

Heat Treatment Technologies in Europe: Scientific Background and Technological State-of-Art

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In: Proceedings of Conference on "Enhancing the durability of lumber and engineered wood products" February 11-13, 2002, Kissimmee, Orlando. Forest Products Society, Madison, US.

Abstract

Recent efforts on thermal treatment of wood lead to the development of several processes introduced to the European market during the last few years. The total production capacity of heat treated wood in 2001 is estimated as approx. 165.000 m³. In the paper the different heat processes are presented. The general technology as well as scientific data on the chemical transformation of the cell wall polymers, on the biological performance, on the physical and mechanical properties of the treated wood are presented and discussed.

INTRODUCTION

It is known since longer that different intrinsic wood properties are changed due to treatment at elevated temperatures (Stamm et al. 1946, Burmester 1973, Giebeler 1983). However, only recently in Europe several attempts were made to develop industrial applicable technology to thermally modify wood. Developments took place in the Netherlands (de Ruyter 1989, Boonstra et al. 1998, Tjeerdsma et al. 1998b, Militz and Tjeerdsma 2000), France (Dirol and Guyonnet 1993, Vernois 2000), Germany (Sailer and Rapp 2000, Rapp et al. 2000) and Finland (Viitanen et al. 1994, Syrjänen et al. 2000, Jämsä and Viitaniemi 1998).

Some of those techniques are in the meanwhile turned to industrial processes with a total production of heat treated timber in year 2001 of approx. 165.000 m³. The following paper gives an overview of the existing processes and the material properties gained. Furthermore, the production capacity of heat treated timber is estimated and possible products from heat treated timber are looked at.¹

2. HEAT TREATMENT PROCESSES

All the European heat processes have in common the treatment of sawn wood at elevated temperatures in the range between 160 °C and 260 °C. The main differences between the processes are to be seen in the process conditions (process steps, oxygen or nitrogen, steaming, wet or dry process, use of oils, steering schedules etc.) and published in several patents (e.g. EP0018446, 1982; EP0612595, 1994; EP0623433, 1994; EP0622163, 1994; EP0759137, 1995; US5678324, 1997, EP 89-2031709).

The main characteristics of the processes are²:

Plato-Process (PLATO BV, The Netherlands)

¹ The information on process technology and production capacity is given by the treatment companies and could not be verified by the author

² information distributed at conference on Heat Treatment Processes organised by NTI, Nordic Wood and SP in Helsinki, Stockholm and Oslo, November 2000

The PLATO-process uses different steps of treatment and combines successively a hydrothermolysis step with a dry curing step. The impact of the hydrothermolysis in the PLATO-treatment results in the occurrence of different chemical transformations. One aim of this 2-step process is the use of the presence of abundant moisture in the woody cell wall during the hydrothermolysis. This provokes an increased reactivity of the cell wall components under relatively low temperature. In order to reach a selective degree of depolymerisation of the hemicellulose during the hydrothermolysis, relative mild conditions can be applied to limit unwanted side reactions (Tjeerdsma et al 1998b).

The PLATO-process (Ruyter 1989, Boonstra et al. 1998) principally consists of two stages with an intermediate drying operation. In the first step (hydrothermolysis) of the process, green or air dried wood, is treated at temperatures typically between 160 °C - 190 °C under increased pressure (superatmospheric pressure). A conventional wood drying process is used to dry the treated wood to a low moisture content (ca. 10%). In the second step (curing) the dry intermediate product is heated again to temperatures between 170 °C - 190 °C.

The process time is depending on the wood species used, the thickness, shape of wood etc., and uses a thermolysis step (4-5 hours) followed by an intermediate drying step (3-5 days) and a final curing step (14-16 hours). In some cases, a conditioning step (2-3 days) is needed. Depending on wood species and thickness of the material, these times can be shorter as well. The heating medium can be steam or heated air.

Retification process (NOW New Option Wood, France)

The process starts with relatively dry wood (approx. 12 %) and heats up the material up to 200 °C – 240 °C in a nitrogen atmosphere (below 2 % oxygen). There are different production sites in France (Duchez 2002).

Bois perdure (BCI-MBS, France)

The process starts with fresh wood, subsequently a fast drying process and heating up to 200 °C – 240 °C under steam atmosphere.

OHT – Process (oil-heat treatment, Menz Holz, Germany)³

The process is performed in a closed process vessel. After loading the process vessel with wood, hot oil is pumped from the stock vessel into the process vessel where the hot oil is kept at high temperatures circulating around the wood. Before unloading the process vessel the hot oil is pumped back into the stock vessel.

For different degrees of upgrading, different temperatures are used. To obtain a maximum durability and a minimum oil consumption the process is operated at 220°C. However, to obtain a maximum durability at acceptable strength reductions, temperatures between 180°C and 200°C are used. It proved to be necessary to keep the desired process temperature (for example 220°C) for 2-4 hours in the middle of the wooden pieces to be treated. Additional time for heating up and cooling down is necessary, depending on the dimension of the wood. Typical process duration for a whole treatment cycle (including heating up and cooling down) for logs with a cross section of 100 mm x 100 mm and length of 4 meters is 18 hours.

The heating medium is crude vegetable oil. The oil serves for a fast and equal transfer of heat to the wood, providing the same heat conditions all over the vessel and furthermore to limit

³ the information on OHT-process is given by Rapp and Sailer 2000

the oxygen in the vessel. Linseed oil proved to be a good medium though the smell that develops during the heat treatment may be a drawback. The smoke point and the tendency to polymerisation are also important for the drying of the oil in the wood and for the stability of the respective oil batch. The ability of the oil to withstand heating to a minimum temperature of 230°C is a prerequisite. The consistency and colour of the oil changes during heat treatment. The oil becomes thicker because volatile components evaporate, the products arising from decomposition of the wood accumulate in the oil and change its composition. This leads to improved setting of the oils.

