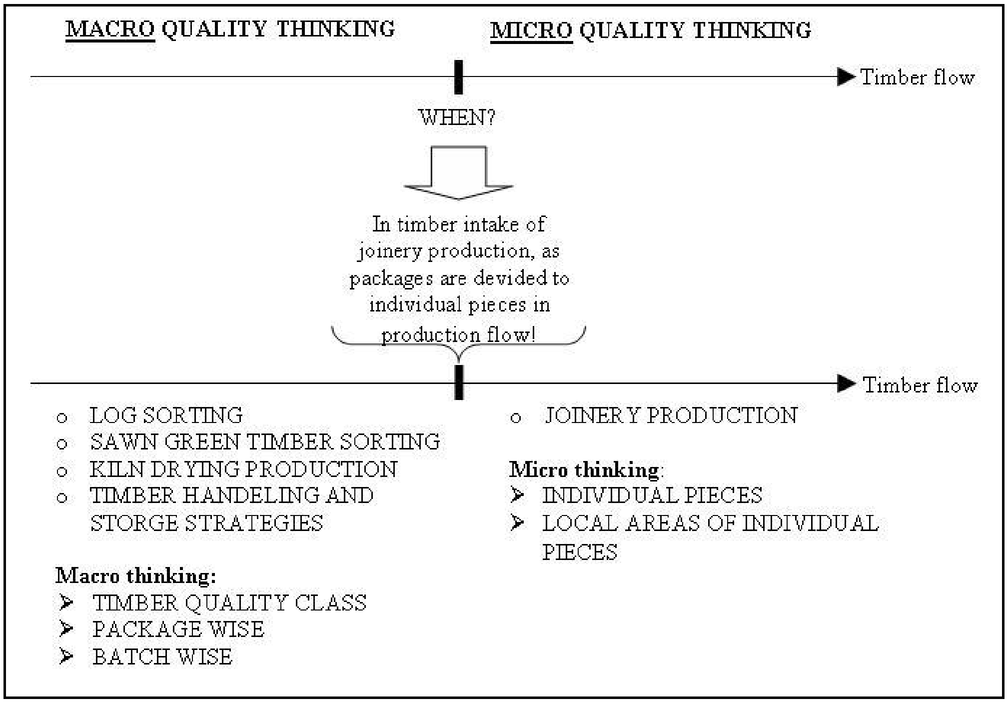



*Figure 7.1Defining quality is not the same in kiln drying production compared with joinery production.*

At the "macro" level quality are referred to EN standards and common requirements for joinery production. At "micro" level, an own standard or quality has to be implemented to suit the own production to be able to achieve a high class end product for the customers. Here only recommendations say that individual pieces should be within 10-14% limits of moisture content and between two pieces which are going to be glued together difference in moisture content should not exceed 2%. Recommended is that case hardening (slicing test) shouldn't exceed 1mm gap for joinery timber.

From the point where timber flow is split up into piece-wise definition of the quality a high class drying quality are reset to estimate timber quality with "new eyes".

## 7.2. Capacitive moisture meter (in-line)

This kind of moisture meter are today further developed and improved to have a better accuracy than few years ago. Traditionally the most common area of usage of in-line capacitive moisture meter has been for rejecting wet pieces from production and be source in an eventual dispute regarding moisture related issues of further processed products; to define timber quality which are in fed to production. The accuracy of the measurements is required to be high, as all too high moisture variation between timber pieces will create problems with deformations and ability to glue if moisture content is differing too much.

Three areas of purpose can be point out to be the usage for this kind of moisture meter in joinery production.

1. For controlling timber quality aimed for production of joinery
2. For collecting information of timber which can be of use as feedback to kiln operators
3. Be a source of information of timber quality at a certain moment

Different brands of in-line capacitive moisture meters have more or less good performance due to different areas. Many investigations have shown that the performance is differing a lot for this kind of equipment due to brand. One brand has better accuracy in one way and some other brand a good accuracy in another way, e.g. one is good in finding $MC_{average}$ for a batch or package, another is better in finding MC for an individual piece etc. Hence, user should be aware of the actual area of performance and for what purpose the moisture meter are planned to be used. Though, these kind of in line moisture meters are further developed from a few years ago, this opens up a wider use of these equipment!

### 7.2.1. Performance of in line capacitive moisture meters are improved

Capacitive in line moisture meters are measuring amount of water due to a certain volume. As the definition of “moisture content” (MC) is the weight of water divided by the weight of absolutely dry wood, implies that a piece of wood sample with high density will have high moisture reading and low density will have low moisture reading. In a “perfect situation”, if every wood piece which are fed through the in line moisture meter had same density, the accuracy in moisture reading would be quite exact. But as we all know; wood is a quite complex material and variations will always be present.

One area which has to be focused on is to optimize timber production *before* joinery production, e.g. sort green timber (or even at log level) in classes. This will make drying process performance to increase as more uniform timber fed in to drying process and further into joinery production, regarding density and moisture variation within packages. This leads to increased in line moisture meter performance, making it possible to set tighter acceptable levels of e.g. moisture content. But as there will be local variations between areas within a single timber piece density compensation are desirable.

- **Density compensation**

High-dense wood contains more water than low-dense wood at same moisture content. The most affecting parameter of capacitive in line moisture meter performance is density variations within the timber. There are also other parameters which are affecting and these are presented in “*Recommendations due to calibration of in-line capacitive moisture meter*”**.**

A package of timber or batch can be proclaimed to be normal distributed in terms of density variation. As capacitive in line moisture meters are highly density dependable, a more uniform density of the pieces within the packages with narrower span of density variation will improve the moisture reading further from today. The demand from users of the in line moisture meters has bring manufacturers to meet the customer, making them forced to develop this equipment further. Today many brands can offer density compensation in the reading and this has improved performance severely.

The problem of an accurate compensation for density is that individual wood pieces are more or less moist, comparing to each other. The accuracy increase as the variation of moisture content in between wood samples decrease (density are connected to volume, and volume are connected to moisture content). But to have as high accuracy as possible determination of complete dry wood is necessary which are not applicable industrially, though, this error within acceptable limits as density are determined automatically.

### 7.2.2. Lengthwise feeding of timber through capacitance in-line moisture meter

Today at one SET joinery producer, a lengthwise fed capacitance in-line moisture meter of timber is installed. Traditionally most common is to use the wise fed capacitance in-line moisture meter. This has set restrictions as just a few (≈3 measurements) measurements have been carried through per piece. Today as capacitance in-line moisture meters are developed further, it is possible to measure each board more detailed as higher number of measurements can be produced/piece, without affecting feeding speed in the production.

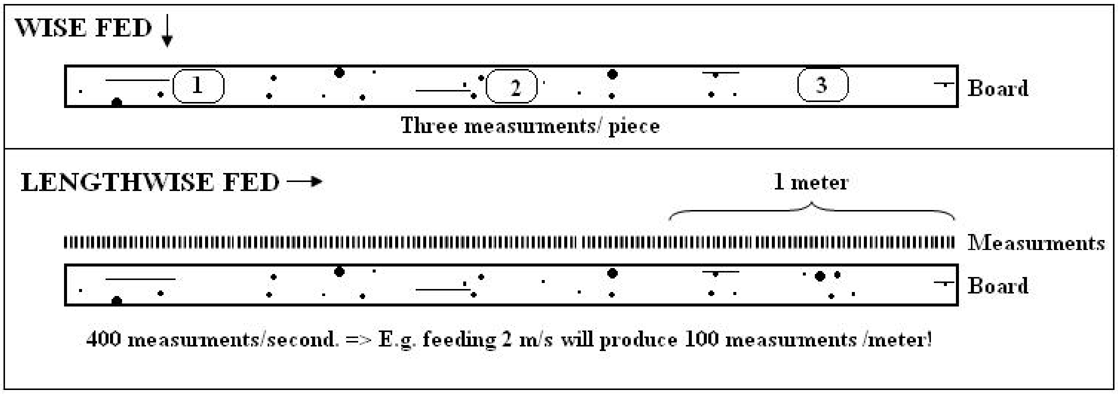



*Figure 7.2 A higher numbers of measurements /piece are produced with new, lengthwise fed timber, allowing better prediction of moisture content in every piece.*

Of the huge number of measurements there are some measurements which are not representative for the wood which are used in the further processed end product, such as knots and other non-representative wood (which often are cut away by the automatic grading system). In feedback purposes to kiln operators, the use of this equipment is to connect all pieces average MC to one package as the determination of this is quite precisely.

*One manufacturer of lengthwise fed in line moisture meter proclaims that standard deviation regarding finding moisture variation is reduced 40% by compensate for density (their equipment measures 400 times/second).*

*With no compensating for density the accuracy of the standard deviation is ±1 of a piece of normal length (4-5m?) and "normal" drying quality with target MC at 12%. This means that 95% of the measurements along the piece will be within 12±1.96·1=10.04-11.96%. A compensation for density will reduce this interval. (Comment: Also observe that the variation between top and root end of the board can differ approximately 1% MC, as top end is often drier than root end. If this is included in the prediction is not expressed).*

### 7.2.3. Recommendations due to calibration of in-line capacitive moisture meter

Ordinary factors which are affecting performance of capacitance in line moisture meters are

- Density
- Dimension
- Specie
- Temperature of wood and surroundings
- Amount of heartwood
- Amount of resin and other compounds
- Surface MC
- Deformations (distance to sensors)
- Feeding speed
- Other "local wood qualities" such as knots, bark etc.
- Moisture gradient within the cross section
- Irregularities in dimensions (wane etc.)

In industry, also awareness by the users of calibration routines has become known. Areas which has to be taken into consideration when calibrating are

- Use timber with density which reflect the average density of the actual timber quality
- Calibrate timber with *low* moisture gradient in one class and calibrate timber with *high* moisture gradient in another class → Calibrate conditioned/unconditioned timber separately even if it is equal in other quality aspects
- Make calibration due to each timber dimension (timber quality)
- Avoid timber rich of knots as sensors can be located so that reading are made on "wrong type of wood quality"
- Avoid timber with wane
- Use at least 50 pieces. 50-100 recommended
- Calibrate to ODM, procedure as standard *EN13183-1*. Do not use electrical moisture meter because this will make uncertainties of correctness include in the calibration.
- Check timber and air temperature to be within acceptable limits (though this are not found to affect calibration but is an easy way of eliminating a factor of error!)
- Calibrate timber from different locations of the log separately, as planks from more centered parts of the log have lower density than boards from outer parts. (Sapwood/heartwood and juvenile/normal wood relation). Guideline for density variations are presented in *Table 7*.

| PINE DENSITY IN SWEDEN (KG/M3) | | Mean for sweden | Boards from *large* diam of logs | Boards from *thin* diam. of logs | Centerpieces from *large* diam of logs | Centerpieces from *thin* diam. of logs |
|---|---|---|---|---|---|---|
| $\rho_{0,raw}$ | Density at dry state compared with raw volume | 425 | 440 | 430 | 435 | 395 |
| $\rho_{0,0}$ | Density at dry state compared with absolutely dry volume | 485 | 500 | 490 | 495 | 455 |

| PINE DENSITY IN FINLAND (KG/M3) | Diameter class (mm) | | | | |
|---|---|---|---|---|---|
| $\rho_{0,raw}$ | 51-150 | 151-200 | 201-250 | 251-300 | 301- |
| Northern | 401 | 404 | 400 | 384 | 381 |
| Southern | 407 | 418 | 410 | 401 | 400 |

*Table 7. Average density for different types of pine wood, can be used for calibration of in line moisture meters (SP Trätek and VTI).*

Further,

- *Make calibration due to instructions from manufacturer*

If these rules are followed, a better accuracy and performance of capacitance in-line moisture meter is met.