Thermo Wood process (Stora, Finforest, Finland)⁴

Since the 1990th comprehensive research on heat treatment had led to commercialised processes in Finland. An industrial scale wood heat treatment process, under trade name of ThermoWood, has been developed at the Finnish Research Center VTT together with the Finnish industry. Today the process is licensed to the members of the Finnish ThermoWood Association. The ThermoWood process can be divided into three main phases:

- **Phase 1.** Temperature increase and high temperature kilning. The kiln temperature is raised at a rapid speed using heat and steam to a level of around 100°C. Thereafter the temperature is increased steadily to 130°C during which time the high temperature drying takes place and the moisture content in the wood reduces to nearly zero.
- **Phase 2.** Intensive heat treatment. Once the high temperature kiln drying has taken place the temperature inside the kiln is increased to a level between 185°C and 230°C, once the target level has been reached the temperature remains constant for 2-3 hours depending on the end-use application.
- **Phase 3.** Cooling and moisture conditioning. The final stage is to lower the temperature down using water spray systems and then once the temperature has reached 80-90°C re-moisturising and conditioning takes place to bring the wood moisture content to a useable level over 4%. When raising or decreasing the temperature a special adjustment system is used in order to prevent surface and inside cracking. The wood's inside temperature regulates the temperature rise in the kiln. The difference between kiln and wood temperature is dependent on the dimensions of the wood specimens.

Raw material can be green or kiln dried wood. If the process starts from green wood the wood can be dried in a very fast steam drying process. Fast drying is possible because we do not have to care for the colour changes and because resins will anyway flow from the wood in heat treatment process. The method is suitable for soft- and hardwoods. The process must be optimised for each wood species.

3. CHEMICAL TRANSFORMATION PROCESSES

Intensive research in Finland (Kotilainen 2000) and the Netherlands (Tjeerdsma et al. 1998a, 1999) proved different chemical transformation processes to occur during the treatment at elevated temperatures.

Kotilainen (2000) studied changes in the chemical composition of different softwood and hardwood species, heated to temperatures between 150 °C and 260 °C for several hours under steam, air and nitrogen atmosphere. He found, that the reaction conditions had a clear influence on the chemical decomposition of the wood. Hardwood species decomposed more

⁴ the information on ThermoWood process is given by Finforest (ThermoWood Handbook, Mayes and Oksanen 2002)

extensively than softwood species. The main volatile compounds, beside water, were carboxylic acids (formic acid, acetic acid), liberated from the hemicelluloses.

Tjeerdsma et al. (1998, 1999) investigated relatively mild treated PLATO-wood with solid phase CP-MAS ^{13}C -NMR to understand at molecular level the reasons for the improvements. All the occurrences described appear to be the consequence of reactions which are well known in wood chemistry. These are the formation of acetic acid liberated from the hemicelluloses, which further catalyses carbohydrates cleavage, causing a reduction of degree of polymerisation of the carbohydrates. Acid catalysed degradation results in the formation of formaldehyde, furfural and other aldehydes as well as some lignin cleavage at $\text{C}\alpha$ and O4 and believed to cause some aldehyde production from lignin units $\text{C}\gamma$, all occurring in the first reaction step. Lignin autocondensation through the cleaved, positively charged benzylic $\text{C}\alpha$ to form some methylene bridges presumably starts already to occur in this first phase. The increase in the number of free reactive sites on the aromatic ring of some lignin units already occurs in this phase but continues into the next.

In the second treatment step completion of the autocondensation of lignin is believed to occur through the formation of methylene bridges connecting aromatic rings. The aromatic nuclei sites are released by demethoxylation and through the cleaved, positively charged benzylic $\text{C}\alpha$. Reactions occur of some of the aldehyde groups formed in the first step phase with lignin aromatic nuclei sites to connect aromatic rings through methylene bridges. The extent of these reactions is mild, but nonetheless they lead to an increase in cross-linking with consequent improvement in its dimensional stability and decreased hygroscopicity of wood.

Wood specimen of Beech (*Fagus silvatica* L.) and Scots pine (*Pinus sylvestris* L.) modified by a hydrothermal treatment process were analysed by means of Fourier Transform Infra Red spectroscopy (FTIR). The chemical transformation of the cell wall material was studied and associated with improved wood qualities. The results were published by Tjeerdsma et al 1999. For this purpose FTIR spectroscopy was used since this technique has been found appropriate to determine the intensity of specific bonds and functional groups within the polymeric structure. Cleavage of acetyl groups of the hemicellulose has been found to occur in the first treatment step under moist conditions and elevated temperature. This results in the formation of carbonic acids, mainly acetic acid. Most of the acetyl groups were found to be cleaved during the treatment of wood at a high temperature, whereas only partial de-acetylation was found to occur at moderate treatment temperature. The concentration of accessible hydroxyl groups was measured by acetylation and found reduced after treating at high temperature. Esterification reactions were found to occur under dry conditions at elevated temperature in the curing step, indicated by the increase of the specific ester carbonyl peak at 1740 cm^{-1} in the FTIR spectrum. The formed esters turned out to be mainly linked to the lignin complex considering that the newly formed carbonyl groups were found present in heat-treated wood, yet were found to be absent in the isolated holocellulose. Esterification contributes to a decrease of hygroscopicity of wood and consequently improvements of its dimensional stability and durability. However the role of esterification in the decrease of hygroscopicity in the examined hydrothermal treatment process is believed to be minor compared to the influence of cross-linking reactions known to occur during thermal treatment of wood.

4. MATERIAL PROPERTIES

Several reports are given on the material properties of heat treated timber (Rapp and Sailer 2000, Vernois 2000, Syrjänen et al. 2000, Militz and Tjeerdsma 2000, Mayes and Oksanen

2002). In general, as it could be shown as well earlier by Stamm et al. (1946), Burmester (1973) and Giebler (1983), different wood properties as durability, sorption behaviour, shrinkage and swelling behaviour and strength properties are changed due to the heat treatment. The level of change is very much depending on the used wood species and the process conditions, in which the temperature and the absence of oxygen play a predominant role.

Resistance against fungi and insects

In general it can be stated for all heat treatment processes, that the durability of wood can be improved considerably, depending on the wood species and treatment conditions (see figures 1-2). For non-durable softwood species (class 4-5 species like Norway spruce *Picea abies*, Scots Pine *Pinus sylvestris* and Maritima Pine *Pinus maritima* sapwood) durability improvements can range from durability class 2-4, depending on the treatment temperature and process duration (Mayes and Oksanen 2002, Tjeerdsma et al. 1998, Rapp and Sailer 2000). Tjeerdsma et al. (1998) looked especially to the influence of moisture during the hydrothermal step of the PLATO-treatment of wood. The resistance against all of the studied types of fungi was improved considerably after the treatment. Especially the resistance against brown rot fungi was increased by the treatment. Also the resistance against white rotters and soft rotters was improved. The increase of the decay resistance was found dependent on the applied process conditions. In the research of Tjeerdsma et al. (1998) the effectiveness of the treatment was improved by applying a hydrothermal step before the dry heat-treatment step. The process conditions in the curing step appeared to have the largest effect on the resistance against soft rot and brown rot decay. White rot decay was less dependent on the curing conditions and found more affected by the hydrothermolysis, suggesting the decomposition of hemicellulose in the hydrothermolysis. The higher effect on brown rotters and soft rotters is partly assigned to the reduced hygroscopicity of the material. Further detailed information on the biological resistance of Plato wood is given in Tjeerdsma et al. (1998) and Tjeerdsma et al (2000).

For the OHT-process, Rapp and Sailer (2000) reported on the resistance of heat treated wood to *Coniophora puteana* with different oil loadings. After 19 weeks incubation, the untreated spruce controls showed 48% loss of mass and pine controls 40% loss of mass. The resistance of heat-treated spruce and pine to the brown rot fungus *C. puteana* was improved with increasing temperatures. Treatment of wood in hot air did not prevent an attack of *C. puteana*. An average mass loss of 11% was determined for Scots pine, 5.5 % for spruce. A noticeably lower loss of mass was determined for oil-heat treated specimens than for air-heat treated specimens. A loss of mass of less than 2% was found in the case of pine sapwood, when oil-heat treatment was applied at 200°C. With spruce, on the other hand, a decisive increase in resistance was only obtained at 220°C.

Mayes and Oksanen (2002) reported a higher resistance of heat treated timber against several fungi. Furthermore, in research performed at the University of Kuopio (Finland) and at the French institute CTBA a higher resistance against longhorn beetles, *Annobium punctatum* and *Lycetus brunneus* was found. However, preliminary trials with termites showed any improvement.

Rapp and Sailer (2000) furthermore reported, that marine tests with heat-treated wood and oil heat treated wood are currently running. Preliminary results after 1 year do indicate that both, heat-treated wood and oil heat treated wood are not resistant against marine borers.

Mechanical properties

For PLATO-treated wood, the bending strength of several wood species, non-treated and heat-treated, is shown in Figure 3. The figure shows that an average strength loss of 5 % to 18 % has been found for wood heat-treated at whole plank scale (40 mm x 150 mm x 2200 mm). Earlier studies on this subject showed in general a strength loss to approximately 50% or more (Seborg et al. 1953).

The results shown in the figure are based on wood samples free of defects and planks treated under mild conditions. During the process high tensions can occur in the wood since this treatment consists of three steps in which the wood is exposed to high temperatures and rapid evaporation of water. Some of the wood species were found difficult to treat and showed a number of defects (mainly cracks), if not treated carefully. Several softwood species are known to have a high resistance against liquid impregnation. These wood species were indeed found difficult to treat and showed a comparative higher strength loss. Altogether the strength was found to be dependent the applied process conditions and affected predominantly by the process temperature in combination with wood species.

The MOE and MOR of OHT-treated wood (Rapp and Sailer 2000) was determined in a three point bending test with medium force applied on 150x10x10 mm³ samples parallel to the grain. Tests of the impact bending strength were performed using a Louis Schopper pendulum impact machine and provide information on the dynamic properties of wood specimens. The highest MOE of more than 11,000 N/mm² were achieved at 200°C in the case of oil-heat treated specimens (Fig. 3). There was no reduction in the values for the MOE of untreated coniferous wood with either heat treatment process. The MOR of wood which was oil-heat-treated at 220°C was about 70% of the value of untreated controls.

As stated by other authors (Rapp and Sailer 2000, Militz and Tjeerdsma 2000, Mayes and Oksanen 2002) the impact bending strength is the most negatively affected strength property for all kinds of heat treatments. Under non optimum process conditions, the impact bending strength can be reduced to only ca. 50 % of its original values (see figure 4).

Hygroscopicity

The changed wood composition results in a lower hygroscopicity (see figure 5). Tjeerdsma et al. (1998) measured the hygroscopicity (expressed as the Equilibrium Moisture Content (EMC)). In this figure the adsorption and desorption curves of heat-treated and non-treated Scotch pine and Beech are given.

The strong impact of the heat-treatment on the hygroscopicity is illustrated in the figure by the sorption curves of the treated wood positioned substantial lower than the sorption curves of the non-treated wood. The absolute change in the hygroscopicity is most pronounced at higher relative humidities (R.H. > 70 %). The relative change in hygroscopicity of Scotch pine appeared independent of the climatic range and differs to untreated wood over the whole range ca. 40% of its original values. For Beech the change under dry climatic conditions is approximately 30 %, even improving to ca. 45 % under more humid conditions of 96 % R.H. The hysteresis effect between sorption and desorption was found to be unchanged by the heat-treatment of wood. From corresponding research it is known that the hygroscopicity of heat-treated wood can vary considerably with varying process time and temperature in the second step of the treatment (Tjeerdsma et al. 1998b).