### 7.2.4. Follow up of kiln drying performance based on measurements made in joinery production

In kiln drying production, as mentioned before in the QHB, a few numbers of samples shall act informative to describe a large-scale production. A better accuracy is needed and here information from capacitive in-line moisture meters can be used due to follow up of kiln drying performance. In joinery production every piece are checked and the information from this has to be transferred backwards in value chain.

Parameters which has to be fixed to increase the informative value from joinery capacitive in-line moisture meters to kiln drying operators are

1. Storage of timber between kiln drying- and joinery production and has to be made without affecting high class drying quality, keeping it equal at high level. As packages often are “mixed up” between kiln drying- and joinery production, a steady state flow of timber between these two processes will increase informative value as timber are handled uniformly (one package is not stored differently than another package e.g. regarding storage time which can have influence of timber EMC and temperature)
2. Measurements made in capacitive in-line moisture meters have to be related to a package to be valid. This will make it possible to connect this to a specific drying kiln or operation made earlier in the timber flow.
3. Calibration of the capacitive in-line moisture meters has to be precise due to the specific quality of the specimen which are measured
4. Information transfer within the company has to be user-friendly. It has to be easy to find and utilize information; otherwise personnel do not use it!

- **Package identities**

Today every package has an identity as identification numbers on every stickered package. As stickered packages has unique identification, this can be used to trace timber packages in production from saw shed trough drying process, storage to un-sticking in joinery production and the other way around, automatically or manually. By have control on stickered packages and identify these from drying process through joinery production, it is possible to trace these backwards to drying production to a specific kiln or any other position.

The in-line capacitance moisture meter in the joinery production is measuring every piece and high accuracy of average moisture content of a package is measured. A vision should be that information from in-line capacitance moisture meter of every single piece should be connected to specific package identity, so the information from these could be connected to a batch in kiln drying. If timber is handled as position 1 mention above, this is valuable information. A source of error can be if disturbances in timber flow within joinery production are interrupted. Timber can be picked out or added within the timber flow, making measurements connected to “wrong” package. Though, if a level of incorrectness is acceptable (one piece out of ≈300) this can have low influence of the measurements (average MC and standard deviation of the actual package). In drying production it is possible to refer package identities to a specific batch by noting these when kiln are loaded or un-loaded.

- **Recommendation**

Use a specific calibration adjusted to every timber quality.

- **Automatic grader or “in line scanner”**

By in line automatic scanner grading equipments (such as WoodEye), using image processing there two parameters which can be used to transfer as feedback to kiln operators;

1. Amount of fissures in the timber. High accuracy of determining fissures is performed by this kind of machines today. Amount of checking related to one particular package can be valuable information if the locations of packages within the kiln are known.
2. Connect length wise fed in-line capacitive moisture meter to the scanner. As mentioned in chapter *Lengthwise feeding of timber through capacitance in-line moisture meter* measurements are collected throughout the whole length of the timber piece and mean MC of the timber piece can be calculated. One possible strategy can be to exclude readings by the in-line capacitive moisture meter where measurements

are made at areas which are “defect” and are going to be cut away and rejected, illustrated in *Figure 7.3*.

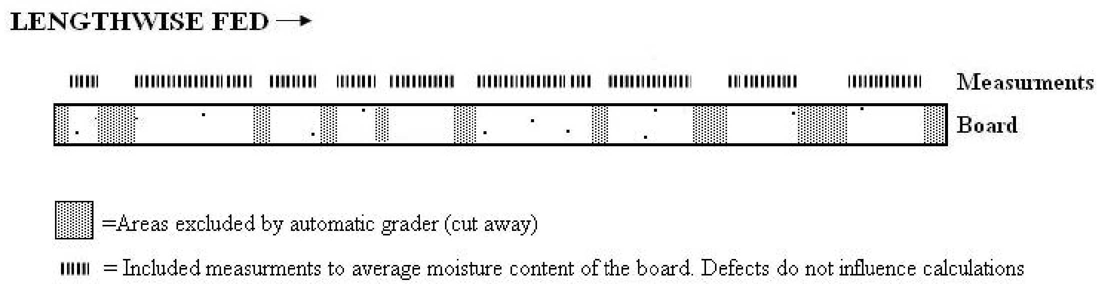



*Figure 7.3 areas which are rejected by automatic grader are not included in calculation of the average MC of the timber piece.*

## 7.3. New technology for density and MC determination

In industry nowadays there are two common methods to determine moisture content, electrical resistance method and capacitive method. R&D has found alternative methods which are suitable to implement for industrial use. And, new technology is implemented to make wooden industry more effective to utilize wooden material, to be able to compete with other type of materials and areas.

- **NMR (Nuclear Magnetic Resonance)**

NMR is a technique which can be used to determine density and moisture content within wood with high accuracy. An advantage of NMR is that measurements can be made at different depths within the sample, making it possible to determine e.g. a moisture gradient within a cross section. The technology can be utilized for levels between 0-120 MC%. A disadvantage of the technique is that measurements are highly time-consuming. Also frozen water appears differently than liquid (or bound) water which can be a problem in industrial usage. Researchers find it interesting to combine NMR technology with CT scanning (X-ray-, microwave-, ultra sound- scanning, etc.) and this may be a future way of measure and inspect, as technology in the future will be able to handle data more rapidly than today.

*Interesting reading about NMR can be found at the website http://www.cis.rit.edu/htbooks/mri/inside.htm which is describing the basics of the NMR technology.*

- **Microwaves**

Microwaves (~$10^9$-$10^{11}$ Hz) are one way to determine density or moisture content within a sample. The method is quite accurate for MC<FSP but has also a quite high performance for MC>FSP. Microwaves can also be used to even out moisture gradients within a cross section of a wood piece. Microwave heating is directly linked to the electric field strength of the applied microwave energy. Microwaves can make moist wood to heat up as microwave energy is transformed into heat, making pressure within the wood to rise. One suitable area can be to even out a moisture gradient within a piece. The applied energy (heating) will force water molecules to be transported toward the surface of the board, making core decrease its MC.

One problem, though, can be that resinous wood even with low MC can absorb microwaves. Hereby, such compound can absorb the energy instead of the moisture, making resinous areas within the wood to start flux. It is also very important to avoid local areas being all too heated in areas with low amount of moisture, this by controlling microwave heating and to move the components within the electric field to achieve uniform heating within the piece. Here all too dry wood can absorb energy instead of more moist areas.

- **Combined meters**

Combined meters are developed but not used industrially. This kind of meter uses microwaves to determine MC, electro magnetic gamma radiation to determine density and IR to measure temperature. An investigation by VTT shows a high accuracy in determine MC at 6-30% (under FSP) as compensation for density within wood samples is made.

- **CT scanning**

CT scanning (Computer Tomography) is another way of determine density using a computer based algorithm. The technique is using X-ray radiation which penetrates the cross cut of a sample, such as a wood piece. High accuracy of MC from >FSP to < FSP can be made with this technique. Same technology is used medical to produce two and three dimensional images of internal organs within bodies. Problem here is that water within wood appears as dense wood and information has to be processed further after scanning. This method has not been developed as much as necessary that it would be able to be applicable industrially today, as the method is too slow.

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# Appendix 1- Example of quality document “Quality Control of batch”

To document and archive such information which can be of later use are important. This is a proposal of pre-designed and standardized form which can be used for manual recording of measurements.

*(Drying report is classified by SET and not presented in this QHB)*

# Appendix 2- Control chart

*(Table/follow-up of a kiln/schedule is classified by SET and not presented in this QHB)*

*Table is an example of how a follow-up of drying of a specific dimension, target MC and schedule. From this data a process control chart can be sketched.*

*(Diagrams of the control charts  is classified by SET and not presented in this QHB)*

*Diagram is a process control chart based on red marked values in. (Warning limits are not included in diagrams).*

# Appendix 3- Identification of processes in kiln drying production

Processes from ISO system which can be adapted to kiln drying of joinery are

- **Measuring**
- **Analysis**
- **Development of the drying process**
- **Development product and drying quality**

**Areas and methods which has to be clarified are**

- To set requirements and specify limits for the particular product so these suit its purposes.
- Who has the responsibility regarding every-day quality work? There should be defined what the personnel can/can not do and what their authorities are.
- Instructions of how to develop a certain product have to be clarified.
- Important equipment for the purposes has to be clarified.
- Equipment which has to be found for the purposes has to be provided.
- Documentation and tractability have to be organized, standardized and defined; what has to be documented?
- To calibrate equipment so it will be reliable.
- Clarify how production has to be controlled. What activities are needed and when do these have to be carried through, to make the demands which where put up reachable
- Standardize a communication with the customer (next step in the production flow) of such information that is of interest, so feedback in both directions is taken place.
- Methods of how to handle, log and utilize feedback have to be clarified.
- How to handle products that aren't within the demands, which were put up for the product
- To not allow a product which aren't within the demands to pass and be sent further into value chain and clarify how to act.
- Measurements that are needed to control a drying process have to be clarified. When it's measured and data is collected from some method, this has to be documented and analyzed in a standardized way.
- Development! Continuous try to make a process more comprehensive and make it suit its purposes even better.
- Statistically analyze why there are irregularities and handle these so they are reduced in the long term
- Define routines for critical activities

# Appendix 4- EMC as function of temperature and relative humidity

RH % / EMC %

DRY BULB TEMPERATURE °C

| PSYCROMETRIC DIFFERENCE °C | −10 | −9 | −8 | −7 | −6 | −5 | −4 | −3 | −2 | −1 |
|---|---|---|---|---|---|---|---|---|---|---|
| 0,2 | 93/ | 94/ | 94/ | 95/ | 95/ | 95/ | 95/ | 96/ | 96/ | 96/ |
| 0,4 | 87/20,0 | 88/20,4 | 88/20,7 | 89/21,0 | 90/21,3 | 90/21,6 | 91/ | 91/ | 92/ | 92/ |
| 0,6 | 80/16,4 | 81/17,2 | 83/18,0 | 84/18,5 | 85/19,0 | 86/19,4 | 86/19,7 | 87/20,0 | 88/20,3 | 88/20,6 |
| 0,8 | 74/14,6 | 75/14,9 | 77/15,5 | 78/15,9 | 79/16,3 | 81/16,9 | 82/17,5 | 82/17,8 | 84/18,1 | 84/18,4 |
| 1,0 | 67/12,8 | 69/13,2 | 71/13,8 | 73/14,4 | 74/14,7 | 76/15,2 | 77/15,5 | 78/15,8 | 79/16,2 | 81/16,9 |
| 1,2 | 61/11,6 | 63/12,0 | 65/12,4 | 67/12,8 | 69/13,2 | 71/13,6 | 73/14,5 | 74/15,0 | 75/15,2 | 77/15,4 |
| 1,4 | 54/10,3 | 57/10,8 | 60/11,3 | 62/11,8 | 64/12,2 | 66/12,6 | 68/13,0 | 70/13,4 | 71/13,8 | 73/14,3 |
| 1,6 | 48/ 9,2 | 51/ 9,7 | 54/10,3 | 57/10,8 | 59/11,3 | 62/11,8 | 64/12,2 | 66/12,6 | 68/12,9 | 69/13,2 |
| 1,8 | 41/ 8,2 | 45/ 8,8 | 48/ 9,3 | 52/ 9,8 | 54/10,3 | 57/10,8 | 59/11,3 | 62/11,8 | 64/12,2 | 66/12,6 |
| 2,0 | 35/ 7,3 | 39/ 7,9 | 43/ 8,4 | 46/ 8,9 | 49/ 9,4 | 52/ 9,9 | 55/10,4 | 57/10,4 | 60/11,3 | 62/11,8 |
| 2,2 | 28/ 6,2 | 33/ 7,0 | 37/ 7,6 | 41/ 8,2 | 45/ 8,8 | 48/ 9,2 | 51/ 9,7 | 53/10,1 | 56/10,6 | 58/11,0 |
| 2,4 | 22/ 5,1 | 27/ 5,9 | 32/ 6,8 | 36/ 7,4 | 40/ 8,0 | 43/ 8,5 | 46/ 8,9 | 49/ 9,4 | 52/ 9,9 | 54/10,4 |
| 2,6 | 16/ 3,9 | 21/ 4,9 | 26/ 5,8 | 31/ 6,6 | 35/ 7,3 | 39/ 7,9 | 42/ 8,3 | 45/ 8,8 | 48/ 9,2 | 51/ 9,7 |
| 2,8 | 9/ 2,3 | 15/ 3,7 | 20/ 4,7 | 25/ 5,6 | 30/ 6,4 | 34/ 7,1 | 38/ 7,7 | 41/ 8,2 | 44/ 8,6 | 47/ 8,9 |
| 3,0 | | 9/ 2,2 | 15/ 3,6 | 20/ 4,7 | 25/ 7,6 | 29/ 6,3 | 33/ 6,9 | 37/ 7,5 | 40/ 8,0 | 43/ 8,5 |
| 3,2 | | | 10/ 2,5 | 15/ 3,7 | 20/ 4,7 | 25/ 5,6 | 29/ 6,2 | 33/ 6,9 | 37/ 7,5 | 40/ 8,0 |
| 3,4 | | | | 10/ 2,5 | 15/ 3,6 | 20/ 4,7 | 25/ 5,5 | 29/ 6,2 | 33/ 6,9 | 36/ 7,6 |
| 3,6 | | | | 5/ 1,3 | 11/ 2,8 | 16/ 3,9 | 21/ 4,9 | 25/ 5,6 | 29/ 6,2 | 33/ 6,9 |
| 3,8 | | | | | 6/ 1,5 | 11/ 2,8 | 17/ 4,1 | 21/ 4,9 | 25/ 5,6 | 29/ 6,2 |
| 4,0 | | | | | | 7/ 1,8 | 12/ 3,0 | 17/ 4,1 | 22/ 5,0 | 26/ 5,7 |
| 4,5 | | | | | | | | 8/ 2,0 | 12/ 3,1 | 17/ 4,2 |
| 5,0 | | | | | | | | | | 8/ 2,0 |

DRY BULB TEMPERATURE °C

| PSYCROMETRIC DIFFERENCE °C | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.2 | 96/25,3 | 97/25,5 | 97/25,7 | 97/25,9 | 97/26,1 | 97/26,3 | 97/26,5 | 97/26,7 | 98/26,9 | 98/27,2 | 98/27,4 |
| 0,4 | 93/23,0 | 93/23,1 | 93/23,2 | 94/23,3 | 94/23,4 | 94/23,5 | 94/23,7 | 95/23,9 | 95/24,1 | 35/24,3 | 95/24,8 |
| 0.6 | 89/20,6 | 90/20,8 | 90/21,0 | 91/21,2 | 91/21,4 | 92/21,6 | 92/21,8 | 92/22,0 | 93/22,2 | 93/22,4 | 93/22,6 |
| 0.8 | 85/18,8 | 86/19,1 | 87/19,4 | 88/19,6 | 88/19,8 | 88/20,0 | 89/20,2 | 89/20,4 | 90/21,6 | 90/20,8 | 90/21,0 |
| 1,0 | 81/17,2 | 83/18,1 | 84/18,3 | 84/18,5 | 85/18,7 | 86/18,9 | 86/19,1 | 87/19,3 | 87/19,5 | 88/19,7 | 88/19,9 |
| 1.2 | 78/16,6 | 80/16,9 | 81/17,1 | 82/17,3 | 82/17,5 | 83/17,7 | 84/17,9 | 84/18,1 | 85/18,3 | 85/18,5 | 86/18,7 |
| 1.4 | 74/14,8 | 76/15,2 | 78/15,6 | 78/15,0 | 79/16,4 | 80/16,8 | 81/17,1 | 82/17,3 | 82/17,5 | 83/17,7 | 83/17,9 |
| 1.6 | 71/31,6 | 73/14,3 | 74/14,7 | 76/15,0 | 77/15,3 | 77/15,6 | 78/15,9 | 79/16,2 | 80/16,5 | 81/16,7 | 81/16,9 |
| 1,8 | 67/12,8 | 70/13,3 | 71/13,8 | 72/14,2 | 74/14,6 | 75/14,9 | 76/15,2 | 77/15,5 | 77/15,7 | 78/15,9 | 79/16,1 |
| 2.0 | 64/12,2 | 66/12,7 | 68/13,1 | 70/13,5 | 71/13,8 | 72/14,1 | 73/14,4 | 74/14,7 | 75/14,9 | 76/15,1 | 77/15,3 |
| 2,2 | 60/11,2 | 63/11,5 | 65/11,9 | 67/12,3 | 68/12,7 | 69/13,1 | 70/13,5 | 72/13,9 | 73/14,2 | 74/14,5 | 74/14,7 |
| 2,4 | 57/10,7 | 59/11,1 | 62/11,6 | 64/11,9 | 65/12,2 | 67/12,5 | 68/12,8 | 69/13,1 | 70/13,4 | 71/13,7 | 72/14,0 |
| 2,6 | 53/10,0 | 56/10,6 | 59/11,1 | 61/11,4 | 62/11,7 | 64/12,0 | 65/12,3 | 67/12,6 | 68/12,9 | 69/13,2 | 70/13,4 |
| 2,8 | 50/ 9,5 | 53/10,0 | 55/10,5 | 58/10,9 | 60/11,2 | 61/11,5 | 63/11,8 | 64/12,0 | 65/12,3 | 67/12,6 | 68/12,8 |
| 3.0 | 46/ 8,9 | 49/ 9,4 | 52/ 9,9 | 55/10,3 | 57/10,6 | 58/10,9 | 60/11,2 | 62/11,4 | 63/11,6 | 64/11,9 | 66/12,2 |
| 3,2 | 43/ 8,4 | 46/ 8,9 | 49/ 9,4 | 52/ 9,8 | 54/10,1 | 56/10,4 | 58/10,7 | 59/11,0 | 61/11,2 | 62/11,4 | 63,11,7 |
| 3,4 | 40/ 7,9 | 43/ 8,4 | 46/ 8,9 | 49/ 9,3 | 51/ 9,6 | 53/ 9,9 | 55/10,2 | 57/10,5 | 58/10,7 | 60/11,0 | 61/11,3 |
| 3,6 | 36/ 7,4 | 40/ 7,9 | 43/ 8,4 | 46/ 8,8 | 48/ 9,2 | 51/ 9,6 | 53/ 9,9 | 54/10,1 | 56/10,4 | 58/10,7 | 59/10,9 |
| 3,8 | 33/ 6,9 | 36/ 7,4 | 40/ 7,9 | 43/ 8,4 | 46/ 8,8 | 48/ 9,1 | 50/ 9,4 | 52/ 9,7 | 54/10,0 | 55/10,2 | 57/10,5 |
| 4,0 | 29/ 6,2 | 33/ 6,8 | 37/ 7,4 | 40/ 7,9 | 43/ 8,3 | 45/ 8,7 | 48/ 9,1 | 50/ 9,4 | 51/ 9,6 | 53/ 9,9 | 55/10,2 |
| 4,5 | 21/ 4,8 | 25/ 5,6 | 29/ 6,2 | 33/ 6,8 | 36/ 7,3 | 39/ 7,8 | 41/ 8,2 | 44/ 8,5 | 46/ 8,8 | 48/ 9,1 | 50/ 9,4 |
| 5.0 | 13/ 3,3 | 17/ 4,2 | 22/ 5,0 | 26/ 5,7 | 29/ 6,2 | 33/ 6,7 | 35/ 7,1 | 36/ 7,5 | 40/ 7,8 | 42/ 8,1 | 44/ 8,4 |
| 5,5 | 5/ 1,5 | 10/ 2,8 | 14/ 3,7 | 19/ 4,5 | 22/ 5,1 | 26/ 5,7 | 29/ 6,2 | 32/ 6,6 | 35/ 7,0 | 37/ 7,3 | 39/ 7,6 |
| 6.0 | | | 7/ 2,0 | 12/ 3,0 | 16/ 3,9 | 20/ 4,7 | 24/ 5,3 | 26/ 5,7 | 29/ 6,1 | 32/ 6,5 | 34/ 6,9 |
| 6,5 | | | | 5/ 1,5 | 9/ 2,5 | 13/ 3,4 | 17/ 4,1 | 21/ 4,8 | 24/ 5,3 | 27/ 5,7 | 29/ 6,1 |
| 7,0 | | | | | | 7/ 2,0 | 11/ 2,9 | 15/ 3,7 | 19/ 4,5 | 22/ 4,9 | 24/ 5,3 |
| 7,5 | | | | | | | 5/ 1,5 | 10/ 2,7 | 14/ 3,4 | 17/ 4,0 | 20/ 4,5 |
| 8,0 | | | | | | | | | 8, 2,2 | 12/ 3,1 | 15/ 3,7 |
| 8,5 | | | | | | | | | | 7/ 2,0 | 10/ 2,7 |
| 9.0 | | | | | | | | | | | 8/ 1,7 |