In Figure 6 and table 1 the percentage of swell at different relative humidities is shown of non-treated and heat-treated Scotch pine. The figure corresponds with the hygroscopicity figures. It can clearly be seen that the swell has been reduced substantially by the heat-treatment. The swell reduction was found independent of the relative humidity. The swell (or shrinking) reduction ASE ranged up to approximately 50%. This was found to be near the maximum reachable ASE under the examined process conditions. In table 1 the average ASE values for several heat treated wood species are shown. The table illustrates that overall the ASE ranges from a minor to a substantial improvement of the dimensional stability of the wood by the treatment. In general the swell reduction in tangential direction in the wood was found to be higher compared to the reduction in radial direction. A decreased difference between the absolute swell in radial and tangential direction (anisotropy) possibly will result in less tensions in the wood when exposed to changeable climatically conditions.

Colour and smell

Due to the high temperatures in the processes, all the treated wood species get a characteristic brownish colour (comparable to the natural colour of *Thuja plicata* Western Red Cedar). Like shown by different authors, the colour is effected by the treatment temperature and the duration of the processes. The higher the temperature and the longer the duration the darker the colour gets. After treatment, the wood gets a very characteristic caramellish smell, which is believed to be related to the release of furfural. Emission measurements performed by VTT/Finland (Kotilainen 2000, Mayes and Oksanen 2002) showed furthermore, that the emission of terpenes, alpha-pinene, camphene and limonene from untreated pinewood is considerably higher than after heat treatment (1490 ug/m²h untreated pine to 240 ug/m²h after treatment at 230 °C). However, the emission of acetic acid was still relatively high (110 ug/m²h).

Paintability and coating performance

The resistance of heat treated timber against weathering (UV-light, wetting) is not changed largely when compared to untreated wood, making a surface treatment with oils or paints necessary. Due to its UV-degradability, opaque systems (water borne acrylic or solvent borne alkyds) are recommended above priming oils and low built stains (Mayes and Oksanen 2002). After several years of outside exposure, heat treated timber performs considerably better than non-treated wood. Most probably due to its higher dimensional stability, less flaking and cracking is reported on heat treated treated samples (Mayes and Oksanen 2002, Rapp et al. 2000, Tjeerdsma 2002).

Gluability

Different laboratories had carried out studies on the gluability of heat treated wood (Tjeerdsma 2002, Mayes and Oksanen 2002, Rapp et al. 2000). The glued wood was evaluated following different standards on its strength and moisture performance (DIN 68603, EN 392, EN 302). The studies showed, that in principal heat treated timber can be glued with many industrial glue types (PVAc polyvinyllic glues, PU polyurethane glues, EPI isocyanate glues, RF resorcinol-phenolic glues). Due to the lowered shear strength, a higher wood failure is reported with heat treated timber. Furthermore, the hydrophobic wood surface causes a slower penetration of the solvents from the glue to the surrounding wood, which makes it necessary to adapt the glue process.

5. ENVIRONMENTAL ASPECTS

During the process, energy is consumed, waste water is produced and gas emission can take place. These aspects must be taken into account when comparing to environmental aspects of

wood preservatives. Following the information given by Thermowood (Mayes and Oksanen 2002), the following aspects are taken into account:

Gas emissions from the process

It has been estimated that heat treatment of 1 m³ of spruce liberates a maximum of 100 - 150 g/m³ acetic acid and all together 20 - 40 kg/m³ different compounds. As the process causes evaporation of not only water, the resulting gases must be treated to avoid unnecessary environmental loading. This is normally accomplished by burning the gases with a special purpose-built burner either as part of the heat-production process or as a separate flare operating with some additional gaseous fuel. Some production units are using scrubbers to treat the gases.

Waste water from the process

The process produces condensate water that is partially acid (pH 3) due to the formic acid and acetic acid evaporated from wood. The water also contains part of the evaporated resin and other solid constituents of the wood material. The solid components of the waste water are separated in a special clarification basin and the rest is processed at waste water works.

Energy consumption

The kiln is heated either by the combination of steam and electricity or by hot-oil heating coils alone. The energy is produced from bark and wood waste or fuel oil. Additionally, pure steam is needed to provide the necessary atmosphere. Energy is needed mainly for drying, which accounts for 80 % of the heat energy used. The total energy demand is thus only 25 % higher than that of the ordinary timber drying process.

6. PRODUCTS AND PRODUCTION CAPACITY

In table 2 an overview is given on the existing production capacity of heat treated wood in different European countries. The total amount in 2001 is estimated as approx. 165.000 m³, with extra 100.000 m³ planned in the following few years.

The main characteristics of the heat treated wood are its improved durability and dimensional stability. Target markets are from this perspective uses indoor and outdoor, where these material qualities are wanted, such as:

- claddings
- windows/ doors
- garden products
- flooring
- specialty products (sauna, bathrooms etc.)

The durability of heat treated wood is depending on the process conditions and will range in durability classes II – IV, however will not be comparable to copper-chromium containing preservatives. The usage of heat treated wood in soil and water contact is therefor in many cases not advised.

The main drawback of heat treated wood, treated at higher treatment temperatures however is its reduced mechanical properties (bending strength, impact strength). Heat treated timber should therefore not be used in load bearing constructions or under circumstances where a high sudden impact can occur (p.e. poles). One of the technological drawbacks is to be seen in the fact, that it is complicated to produce highly durable (high temperature needed) and at the same time strong (lower temperatures are needed) material. From this reason, some producers like the Finnish Thermowood Association are defining quality classes (see tables 3), allowing to link end uses to material quality classes (Mayes and Oksanen 2002).