## DRY BULB TEMPERATURE °C

PSYCROMETRIC DIFFERENCE °C

| | 11 | 12 | 13 | 14 | 15 | $t-t_v$ | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0,2 | 98/27,7 | 98/27,9 | 98/27,7 | 98/27,7 | 98/27,7 | 0,5 | 95/24,0 | 95/24,1 | 95/24,2 | 95/24,3 | 96/24,4 |
| 0,4 | 95/24,9 | 96/25,0 | 96/25,0 | 96/24,9 | 96/24,9 | 1,0 | 90/20,9 | 90/20,9 | 91/20,9 | 91/21,0 | 91/21,0 |
| 0,6 | 93/22,7 | 93/22,8 | 93/23,0 | 94/23,1 | 94/23,1 | 1,5 | 85/18,4 | 86/18,6 | 86/18,8 | 87/18,9 | 87/19,0 |
| 0,8 | 91/21,2 | 91/21,4 | 91/21,6 | 92/21,0 | 92/22,0 | 2,0 | 81/16,6 | 81/16,7 | 82/16,9 | 82/16,9 | 83/17,1 |
| 1,0 | 89/20,1 | 89/20,3 | 89/20,5 | 90/20,7 | 90/20,9 | 2,5 | 76/14,9 | 76/14,8 | 77/15,1 | 78/15,5 | 78/15,5 |
| 1,2 | 86/18,9 | 87/19,1 | 87/19,3 | 88/19,5 | 88/19,7 | 3,0 | 71/13,4 | 72/13,7 | 73/13,9 | 74/14,1 | 74/14,2 |
| 1,4 | 84/18,1 | 85/18,3 | 85/18,5 | 86/18,7 | 88/18,9 | 3,5 | 67/12,5 | 68/12,7 | 69/12,9 | 70/13,0 | 70/13,1 |
| 1,6 | 82/17,1 | 82/17,3 | 83/17,5 | 84/17,7 | 84/17,9 | 4,0 | 63/11,5 | 64/11,7 | 65/11,8 | 65/11,9 | 66/12,0 |
| 1,8 | 80/16,3 | 80/16,5 | 81/16,7 | 82/16,9 | 82/17,1 | 4,5 | 58/10,6 | 60/10,8 | 61/11,0 | 62/11,2 | 63/11,4 |
| 2,0 | 78/15,5 | 78/15,7 | 79/15,9 | 79/16,1 | 80/16,3 | 5,0 | 54/ 9,9 | 55/10,1 | 57/10,5 | 58/10,5 | 59/10,7 |
| 2,2 | 75/14,9 | 76/15,1 | 77/15,3 | 78/15,5 | 78/15,7 | 5,5 | 50/ 9,2 | 51/ 9,4 | 53/ 9,6 | 54/ 9,8 | 55/10,0 |
| 2,4 | 73/14,2 | 74/14,4 | 75/14,6 | 76/14,8 | 76/15,0 | 6,0 | 46/ 8,5 | 47/ 8,7 | 49/ 8,9 | 50/ 9,1 | 51/ 9,3 |
| 2,6 | 71/13,6 | 72/13,8 | 73/14,0 | 74/14,2 | 74/14,4 | 6,5 | 42/ 7,9 | 43/ 8,2 | 45/ 8,4 | 46/ 8,6 | 48/ 8,8 |
| 2,8 | 69/13,0 | 70/13,3 | 71/13,5 | 72/13,8 | 73/14,0 | 7,0 | 38/ 7,4 | 40/ 7,6 | 41/ 7,8 | 43/ 8,0 | 44/ 8,2 |
| 3,0 | 67/12,5 | 68/12,8 | 69/13,0 | 70/13,2 | 71/13,4 | 7,5 | 34/ 6,8 | 36/ 7,1 | 38/ 7,3 | 39/ 7,5 | 41/ 7,7 |
| 3,2 | 65/12,0 | 66/12,3 | 67/12,5 | 68/12,7 | 69/12,9 | 8,0 | 30/ 6,2 | 32/ 6,5 | 34/ 6,7 | 36/ 6,9 | 37/ 7,1 |
| 3,4 | 62/11,6 | 64/11,9 | 65/12,1 | 66/12,3 | 67/12,5 | 8,5 | 26/ 5,5 | 28/ 5,9 | 30/ 6,2 | 32/ 6,5 | 34/ 6,7 |
| 3,6 | 60/11,1 | 62/11,4 | 63/11,6 | 64/11,8 | 65/12,0 | 9,0 | 23/ 5,0 | 25/ 5,3 | 27/ 5,6 | 29/ 5,9 | 31/ 6,2 |
| 3,8 | 58/10,7 | 60/11,0 | 61/11,2 | 62/11,4 | 63/11,6 | 9,5 | 19/ 4,4 | 21/ 4,7 | 23/ 5,1 | 26/ 5,4 | 28/ 5,7 |
| 4,0 | 56/10,5 | 58/10,7 | 59/10,8 | 60/11,0 | 61/11,1 | 10,0 | 15/ 3,8 | 18/ 4,2 | 20/ 4,5 | 22/ 4,8 | 24/ 5,1 |
| 4,5 | 51/ 9,6 | 53/ 9,8 | 54/10,0 | 56/10,2 | 57/10,4 | 10,5 | 12/ 3,0 | 14/ 3,5 | 17/ 4,0 | 19/ 4,4 | 21/ 4,7 |
| 5,0 | 46/ 8,7 | 48/ 9,0 | 50/ 9,3 | 51/ 9,5 | 53/ 9,7 | 11,0 | 8/ 2,2 | 11/ 2,9 | 14/ 3,5 | 16/ 3,9 | 18/ 4,2 |
| 5,5 | 41/ 7,9 | 43/ 8,2 | 45/ 8,5 | 47/ 8,7 | 48/ 8,9 | 11,5 | 5/ 1,4 | 8/ 2,2 | 10/ 2,7 | 13/ 3,2 | 15/ 3,6 |
| 6,0 | 36/ 7,3 | 39/ 7,6 | 41/ 7,8 | 42/ 8,0 | 44/ 8,2 | 12,0 | | | 7/ 2,0 | 10/ 2,5 | 12/ 3,0 |
| 6,5 | 32/ 6,5 | 34/ 6,8 | 36/ 7,1 | 38/ 7,4 | 40/ 7,7 | 12,5 | | | | 7/ 2,0 | 9/ 2,5 |
| 7,0 | 27/ 5,7 | 29/ 6,1 | 32/ 6,5 | 34/ 6,8 | 36/ 7,1 | 13,0 | | | | | 6/ 1,6 |
| 7,5 | 22/ 4,9 | 25/ 5,4 | 28/ 5,8 | 30/ 6,1 | 32/ 6,4 | | | | | | |
| 8,0 | 18/ 4,2 | 21/ 4,8 | 23/ 5,1 | 26/ 5,4 | 27/ 5,6 | | | | | | |
| 8,5 | 13/ 3,3 | 16/ 3,9 | 19/ 4,4 | 22/ 4,8 | 24/ 5,2 | | | | | | |
| 9,0 | 9/ 2,5 | 12/ 3,1 | 15/ 3,7 | 18/ 4,2 | 20/ 4,6 | | | | | | |
| 9,5 | 5/ 1,4 | 8/ 2,2 | 11/ 2,8 | 14/ 3,4 | 16/ 3,7 | | | | | | |
| 10,0 | | | 7/ 2,0 | 10/ 2,6 | 13/ 3,2 | | | | | | |
| 10,5 | | | | 6/ 1,7 | 9/ 2,5 | | | | | | |
| 11,0 | | | | | 6/ 1,6 | | | | | | |

## DRY BULB TEMPERATURE °C

PSYCROMETRIC DIFFERENCE °C

| | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 |
|---|---|---|---|---|---|---|---|---|---|---|
| 0,5 | 96/24,5 | 96/24,5 | 96/24,4 | 96/24,4 | 96/24,4 | 96/24,4 | 96/24,3 | 96/24,3 | 96/24,3 | 96/24,3 |
| 1,0 | 91/21,0 | 92/21,2 | 92/21,3 | 92/21,4 | 92/21,5 | 92/21,6 | 92/21,7 | 93/21,8 | 93/21,9 | 93/21,8 |
| 1,5 | 87/19,0 | 87/19,0 | 88/19,3 | 88/19,3 | 88/19,4 | 88/19,7 | 88/19,9 | 89/19,9 | 89/19,9 | 89/19,9 |
| 2,0 | 83/17,2 | 83/17,4 | 84/17,6 | 84/17,6 | 84/17,7 | 85/17,9 | 85/17,9 | 85/17,9 | 86/18,0 | 86/18,0 |
| 2,5 | 79/15,9 | 80/16,0 | 80/16,0 | 80/16,0 | 81/16,1 | 81/16,3 | 81/16,5 | 82/16,6 | 82/16,7 | 83/16,8 |
| 3,0 | 75/14,4 | 76/14,6 | 76/14,7 | 77/14,9 | 77/14,9 | 78/15,0 | 78/15,0 | 78/15,1 | 79/15,2 | 79/15,4 |
| 3,5 | 71/13,3 | 72/13,4 | 72/13,5 | 73/13,7 | 74/13,9 | 74/14,0 | 75/14,1 | 75/14,1 | 76/14,2 | 76/14,3 |
| 4,0 | 67/12,2 | 68/12,4 | 69/12,6 | 69/12,8 | 70/12,9 | 71/13,0 | 71/13,1 | 72/13,2 | 72/13,3 | 73/13,4 |
| 4,5 | 64/11,5 | 64/11,6 | 65/11,8 | 66/11,9 | 67/12,1 | 67/12,2 | 68/12,3 | 69/12,5 | 69/12,6 | 70/12,7 |
| 5,0 | 60/10,8 | 61/10,9 | 62/11,0 | 62/11,1 | 63/11,2 | 64/11,4 | 65/11,5 | 65/11,6 | 66/11,7 | 67/11,8 |
| 5,5 | 56/10,1 | 57/10,2 | 58/10,4 | 59/10,6 | 60/10,7 | 61/10,8 | 62/10,9 | 62/11,0 | 63/11,1 | 64/11,2 |
| 6,0 | 53/ 9,5 | 54/ 9,7 | 55/ 9,9 | 56/10,0 | 57/10,1 | 58/10,2 | 58/10,3 | 59/10,4 | 60/10,5 | 61/10,6 |
| 6,5 | 49/ 9,0 | 50/ 9,1 | 52/ 9,3 | 53/ 9,5 | 54/ 9,6 | 54/ 9,7 | 56/ 9,8 | 56/ 9,9 | 58/10,0 | 58/10,1 |
| 7,0 | 46/ 8,4 | 47/ 8,6 | 48/ 8,7 | 49/ 8,9 | 50/ 9,1 | 51/ 9,2 | 52/ 9,3 | 53/ 9,4 | 54/ 9,5 | 55/ 9,7 |
| 7,5 | 42/ 7,8 | 44/ 8,0 | 45/ 8,2 | 46/ 8,3 | 47/ 8,5 | 49/ 8,8 | 50/ 8,9 | 51/ 9,0 | 52/ 9,1 | 52/ 9,1 |
| 8,0 | 39/ 7,3 | 40/ 7,5 | 42/ 7,7 | 43/ 7,9 | 44/ 8,1 | 46/ 8,3 | 47/ 8,4 | 48/ 8,6 | 49/ 8,7 | 50/ 8,8 |
| 8,5 | 36/ 6,9 | 37/ 7,1 | 39/ 7,3 | 40/ 7,5 | 41/ 7,7 | 43/ 7,9 | 44/ 8,0 | 45/ 8,1 | 46/ 8,2 | 47/ 8,4 |
| 9,0 | 32/ 6,4 | 34/ 6,6 | 36/ 6,9 | 37/ 7,1 | 39/ 7,3 | 40/ 7,4 | 41/ 7,5 | 42/ 7,6 | 43/ 7,8 | 44/ 7,9 |
| 9,5 | 29/ 5,9 | 31/ 6,2 | 33/ 6,4 | 34/ 6,6 | 36/ 6,8 | 37/ 7,0 | 38/ 7,2 | 40/ 7,4 | 41/ 7,5 | 42/ 7,6 |
| 10,0 | 26/ 5,4 | 28/ 5,7 | 30/ 6,0 | 31/ 6,2 | 33/ 6,4 | 34/ 6,6 | 36/ 6,8 | 37/ 7,0 | 38/ 7,1 | 39/ 7,2 |
| 10,5 | 23/ 5,0 | 25/ 5,3 | 27/ 5,6 | 29/ 5,8 | 30/ 6,0 | 32/ 6,2 | 33/ 6,4 | 34/ 6,6 | 36/ 6,8 | 37/ 6,9 |
| 11,0 | 20/ 4,5 | 22/ 4,8 | 24/ 5,1 | 26/ 5,4 | 28/ 5,6 | 29/ 5,8 | 31/ 6,0 | 32/ 6,2 | 33/ 6,4 | 35/ 6,6 |
| 11,5 | 17/ 4,0 | 19/ 4,3 | 21/ 4,6 | 23/ 4,9 | 25/ 5,2 | 26/ 5,4 | 28/ 5,6 | 29/ 5,8 | 31/ 6,0 | 32/ 6,1 |
| 12,0 | 14/ 3,5 | 17/ 3,9 | 19/ 4,2 | 20/ 4,5 | 22/ 4,8 | 24/ 5,0 | 26/ 5,2 | 27/ 5,4 | 28/ 5,6 | 30/ 5,8 |
| 12,5 | 12/ 3,0 | 14/ 3,4 | 16/ 3,7 | 18/ 4,0 | 20/ 4,3 | 21/ 4,6 | 23/ 4,9 | 25/ 5,1 | 26/ 5,3 | 28/ 5,5 |
| 13,0 | 9/ 2,3 | 11/ 2,8 | 13/ 3,2 | 15/ 3,6 | 17/ 3,9 | 19/ 4,2 | 21/ 4,4 | 22/ 4,7 | 24/ 4,9 | 25/ 5,1 |
| 13,5 | 6/ 1,6 | 8/ 2,1 | 11/ 2,6 | 13/ 3,1 | 15/ 3,5 | 17/ 3,8 | 18/ 4,0 | 20/ 4,3 | 22/ 4,6 | 23/ 4,8 |
| 14,0 | | 6/ 1,6 | 8/ 2,1 | 10/ 2,5 | 12/ 2,9 | 14/ 3,3 | 16/ 3,7 | 18/ 4,0 | 19/ 4,2 | 21/ 4,4 |
| 14,5 | | 6/ 1,6 | 8/ 2,1 | 10/ 2,6 | 12/ 2,9 | 12/ 2,9 | 14/ 3,2 | 16/ 3,5 | 17/ 3,8 | 19/ 4,1 |
| 15,0 | | | | 5/ 1,4 | 8/ 2,1 | 10/ 2,6 | 12/ 2,9 | 13/ 3,2 | 15/ 3,5 | 17/ 3,8 |
| 16,0 | | | | | | 5/ 1,4 | 7/ 1,9 | 9/ 2,3 | 11/ 2,7 | 13/ 3,0 |
| 17,0 | | | | | | | | 5/ 1,4 | 7/ 1,9 | 9/ 2,3 |
| 18,0 | | | | | | | | | | 5/ 1,4 |

## DRY BULB TEMPERATURE °C

| PSYCROMETRIC DIFFERENCE °C | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.5 | 96/24,3 | 96/24,3 | 97/24,2 | 97/24,2 | 97/24,2 | 97/24,2 | 97/24,2 | 97/24,2 | 97/24,2 | 97/24,2 |
| 1.0 | 93/21,8 | 93/21,8 | 93/21,8 | 93/21,8 | 94/21,8 | 94/21,8 | 94/21,8 | 94/21,8 | 94/21,8 | 94/21,8 |
| 1.5 | 90/20,0 | 90/20,0 | 90/19,9 | 90/19,9 | 90/19,9/ | 90/19,9 | 90/19,9 | 90/19,9 | 90/19,9 | 91/19,8 |
| 2.0 | 86/18,0 | 86/18,0 | 87/18,1 | 87/18,1 | 87/18,1 | 87/18,1 | 87/18,2 | 88/18,2 | 88/18,2 | 88/18,2 |
| 2.5 | 83/16,8 | 83/16,8 | 83/16,9 | 84/17,0 | 84/17,0 | 84/17,0 | 84/17,0 | 84/16,9 | 85/16,9 | 85/16,9 |
| 3.0 | 80/15,5 | 80/15,6 | 80/15,7 | 81/15,8 | 81/15,8 | 81/15,8 | 82/15,5 | 82/15,9 | 82/15,8 | 82/15,8 |
| 3.5 | 77/14,4 | 77/14,5 | 77/14,5 | 77/14,6 | 77/14,7 | 77/14,8 | 79/14,9 | 79/15,0 | 80/15,0 | 80/15,0 |
| 4.0 | 73/13,5 | 74/13,6 | 74/13,7 | 75/13,8 | 75/13,8 | 75/13,8 | 76/13,9 | 76/14,0 | 77/14,1 | 77/14,2 |
| 4.5 | 70/12,7 | 71/12,8 | 71/12,8 | 72/12,9 | 72/13,1 | 73/13,2 | 73/13,3 | 74/13,3 | 74/13,2 | 74/13,2 |
| 5.0 | 67/11,9 | 68/12,0 | 68/12,0 | 69/12,0 | 69/12,1 | 70/12,0 | 70/12,3 | 71/12,4 | 72/12,5 | 72/12,6 |
| 5.5 | 64/11,3 | 65/11,4 | 66/11,5 | 66/11,6 | 67/11,6 | 67/11,7 | 68/11,8 | 68/11,8 | 69/11,9 | 69/11,9 |
| 6.0 | 61/10,7 | 62/10,8 | 63/10,9 | 63/10,9 | 64/11,0 | 64/11,1 | 65/11,2 | 66/11,3 | 67/11,4 | 67/11,4 |
| 6.5 | 59/10,2 | 60/10,3 | 60/10,4 | 60/10,5 | 61/10,6 | 62/10,7 | 63/10,8 | 63/10,8 | 64/10,8 | 64/10,8 |
| 7.0 | 56/ 9,8 | 57/ 9,9 | 57/ 9,9 | 58/10,0 | 59/10,1 | 59/10,2 | 60/10,3 | 61/10,4 | 62/10,5 | 62/10,4 |
| 7.5 | 53/ 9,2 | 54/ 9,4 | 55/ 9,5 | 56/ 9,6 | 56/ 9,6 | 57/ 9,7 | 58/ 9,8 | 58/ 9,8 | 59/ 9,9 | 59/ 9,9 |
| 8.0 | 51/ 8,9 | 51/ 8,9 | 52/ 9,0 | 53/ 9,2 | 54/ 9,2 | 54/ 9,3 | 55/ 9,4 | 56/ 9,5 | 57/ 9,5 | 57/ 9,5 |
| 8.5 | 48/ 8,5 | 49/ 8,6 | 50/ 8,7 | 51/ 8,8 | 51/ 8,8 | 52/ 8,9 | 53/ 9,0 | 54/ 9,0 | 54/ 9,0 | 54/ 9,0 |
| 9.0 | 45/ 8,0 | 46/ 8,1 | 47/ 8,3 | 48/ 8,4 | 49/ 8,5 | 50/ 8,6 | 51'5 8,7 | 51/ 8,8 | 53/ 8,9 | 53/ 8,9 |
| 9.5 | 43/ 7,7 | 44/ 7,9 | 45/ 8,0 | 46/ 8,1 | 47/ 8,2 | 48/ 8,3 | 48/ 8,5 | 49/ 8,5 | 51/ 8,6 | 51/ 8,6 |
| 10.0 | 40/ 7,3 | 41/ 7,4 | 42/ 7,5 | 43/ 7,6 | 44/ 7,7 | 45/ 7,8 | 46/ 7,9 | 47/ 8,0 | 48/ 8,0 | 48/ 8,1 |
| 10.5 | 38/ 7,0 | 39/ 7,1 | 40/ 7,2 | 41/ 7,3 | 42/ 7,4 | 43/ 7,5 | 44/ 7,6 | 45/ 7,7 | 46/ 7,8 | 46/ 7,8 |
| 11.0 | 36/ 6,7 | 37/ 6,8 | 38/ 6,9 | 39/ 7,1 | 40/ 7,2 | 41/ 7,3 | 42/ 7,3 | 43/ 7,4 | 43/ 7,4 | 44/ 7,5 |
| 11.5 | 33/ 6,3 | 35/ 6,5 | 36/ 6,6 | 37/ 6,8 | 36/ 6,9 | 39/ 7,0 | 40/ 7,1 | 41/ 7,2 | 42/ 7,2 | 42/ 7,2 |
| 12.0 | 31/ 6,2 | 32/ 6,3 | 33/ 6,4 | 35/ 6,5 | 36/ 6,7 | 37/ 6,8 | 38/ 6,8 | 39/ 6,9 | 39/ 7,0 | 40/ 7,0 |
| 12,5 | 29/ 5,7 | 30/ 5,8 | 31/ 5,9 | 32/ 6,1 | 34/ 6,3 | 35/ 6,4 | 36/ 6,5 | 37/ 6,6 | 38/ 6,7 | 38/ 6,7 |
| 13,0 | 27/ 5,3 | 28/ 5,5 | 29/ 5,6 | 30/ 5,8 | 32/ 6,0 | 33/ 6,1 | 34/ 6,2 | 35/ 6,3 | 36/ 6,4 | 36/ 6,4 |
| 13,5 | 25/ 5,0 | 26/ 5,2 | 27/ 5,3 | 28/ 5,5 | 30/ 5,7 | 31/ 5,8 | 32/ 5,9 | 33/ 6,0 | 34/ 6,1 | 35/ 6,2 |
| 14,0 | 22/ 4,5 | 24/ 4,7 | 25/ 4,9 | 26/ 5,1 | 28/ 5,3 | 29/ 5,5 | 30/ 5,6 | 31/ 5,7 | 32/ 5,8 | 33/ 5,9 |
| 14,5 | 20/ 4,3 | 22/ 4,5 | 23/ 4,7 | 24/ 4,8 | 26/ 5,0 | 27/ 5,2 | 28/ 5,3 | 29/ 5,4 | 30/ 5,5 | 31/ 5,6 |
| 15,0 | 18/ 4,0 | 20/ 4,2 | 21/ 4,4 | 23/ 4,6 | 24/ 4,8 | 25/ 4,9 | 26/ 5,0 | 27/ 5,1 | 28/ 5,2 | 29/ 5,4 |
| 16,0 | 14/ 3,3 | 16/ 3,6 | 17/ 3,8 | 19/ 4,0 | 20/ 4,2 | 21/ 4,3 | 21/ 4,3 | 23/ 4,5 | 25/ 4,8 | 26/ 4,9 |
| 17,0 | 11/ 2,6 | 12/ 2,9 | 14/ 3,2 | 14/ 3,2 | 15/ 3,4 | 17/ 3,6 | 18/ 3,8 | 20/ 4,1 | 22/ 4,3 | 23/ 4,4 |
| 18,0 | 7/ 1,8 | 9/ 2,1 | 10/ 2,4 | 12/ 2,7 | 13/ 2,9 | 13/ 2,9 | 15/ 3,2 | 16/ 3,4 | 18/ 3,8 | 20/ 4,0 |
| 19,0 | | 5/ 1,3 | 7/ 1,7 | 8/ 2,0 | 10/ 2,3 | 11/ 2,6 | 13/ 2,8 | 14/ 3,0 | 15/ 3,2 | 16/ 3,4 |
| 20,0 | | | | 5/ 1,3 | 7/ 1,6 | 8/ 1,9 | 10/ 2,2 | 11/ 2,5 | 12/ 2,8 | 14/ 3,0 |