7. GENERAL CONCLUSIONS AND OUTLOOK

The results of joint efforts of European research institutes and industrial companies led to several heat treatment processes, with a total production of approx. 165.000 m³ in 2001. Comprehensive research on the main important wood properties showed an improved durability and dimensional stability of several softwood and hardwood species. These improvements are due to severe changes of the intrinsic cell wall chemistry, caused by the elevated temperatures. However, at the same time, some mechanical properties (impact bending, MOR) are negatively influenced by the high treatment temperatures. The near future will show, if the industrial companies will be able by a strict process control and a quality insurance system to guarantee a steady and even product quality.

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Acknowledgements

I thank my colleagues Boko Tjeerdsma, Andreas Rapp, Michel Vernois, Tuula Syrjänen and Pertti Viitaniemi for being able to use their comprehensive information on heat treatment processes

	Radial ASE %	Tangential ASE %
Wood		
Beech	10	13
Douglas fir	13	23
Spruce (poles)	11	40
Scotch	33	41
Radiata	35	40

Spruce has been treated as poles; 100 mm diameter X 2200 mm length.

Table 1: Dimensional stability (Anti shrinking Efficiency ASE) of several heat-treated wood species (from Tjeerdsma et al. 1998).

	Production capacity 2001 [m ³]	Estimated capacity 2002/2003 [m ³]
Finland	150.000	200.000
France	15.000	25.000
Germany	0	10.000
The Netherlands	0	30.000

Table 2: Production capacity of heat treated wood in Europe. Figures for real capacity 2001 and planned capacity for 2002/2003 are given by the industry.

Heat treatment class	Properties	Temperature	Quality control parameters - ASE (swelling) - L-component (colour) - Free radicals	Durability class
0	Shrinkage 6 - 8 - 10 % Bending strength 41 - 100 - 205 N/mm ² Equilibrium moisture content 13,5 %			sapwood 5 heartwood 3 / 4
1	Shrinkage 6 - 7,5 % Bending strength unchanged Equilibrium moisture content 7 %	190 ± 3 °C	ASE = 20 - 35 % L = 60 - 65 Rad = 10 - 15	3
2	Shrinkage 5 - 6 % Bending strength decreased 0 - 15 % Equilibrium moisture content 6 %	212 ± 3 °C	ASE = 35 - 50 % L = 50 - 55 Rad = 30 - 50	2

Heat treatment class	Properties	Temperature	Durability class
0	Shrinkage 8 % Bending strength 76 - 147 - 155 N/mm ² Equilibrium moisture content 10,5 %		5
1	Shrinkage 7 - 9 % Bending strength slightly decreased Equilibrium moisture content 7 %	180 ± 3 °C	4-5
2	Shrinkage 6 – 8 % Bending strength decreased 4 - 20 % Equilibrium moisture content 6 %	200 ± 3 °C	3-4

Table 3: Classification system of heat treated softwoods (above) and hardwoods (below) (from Thermowood, Mayes and Oksanen 2002).

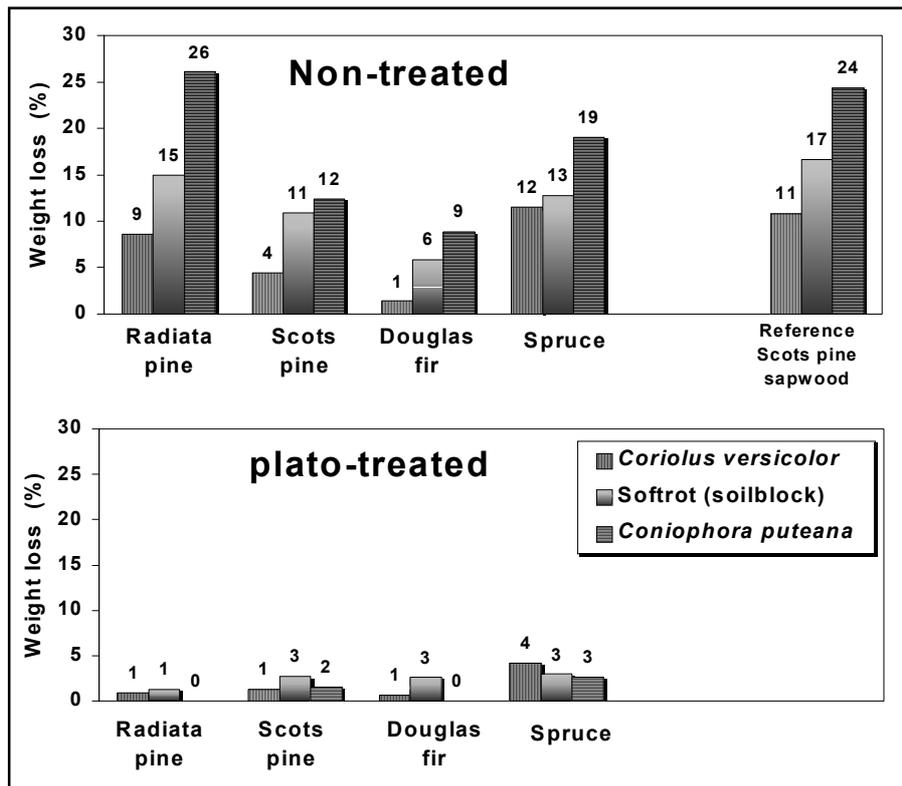


Figure 1: Weight loss of PLATO-treated and non-treated wood. Weight losses determined in the miniblock biotest (Bravery 1979) and in the soilblock test after 16 weeks of incubation. Distance of heat treated Plato Wood against wood attacking fungi (from: Tjeerdsma et al 2000). Comparison of natural durability of some woodspecies and Plato Wood.