## DRY BULB TEMPERATURE °C

| PSYCROMETRIC DIFFERENCE °C | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 50 |
|---|---|---|---|---|---|---|---|---|---|---|
| 0,5 | 97/24,2 | 97/24,2 | 97/24,2 | 97/24,1 | 97/24,1 | 97/24,1 | 97/24,1 | 97/24,0 | 97/24,0 | 97/24,0 |
| 1,0 | 94/21,8 | 94/21,8 | 94/21,8 | 94/21,8 | 94/21,8 | 94/21,7 | 94/21,7 | 94/21,7 | 94/21,7 | 94/21,7 |
| 1,5 | 91/20,0 | 91/20,0 | 91/20,0 | 91/20,0 | 91/19,9 | 91/19,8 | 91/19,8 | 91/19,8 | 91/19,8 | 91/19,8 |
| 2,0 | 88/18,2 | 88/18,2 | 88/18,2 | 89/18,2 | 89/18,1 | 89/18,1 | 89/18,1 | 89/18,1 | 89/18,0 | 90/18,0 |
| 2,5 | 85/17,0 | 85/17,0 | 85/17,0 | 86/17,0 | 86/17,0 | 86/17,0 | 86/17,0 | 86/16,9 | 86/16,9 | 87/16,9 |
| 3,0 | 83/15,8 | 83/15,9 | 83/15,9 | 83/15,9 | 83/15,9 | 84/15,9 | 84/15,9 | 84/15,8 | 84/15,8 | 85/15,8 |
| 3,5 | 80/14,8 | 80/14,9 | 80/14,9 | 80/14,9 | 80/14,9 | 81/15,0 | 81/15,0 | 81/14,9 | 81/14,9 | 82/14,9 |
| 4,0 | 78/13,9 | 78/14,0 | 78/14,0 | 78/14,0 | 78/14,0 | 79/14,1 | 79/14,1 | 79/14,1 | 79/14,1 | 80/14,1 |
| 4,5 | 75/13,2 | 75/13,2 | 75/13,3 | 75/13,3 | 75/13,3 | 76/13,4 | 77/13,4 | 77/13,4 | 77/13,4 | 77/13,4 |
| 5,0 | 73/12,6 | 73/12,6 | 73/12,6 | 73/12,7 | 73/12,7 | 74/12,7 | 74/12,8 | 75/12,8 | 75/12,8 | 75/12,8 |
| 5,5 | 70/12,0 | 70/12,0 | 70/12,1 | 71/12,1 | 71/12,1 | 71/12,2 | 71/12,1 | 71/12,2 | 72/12,3 | 73/12,3 |
| 6,0 | 68/11,5 | 68/11,5 | 68/11,6 | 69/11,6 | 69/11,6 | 69/11,7 | 69/11,7 | 70/11,7 | 70/11,8 | 71/11,8 |
| 6,5 | 65/11,0 | 65/11,0 | 66/11,0 | 66/11,0 | 66/11,1 | 67/11,1 | 67/11,2 | 68/11,2 | 69/11,3 | 69/11,3 |
| 7,0 | 63/10,6 | 63/10,6 | 64/10,7 | 64/10,7 | 64/10,7 | 65/10,8 | 65/10,8 | 66/10,8 | 66/10,8 | 67/10,8 |
| 7,5 | 60/10,1 | 61/10,1 | 62/10,2 | 62/10,2 | 62/10,2 | 63/10,2 | 63/10,2 | 64/10,3 | 64/10,3 | 64/10,3 |
| 8,0 | 58/ 9,6 | 59/ 9,7 | 60/ 9,7 | 60/ 9,7 | 60/ 9,6 | 61/ 9,8 | 61/ 9,8 | 62/ 9,9 | 62/ 9,9 | 62/ 9,9 |
| 8,5 | 56/ 9,3 | 56/ 9,3 | 57/ 9,4 | 57/ 9,4 | 57/ 9,4 | 57/ 9,5 | 58/ 9,5 | 59/ 9,6 | 60/ 9,6 | 60/ 9,6 |
| 9,0 | 54/" 9,0 | 54/ 9,0 | 55/ 9,1 | 55/ 9,1 | 55/ 9,2 | 56/ 9,2 | 56/ 9,3 | 57/ 9,3 | 58/ 9,4 | 59/ 9,4 |
| 9,5 | 52/ 8,6 | 52/ 8,7 | 53/ 8,8 | 53/ 8,8 | 53/ 8,9 | 54/ 8,9 | 54/ 9,0 | 55/ 9,0 | 56/ 9,0 | 57/ 9,0 |
| 10,0 | 49/ 8,3 | 50/ 8,4 | 51/ 8,5 | 51/ 8,5 | 52/ 8,7 | 53/ 8,6 | 53/ 8,6 | 54/ 8,7 | 54/ 8,7 | 55/ 8,7 |
| 10,5 | 47/ 7,9 | 48/ 7,9 | 49/ 8,0 | 49/ 8,1 | 51/ 8,1 | 51/ 8,1 | 52/ 8,1 | 52/ 8,1 | 52/ 8,1 | 53/ 8,2 |
| 11,0 | 45/ 7,5 | 46/ 7,6 | 47/ 7,6 | 48/ 7,6 | 48/ 7,7 | 49/ 7,7 | 49/ 7,7 | 50/ 7,8 | 50/ 7,8 | 51/ 7,8 |
| 11,5 | 43/ 7,3 | 44/ 7,3 | 45/ 7,4 | 46/ 7,4 | 46/ 7,5 | 47/ 7,5 | 47/ 7,5 | 48/ 7,6 | 48/ 7,6 | 49/ 7,6 |
| 12,0 | 41/ 7,1 | 42/ 7,1 | 43/ 7,2 | 44/ 7,2 | 44/ 7,3 | 45/ 7,3 | 45/ 7,4 | 46/ 7,4 | 47/ 7,4 | 48/ 7,5 |
| 12,5 | 39/ 6,8 | 40/ 6,8 | 41/ 6,9 | 42/ 7,0 | 42/ 7,1 | 43/ 7,1 | 43/ 7,2 | 44/ 7,2 | 45/ 7,2 | 46/ 7,3 |
| 13,0 | 38/ 6,5 | 39/ 6,6 | 39/ 6,7 | 40/ 6,8 | 41/ 6,9 | 42/ 7,0 | 42/ 7,0 | 43/ 7,1 | 43/ 7,1 | 44/ 7,2 |
| 13,5 | 36/ 6,2 | 37/ 6,3 | 37/ 6,4 | 38/ 6,5 | 39/ 6,6 | 40/ 6,6 | 40/ 6,7 | 41/ 6,8 | 41/ 6,8 | 42/ 6,9 |
| 14,0 | 34/ 6,0 | 35/ 6,1 | 36/ 6,2 | 37/ 6,3 | 37/ 6,4 | 38/ 6,4 | 39/ 6,5 | 40/ 6,5 | 40/ 6,5 | 41/ 6,6 |
| 14,5 | 32/ 5,7 | 33/ 5,8 | 34/ 5,9 | 35/ 6,0 | 35/ 6,1 | 36/ 6,1 | 37/ 6,2 | 38/ 6,3 | 38/ 6,4 | 39/ 6,4 |
| 15,0 | 31/ 5,5 | 32/ 5,6 | 32/ 5,7 | 33/ 5,8 | 34/ 5,8 | 35/ 5,9 | 35/ 6,0 | 36/ 6,1 | 37/ 6,2 | 38/ 6,2 |
| 16 | 27/ 5,0 | 29/ 5,1 | 30/ 5,2 | 30/ 5,3 | 31/ 5,3 | 32/ 5,4 | 32/ 5,5 | 33/ 5,6 | 34/ 5,7 | 35/ 5,7 |
| 17 | 24/ 4,5 | 25/ 4,6 | 26/ 4,7 | 27/ 4,8 | 28/ 4,9 | 29/ 5,0 | 30/ 5,1 | 31/ 5,2 | 31/ 5,3 | 32/ 5,3 |
| 18 | 21/ 4,2 | 22/ 4,3 | 23/ 4,4 | 24/ 4,5 | 25/ 4,6 | 26/ 4,7 | 27/ 4,8 | 28/ 4,9 | 28/ 5,0 | 29/ 5,0 |
| 19 | 17/ 3,6 | 19/ 3,8 | 20/ 4,0 | 21/ 4,1 | 22/ 4,2 | 23/ 4,3 | 24/ 4,4 | 25/ 4,5 | 26/ 4,6 | 27/ 4,7 |
| 20 | 15/ 3,2 | 16/ 3,4 | 17/ 3,6 | 18/ 3,7 | 19/ 3,8 | 20/ 3,9 | 21/ 4,0 | 22/ 4,1 | 23/ 4,2 | 24/ 4,3 |
| 21 | 12/ 2,7 | 14/ 2,9 | 15/ 3,1 | 16/ 3,3 | 17/ 3,4 | 18/ 3,5 | 19/ 3,6 | 20/ 3,7 | 21/ 3,8 | 22/ 3,9 |
| 22 | 9/ 2,2 | 11/ 2,4 | 12/ 2,6 | 13/ 2,8 | 14/ 2,9 | 15/ 3,1 | 16/ 3,3 | 17/ 3,4 | 18/ 3,5 | 19/ 3,6 |
| 23 | 6/ 1,6 | 8/ 1,9 | 9/ 2,1 | 11/ 2,3 | 12/ 2,4 | 13/ 2,6 | 14/ 2,7 | 15/ 2,9 | 16/ 3,1 | 17/ 3,2 |
| 24 | | | | | 9/ 2,0 | 10/ 2,2 | 11/ 2,4 | 12/ 2,6 | 13/ 2,8 | 15/ 2,9 |
| 25 | | | | | 7/ 1,5 | 8/ 1,8 | 9/ 2,0 | 10/ 2,2 | 11/ 2,4 | 13/ 2,5 |

## DRY BULB TEMPERATURE °C

PSYCOMETRIC DIFFERENCE °C

| | 51 | 52 | 53 | 54 | 55 | 56 | 57 | 58 | 59 | 60 |
|---|---|---|---|---|---|---|---|---|---|---|
| 0,5 | 97/23,9 | 97/23,9 | 97/23,8 | 97/23,8 | 97/23,7 | 97/23,7 | 97/23,6 | 97/23,6 | 96/23,5 | 98/23,5 |
| 1,0 | 95/21,7 | 95/21,6 | 95/21,6 | 95/21,6 | 95/21,5 | 95/21,5 | 95/21,4 | 95/21,4 | 95/21,3 | 95/21,2 |
| 1,5 | 92/19,8 | 92/19,8 | 92/19,8 | 92/19,8 | 92/19,8 | 92/19,8 | 92/19,8 | 92/19,8 | 92/19,8 | 93/19,8 |
| 2,0 | 90/18,0 | 90/18,0 | 90/17,9 | 90/17,9 | 90/17,8 | 90/17,8 | 90/17,8 | 90/17,7 | 90/17,7 | 91/17,6 |
| 2,5 | 87/16,8 | 87/16,8 | 87/16,8 | 87/16,8 | 87/16,7 | 87/16,7 | 87/16,7 | 88/16,6 | 88/16,6 | 88/16,5 |
| 3,0 | 85/15,7 | 85/15,7 | 85/15,7 | 85/15,6 | 85/15,6 | 85/15,6 | 85/15,6 | 86/15,5 | 86/15,5 | 86/15,5 |
| 3,5 | 82/14,9 | 82/14,9 | 82/14,8 | 83/14,8 | 83/14,7 | 83/14,7 | 83/14,7 | 83/14,6 | 83/14,6 | 84/14,6 |
| 4,0 | 80/14,1 | 80/14,1 | 80/14,0 | 80/14,0 | 81/13,9 | 81/13,9 | 81/13,9 | 81/13,8 | 81/13,9 | 82/13,7 |
| 4,5 | 77/13,4 | 78/13,4 | 78/13,3 | 78/13,3 | 78/13,3 | 79/13,2 | 79/13,2 | 79/13,2 | 79/13,1 | 80/13,1 |
| 5,0 | 75/12,8 | 76/12,8 | 76/12,7 | 76/12,7 | 76/12,7 | 77/12,6 | 77/12,6 | 77/12,6 | 77/12,5 | 78/12,5 |
| 5,5 | 73/12,3 | 73/12,3 | 73/12,0 | 74/12,0 | 74/12,0 | 75/12,0 | 75/12,0 | 75/12,0 | 75/12,0 | 76/12,0 |
| 6,0 | 71/11,8 | 71/11,8 | 71/11,8 | 72/11,8 | 72/11,8 | 73/11,8 | 73/11,7 | 73/11,7 | 73/11,7 | 74/11,7 |
| 6,5 | 69/11,4 | 69/11,4 | 69/11,3 | 70/11,3 | 70/11,3 | 71/11,3 | 71/11,3 | 71/11,2 | 71/11,2 | 72/11,2 |
| 7,0 | 67/10,9 | 67/10,9 | 67/10,9 | 68/10,9 | 69/10,9 | 69/10,8 | 60/10,8 | 69/10,8 | 69/10,8 | 70/10,8 |
| 7,5 | 64/10,4 | 65/10,4 | 65/10,4 | 66/10,4 | 66/10,4 | 67/10,4 | 67/10,4 | 67/10,4 | 67/10,4 | 68/10,3 |
| 8,0 | 62/ 9,9 | 63/10,0 | 63/10,0 | 64/10,0 | 64/10,0 | 65/10,0 | 65/10,0 | 65/10,0 | 65/10,0 | 66/ 9,9 |
| 8,5 | 60/ 9,6 | 61/ 9,7 | 61/ 9,7 | 62/ 9,7 | 62/ 9,7 | 63/ 9,7 | 63/ 9,7 | 63/ 9,7 | 63/ 9,7 | 64/ 9,7 |
| 9,0 | 59/ 9,4 | 59/ 9,4 | 59/ 9,4 | 60/ 9,4 | 60/ 9,4 | 61/ 9,4 | 61/ 9,4 | 62/ 9,4 | 62/ 9,4 | 62/ 9,3 |
| 9,5 | 57/ 9,0 | 57/ 9,1 | 57/ 9,1 | 58/ 9,1 | 58/ 9,1 | 59/ 9,1 | 59/ 9,1 | 60/ 9,1 | 60/ 9,1 | 60/ 9,0 |
| 10,0 | 55/ 8,7 | 56/ 8,8 | 56/ 8,8 | 57/ 8,8 | 57/ 8,8 | 57/ 8,8 | 57/ 8,8 | 58/ 8,8 | 58/ 8,8 | 59/ 8,8 |
| 10,5 | 53/ 8,3 | 54/ 8,3 | 54/ 8,3 | 55/ 8,3 | 55/ 8,4 | 55/ 8,4 | 55/ 8,4 | 56/ 8,4 | 56/ 8,4 | 57/ 8,4 |
| 11,0 | 51/ 7,9 | 52/ 7,9 | 52/ 7,9 | 53/ 8,0 | 53/ 8,0 | 54/ 8,0 | 54/ 8,1 | 55/ 8,1 | 55/ 8,1 | 56/ 8,1 |
| 11,5 | 49/ 7,7 | 50/ 7,7 | 50/ 7,7 | 51/ 7,8 | 51/ 7,8 | 52/ 7,8 | 52/ 7,8 | 53/ 7,9 | 53/ 7,9 | 54/ 7,9 |
| 12,0 | 48/ 7,5 | 49/ 7,5 | 49/ 7,5 | 50/ 7,6 | 50/ 7,6 | 51/ 7,6 | 51/ 7,6 | 51/ 7,7 | 51/ 7,7 | 52/ 7,7 |
| 12,5 | 46/ 7,3 | 47/ 7,3 | 47/ 7,3 | 48/ 7,4 | 48/ 7,4 | 49/ 7,4 | 49/ 7,4 | 48/ 7,4 | 49/ 7,4 | 50/ 7,4 |
| 13,0 | 45/ 7,2 | 46/ 7,2 | 47/ 7,2 | 47/ 7,2 | 47/ 7,2 | 48/ 7,2 | 48/ 7,2 | 48/ 7,2 | 48/ 7,2 | 49/ 7,2 |
| 13,5 | 43/ 6,9 | 44/ 6,9 | 44/ 6,9 | 45/ 6,9 | 45/ 6,9 | 46/ 6,9 | 46/ 6,9 | 48/ 6,9 | 46/ 6,9 | 47/ 6,9 |
| 14,0 | 41/ 6,6 | 42/ 6,6 | 42/ 6,7 | 43/ 6,7 | 43/ 6,7 | 44/ 6,7 | 44/ 6,7 | 45/ 6,7 | 45/ 6,7 | 46/ 6,8 |
| 14,5 | 39/ 6,4 | 40/ 6,4 | 40/ 6,5 | 41/ 6,5 | 41/ 6,5 | 42/ 6,5 | 42/ 6,5 | 43/ 6,5 | 43/ 6,5 | 44/ 6,6 |
| 15,0 | 38/ 6,2 | 38/ 6,2 | 39/ 6,3 | 40/ 6,3 | 40/ 6,3 | 40/ 6,3 | 41/ 6,3 | 41/ 6,4 | 42/ 6,4 | 43/ 6,4 |
| 16,0 | 35/ 5,7 | 36/ 5,8 | 36/ 5,8 | 37/ 5,9 | 38/ 5,9 | 39/ 5,9 | 39/ 6,0 | 40/ 6,0 | 40/ 6,0 | 41/ 6,1 |
| 17,0 | 32/ 5,4 | 33/ 5,4 | 34/ 5,4 | 35/ 5,5 | 35/ 5,5 | 36/ 5,5 | 36/ 5,6 | 37/ 5,6 | 37/ 5,6 | 38/ 5,7 |
| 18,0 | 30/ 5,1 | 31/ 5,1 | 31/ 5,1 | 32/ 5,2 | 32/ 5,2 | 33/ 5,2 | 33/ 5,3 | 34/ 5,3 | 35/ 5,3 | 36/ 5,4 |
| 19,0 | 27/ 4,7 | 28/ 4,8 | 28/ 4,8 | 29/ 4,8 | 30/ 4,9 | 31/ 4,9 | 31/ 5,0 | 32/ 5,0 | 32/ 5,0 | 33/ 5,1 |
| 20,0 | 24/ 4,3 | 25/ 4,4 | 26/ 4,4 | 27/ 4,5 | 27/ 4,5 | 28/ 4,6 | 28/ 4,6 | 29/ 4,7 | 30/ 4,7 | 31/ 4,8 |
| 21,0 | 22/ 3,9 | 23/ 4,0 | 24/ 4,1 | 25/ 4,1 | 25/ 4,2 | 26/ 4,2 | 26/ 4,3 | 27/ 4,3 | 27/ 4,4 | 28/ 4,4 |
| 22,0 | 20/ 3,7 | 21/ 3,8 | 21/ 3,8 | 22/ 3,9 | 23/ 3,9 | 24/ 4,0 | 24/ 4,0 | 25/ 4,1 | 25/ 4,1 | 26/ 4,2 |
| 23,0 | 17/ 3,3 | 18/ 3,4 | 19/ 3,5 | 20/ 3,6 | 20/ 3,6 | 21/ 3,7 | 22/ 3,7 | 23/ 3,8 | 23/ 3,8 | 24/ 3,9 |
| 24,0 | 15/ 3,0 | 16/ 3,1 | 17/ 3,2 | 18/ 3,3 | 18/ 3,3 | 19/ 3,4 | 20/ 3,5 | 21/ 3,5 | 21/ 3,6 | 22/ 3,7 |
| 25,0 | 13/ 2,6 | 14/ 2,7 | 15/ 2,8 | 16/ 2,9 | 16/ 2,9 | 17/ 3,0 | 18/ 3,1 | 19/ 3,2 | 19/ 3,3 | 20/ 3,4 |