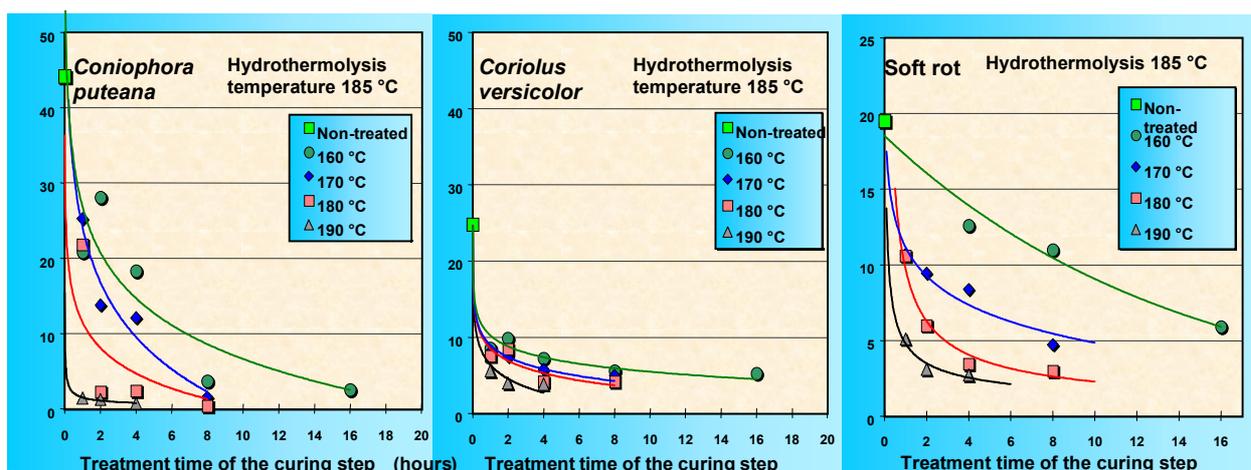
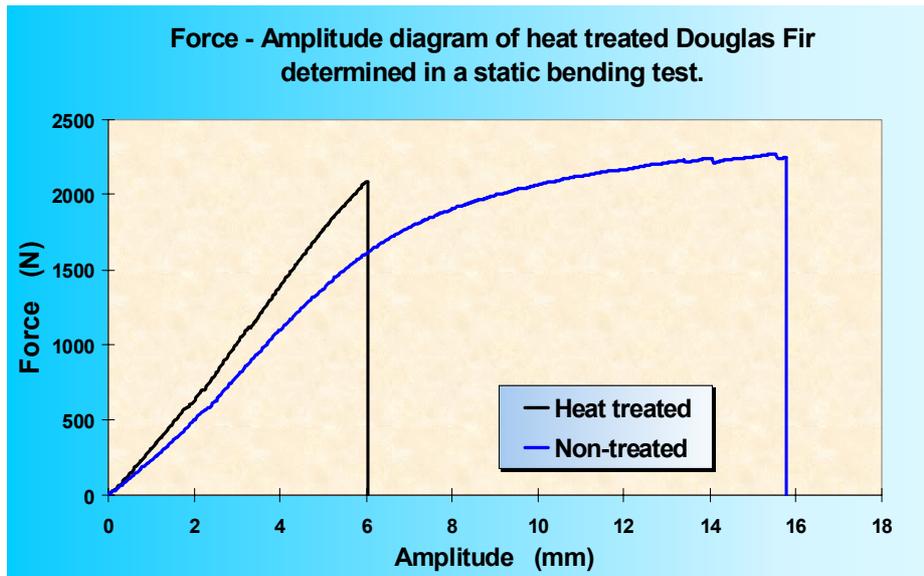


Figure 2: Influence of process conditions on the resistance of heat treated wood (Plato process) against brown rot, white rot and soft rot fungi (from: Tjeerdsma et al. 2000).

A



B

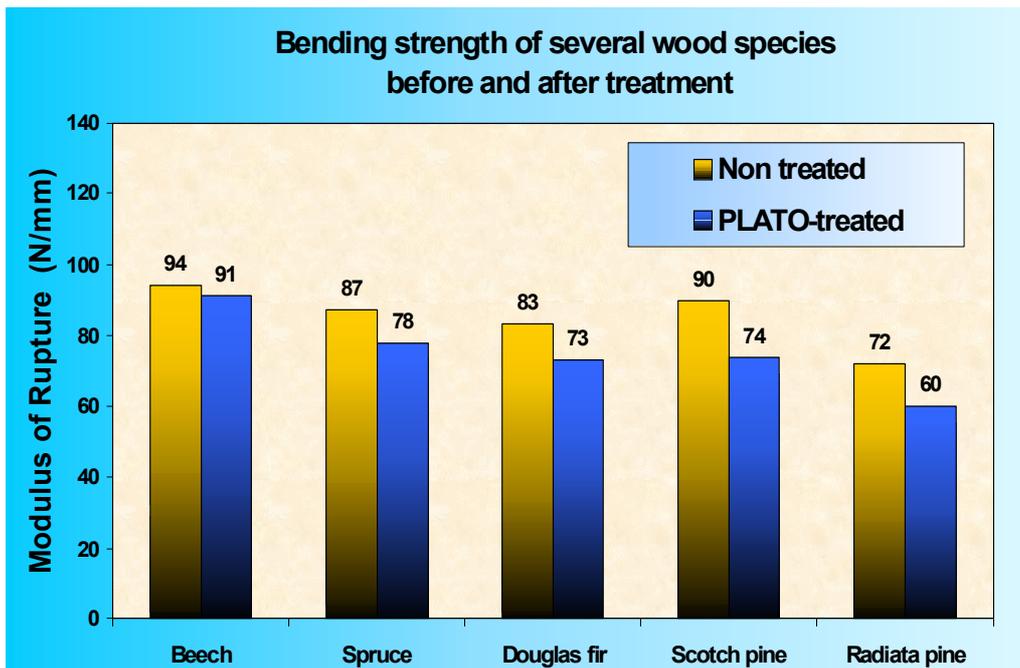


Figure 3: Bending strength and modulus of elasticity and modulus of rupture of heat treated wood (from: Tjeerdsma et al. 1998 b).

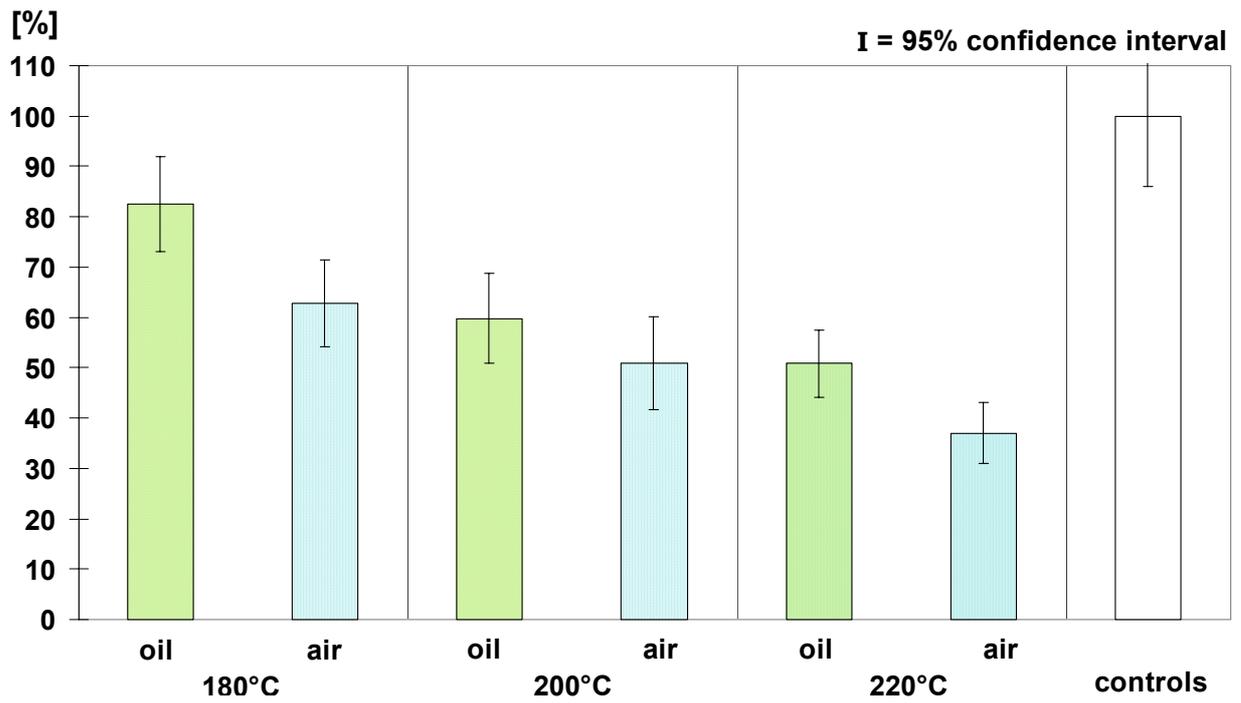


Figure 4: Influence of process conditions on Impact bending strength of oil-heat treated wood (from: Rapp and Sailer 2000).

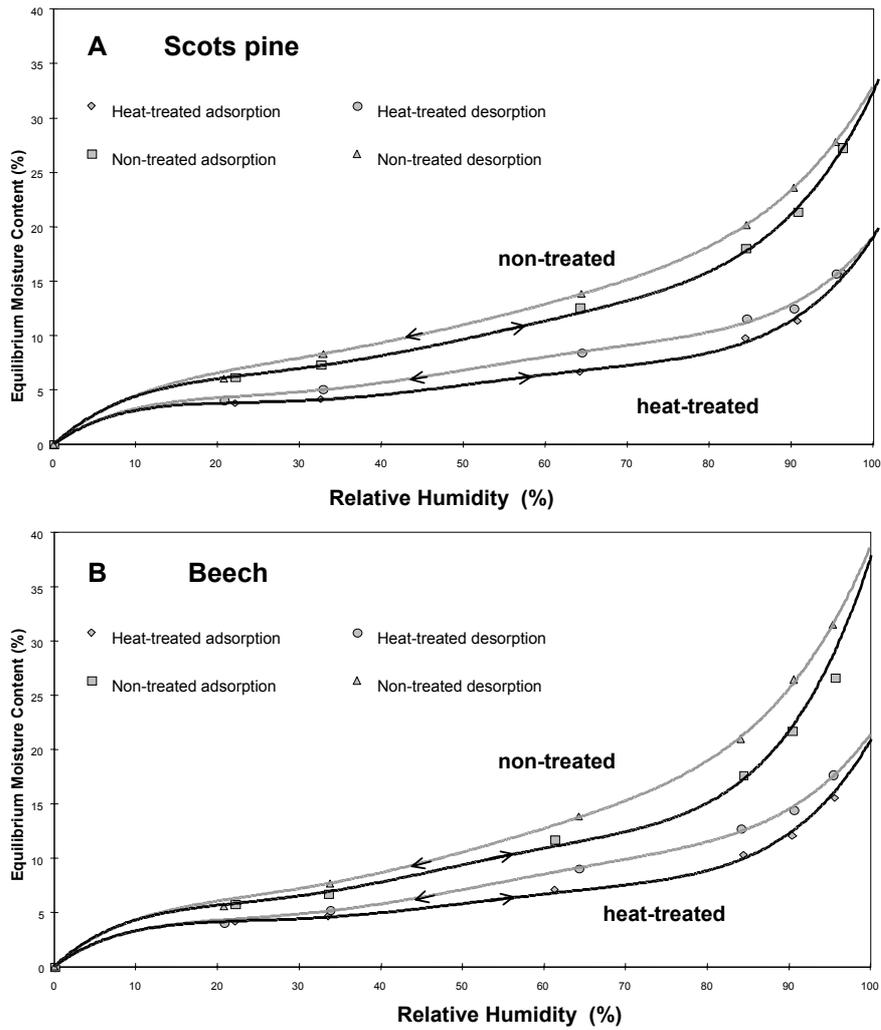


Figure 5: Sorption curves of non-treated and heat-treated Scots pine and Beech (from: Tjeerdsma et al. 1998).