## DRY BULB TEMPERATURE °C

PSYCOMETRIC DIFFERENCE °C

| | 61 | 62 | 63 | 64 | 65 | 66 | 67 | 68 | 69 | 70 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1,0 | 95/21,0 | 95/20,9 | 95/20,7 | 95/20,6 | 95/20,4 | 95/20,2 | 96/20,8 | 96/20,7 | 96/20,6 | 96/20,4 |
| 1,5 | 93/19,2 | 93/19,1 | 93/19,0 | 93/18,9 | 93/18,8 | 93/18,6 | 93/18,4 | 93/18,3 | 93/18,1 | 93/18,0 |
| 2,0 | 91/17,8 | 91/17,6 | 91/17,5 | 91/17,4 | 91/17,3 | 91/17,2 | 91/17,1 | 91/17,0 | 91/16,9 | 91/16,8 |
| 2,5 | 88/16,2 | 88/16,1 | 88/16,0 | 89/16,4 | 89/16,3 | 89/16,2 | 89/16,1 | 89/16,0 | 89/15,9 | 89/15,8 |
| 3,0 | 86/15,4 | 86/15,2 | 86/15,1 | 87/15,4 | 87/15,3 | 87/15,2 | 87/15,1 | 87/15,0 | 87/14,9 | 87/14,8 |
| 3,5 | 84/14,7 | 84/14,6 | 84/14,5 | 84/14,6 | 85/14,6 | 85/14,5 | 85/14,4 | 85/14,3 | 85/14,2 | 85/14,1 |
| 4,0 | 82/14,0 | 82/13,8 | 82/13,7 | 82/13,6 | 82/13,6 | 83/13,7 | 83/13,7 | 83/13,6 | 83/13,5 | 83/13,4 |
| 4,5 | 80/13,4 | 80/13,3 | 80/13,2 | 80/13,0 | 80/13,0 | 81/13,1 | 81/13,1 | 81/13,0 | 81/12,9 | 81/12,8 |
| 5,0 | 78/12,7 | 78/12,6 | 78/12,6 | 78/12,5 | 79/12,6 | 79/12,6 | 79/12,5 | 79/12,4 | 79/12,3 | 79/12,2 |
| 5,5 | 76/12,1 | 76/12,0 | 76/11,9 | 76/11,8 | 77/12,0 | 77/12,0 | 77/11,9 | 77/11,8 | 77/11,7 | 77/11,6 |
| 6,0 | 74/11,7 | 74/11,6 | 74/11,5 | 75/11,6 | 75/11,5 | 75/11,5 | 75/11,4 | 76/11,5 | 76/11,4 | 76/11,3 |
| 6,5 | 72/11,2 | 72/11,1 | 73/11,2 | 73/11,2 | 73/11,0 | 73/11,0 | 73/10,9 | 73/10,9 | 74/11,0 | 74/10,9 |
| 7,0 | 70/10,8 | 70/10,7 | 71/10,8 | 71/10,7 | 71/10,6 | 71/10,6 | 71/10,4 | 72/10,6 | 72/10,5 | 72/10,4 |
| 7,5 | 68/10,4 | 68/10,3 | 69/10,4 | 69/10,3 | 69/10,2 | 69/10,2 | 70/10,2 | 70/10,2 | 70/10,1 | 71/10,1 |
| 8,0 | 66/10,0 | 67/10,0 | 67/10,0 | 67/ 9,9 | 67/ 9,8 | 68/ 9,9 | 68/ 9,9 | 68/ 9,8 | 69/ 9,9 | 69/ 9,8 |
| 8,5 | 65/ 9,8 | 65/ 9,7 | 65/ 9,6 | 65/ 9,5 | 66/ 9,6 | 66/ 9,6 | 66/ 9,4 | 67/ 9,5 | 67/ 9,5 | 67/ 9,4 |
| 9,0 | 63/ 9,4 | 63/ 9,3 | 64/ 9,4 | 64/ 9,3 | 64/ 9,3 | 64/ 9,2 | 65/ 9,2 | 65/ 9,2 | 65/ 9,2 | 65/ 9,1 |
| 9,5 | 61/ 9,0 | 61/ 9,0 | 62/ 9,0 | 62/ 9,0 | 63/ 8,9 | 63/ 9,0 | 63/ 8,9 | 63/ 8,9 | 63/ 8,8 | 64/ 8,8 |
| 10,0 | 59/ 8,8 | 60/ 8,8 | 60/ 8,8 | 60/ 8,7 | 61/ 8,7 | 61/ 8,7 | 62/ 8,7 | 62/ 8,6 | 62/ 8,5 | 62/ 8,4 |
| 10,5 | 58/ 8,6 | 58/ 8,5 | 58/ 8,5 | 59/ 8,5 | 59/ 8,5 | 59/ 8,5 | 60/ 8,5 | 60/ 8,4 | 60/ 8,4 | 60/ 8,3 |
| 11,0 | 56/ 8,3 | 57/ 8,3 | 57/ 8,3 | 57/ 8,3 | 58/ 8,3 | 58/ 8,3 | 58/ 8,2 | 58/ 8,1 | 59/ 8,2 | 59/ 8,2 |
| 11,5 | 54/ 8,0 | 54/ 8,0 | 55/ 8,1 | 55/ 8,0 | 56/ 8,1 | 57/ 8,1 | 57/ 8,1 | 57/ 8,0 | 57/ 8,0 | 57/ 7,9 |
| 12,0 | 53/ 7,8 | 53/ 7,8 | 54/ 7,8 | 54/ 7,8 | 55/ 7,9 | 55/ 7,9 | 55/ 7,8 | 56/ 7,8 | 56/ 7,8 | 56/ 7,7 |
| 12,5 | 51/ 7,6 | 52/ 7,6 | 52/ 7,5 | 53/ 7,6 | 53/ 7,6 | 53/ 7,6 | 54/ 7,6 | 54/ 7,5 | 55/ 7,6 | 55/ 7,5 |
| 13,0 | 50/ 7,4 | 50/ 7,3 | 51/ 7,3 | 51/ 7,3 | 52/ 7,4 | 52/ 7,4 | 52/ 7,3 | 53/ 7,4 | 53/ 7,3 | 53/ 7,2 |
| 13,5 | 48/ 7,1 | 48/ 7,0 | 49/ 7,1 | 50/ 7,2 | 50/ 7,2 | 50/ 7,1 | 51/ 7,1 | 51/ 7,1 | 51/ 7,0 | 52/ 7,0 |
| 14,0 | 47/ 6,9 | 47/ 6,9 | 48/ 6,9 | 48/ 6,9 | 49/ 7,0 | 49/ 6,9 | 49/ 6,9 | 50/ 6,9 | 50/ 6,9 | 50/ 6,8 |
| 14,5 | 46/ 6,7 | 46/ 6,7 | 47/ 6,7 | 47/ 6,7 | 48/ 6,7 | 48/ 6,7 | 49/ 6,8 | 49/ 6,7 | 49/ 6,7 | 49/ 6,6 |
| 15,0 | 44/ 6,5 | 45/ 6,6 | 45/ 6,5 | 45/ 6,5 | 46/ 6,5 | 46/ 6,5 | 46/ 6,4 | 47/ 6,5 | 47/ 6,5 | 48/ 6,5 |
| 16,0 | 41/ 6,1 | 42/ 6,2 | 42/ 6,2 | 43/ 6,2 | 43/ 6,2 | 44/ 6,3 | 44/ 6,2 | 44/ 6,2 | 45/ 6,2 | 45/ 6,2 |
| 17,0 | 38/ 5,8 | 39/ 5,8 | 40/ 5,8 | 40/ 5,8 | 41/ 5,9 | 41/ 5,9 | 41/ 5,8 | 42/ 5,9 | 42/ 5,8 | 43/ 5,9 |
| 18,0 | 36/ 5,5 | 37/ 5,5 | 37/ 5,5 | 38/ 5,6 | 38/ 5,5 | 39/ 5,6 | 39/ 5,6 | 40/ 5,6 | 40/ 5,6 | 41/ 5,6 |
| 19,0 | 34/ 5,1 | 34/ 5,1 | 35/ 5,2 | 35/ 5,2 | 36/ 5,2 | 36/ 5,2 | 37/ 5,3 | 37/ 5,2 | 38/ 5,3 | 38/ 5,2 |
| 20,0 | 31/ 4,8 | 32/ 4,8 | 32/ 4,8 | 33/ 4,9 | 34/ 5,0 | 34/ 4,9 | 34/ 4,9 | 35/ 4,9 | 35/ 4,9 | 36/ 4,9 |
| 21,0 | 29/ 4,5 | 30/ 4,5 | 30/ 4,5 | 41/ 4,6 | 41/ 4,6 | 32/ 4,6 | 32/ 4,6 | 33/ 4,7 | 33/ 4,6 | 34/ 4,7 |
| 22,0 | 27/ 4,2 | 28/ 4,3 | 28/ 4,2 | 29/ 4,3 | 29/ 4,3 | 30/ 4,4 | 31/ 4,4 | 31/ 4,4 | 32/ 4,5 | 32/ 4,4 |
| 23,0 | 25/ 4,0 | 25/ 4,0 | 26/ 4,0 | 26/ 4,0 | 27/ 4,1 | 27/ 4,0 | 28/ 4,1 | 28/ 4,1 | 29/ 4,2 | 29/ 4,1 |
| 24,0 | 23/ 3,7 | 24/ 3,8 | 24/ 3,8 | 25/ 3,8 | 25/ 3,8 | 26/ 3,9 | 26/ 3,9 | 27/ 3,9 | 27/ 3,9 | 28/ 4,0 |
| 25,0 | 21/ 3,4 | 22/ 3,5 | 22/ 3,5 | 23/ 3,6 | 23/ 3,6 | 24/ 3,7 | 24/ 3,6 | 25/ 3,7 | 25/ 3,6 | 26/ 3,7 |

## DRY BULB TEMPERATURE °C

PSYCROMETRIC DIFFERENCE °C

| | 70 | 75 | 80 | 85 | 90 | 95 | 100 |
|---|---|---|---|---|---|---|---|
| 1 | 96/20,5 | 96/20,0 | 96/19,6 | 96/19,2 | 96/18,7 | 96/18,3 | 96/17,9 |
| 2 | 91/17,0 | 92/16,7 | 92/16,4 | 92/16,1 | 93/15,8 | 93/15,5 | 93/15,1 |
| 3 | 87/14,8 | 88/14,6 | 88/14,3 | 89/14,1 | 89/13,8 | 89/13,6 | 89/13,4 |
| 4 | 83/13,3 | 84/13,1 | 85/12,8 | 85/12,7 | 86/12,5 | 86/12,3 | 86/12,1 |
| 5 | 79/12,1 | 80/11,9 | 81/11,7 | 82/11,6 | 82/11,4 | 82/11,2 | 83/11,0 |
| 6 | 76/11,1 | 77/11,0 | 78/10,8 | 78/10,7 | 79/10,5 | 79/10,3 | 80/10,1 |
| 7 | 72/10,3 | 73/10,2 | 74/10,0 | 75/ 9,8 | 76/ 9,6 | 76/ 9,5 | 77/ 9,3 |
| 8 | 69/ 9,7 | 70/ 9,5 | 71/ 9,3 | 72/ 9,2 | 73/ 9,0 | 73/ 8,9 | 74/ 8,7 |
| 9 | 65/ 9,1 | 67/ 8,9 | 68/ 8,7 | 69/ 8,6 | 70/ 8,4 | 70/ 8,3 | 71/ 8,1 |
| 10 | 62/ 8,5 | 64/ 8,4 | 65/ 8,2 | 66/ 8,1 | 67/ 7,9 | 67/ 7,8 | 68/ 7,6 |
| 11 | 59/ 8,0 | 61/ 7,9 | 62/ 7,8 | 63/ 7,6 | 64/ 7,4 | 65/ 7,3 | 66/ 7,1 |
| 12 | 56/ 7,5 | 58/ 7,4 | 59/ 7,3 | 61/ 7,2 | 62/ 7,0 | 62/ 6,9 | 63/ 6,7 |
| 13 | 53/ 7,1 | 55/ 7,1 | 56/ 7,0 | 58/ 6,9 | 59/ 6,7 | 60/ 6,6 | 61/ 6,4 |
| 14 | 50/ 6,8 | 52/ 6,8 | 54/ 6,7 | 55/ 6,6 | 57/ 6,4 | 58/ 6,2 | 59/ 6,0 |
| 15 | 48/ 6,4 | 50/ 6,4 | 51/ 6,3 | 53/ 6,2 | 54/ 6,0 | 55/ 5,9 | 56/ 5,7 |
| 16 | 45/ 6,1 | 47/ 6,1 | 49/ 5,9 | 51/ 5,8 | 52/ 5,7 | 53/ 5,6 | 54/ 5,4 |
| 17 | 43/ 5,7 | 45/ 5,7 | 46/ 5,6 | 48/ [illegible] | 49/ 5,4 | 50/ 5,3 | 51/ 5,2 |
| 18 | 40/ 5,4 | 43/ 5,4 | 44/ 5,4 | 46/ 5,3 | 47/ 5,2 | 48/ 5,1 | 49/ 5,0 |
| 19 | 38/ 5,2 | 40/ 5,2 | 42/ 5,2 | 44/ 5,1 | 45/ 5,0 | 46/ 4,9 | 47/ 4,8 |
| 20 | 36/ 4,9 | 38/ 4,9 | 40/ 4,9 | 42/ 4,9 | 43/ 4,8 | 44/ 4,7 | 45/ 4,6 |
| 21 | 34/ 4,6 | 36/ 4,6 | 38/ 4,7 | 40/ 4,6 | 41/ 4,5 | 42/ 4,5 | 43/ 4,4 |
| 22 | 32/ 4,4 | 34/ 4,4 | 36/ 4,4 | 38/ 4,4 | 39/ 4,3 | 40/ 4,3 | 41/ 4,2 |
| 23 | 30/ 4,1 | 32/ 4,1 | 34/ 4,2 | 36/ 4,2 | 37/ 4,2 | 38/ 4,2 | 39/ 4,2 |
| 24 | 28/ 3,9 | 30/ 3,9 | 32/ 4,0 | 34/ 4,0 | 36/ 4,0 | 37/ 4,0 | 38/ 4,0 |
| 25 | 26/ 3,7 | 29/ 3,7 | 30/ 3,8 | 32/ 3,8 | 34/ 3,8 | 35/ 3,8 | 36/ 3,8 |

# Appendix 5- Figures

Pictures are made by author.