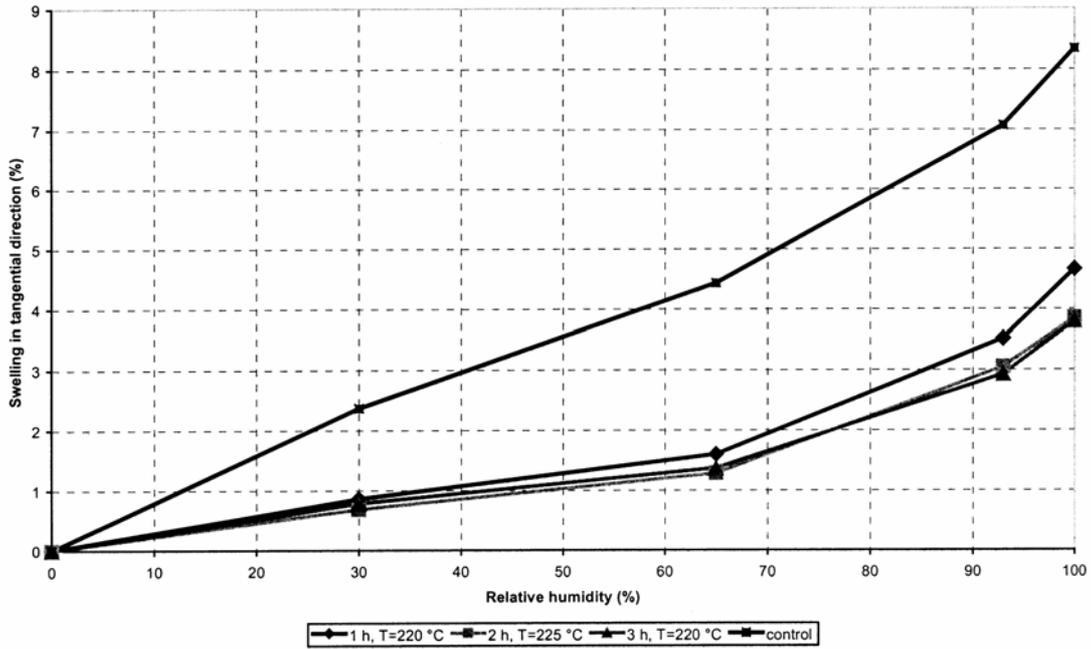


Figure 6: Tangential swelling of untreated and head treated spruce wood (from: Thermowood 2002).

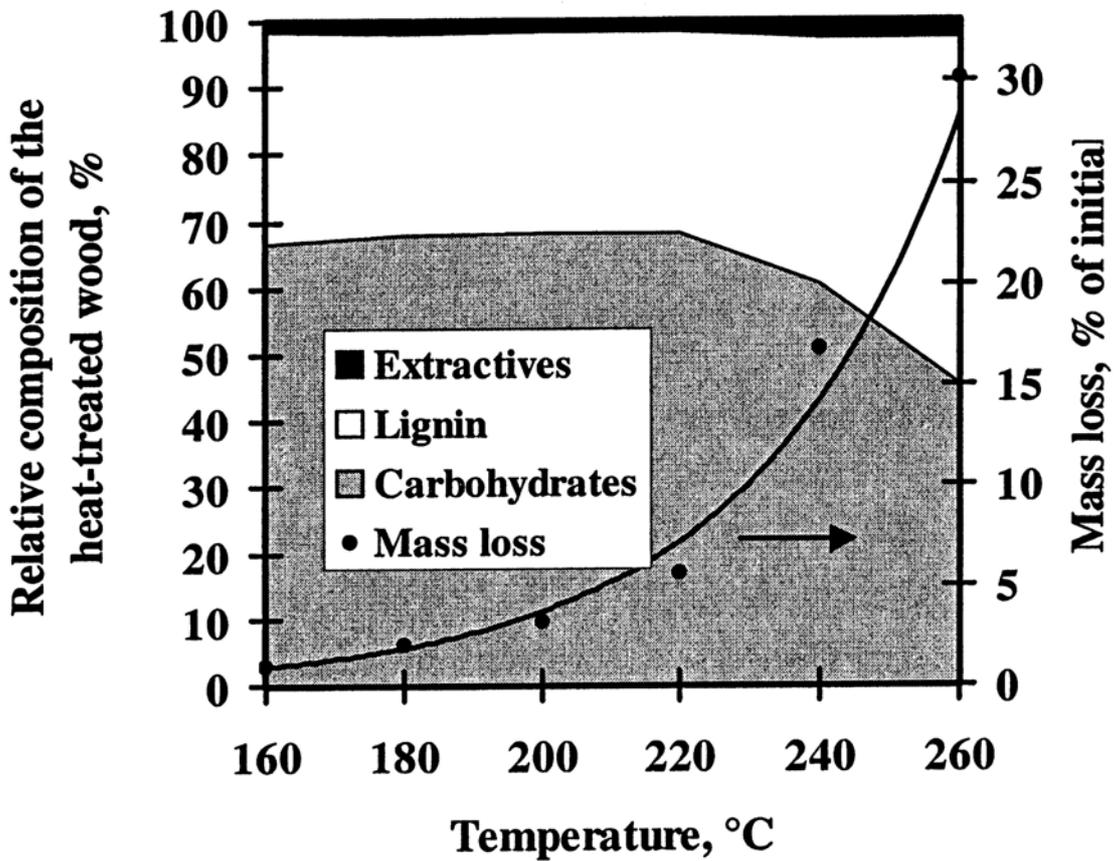


Figure 7: Change in relative mass proportion of carbohydrates, lignin, and extractives of heat treated Norway spruce samples in the temperature range 160 – 260 °C with reaction time 300 min. (from: Kotilainen 2000).

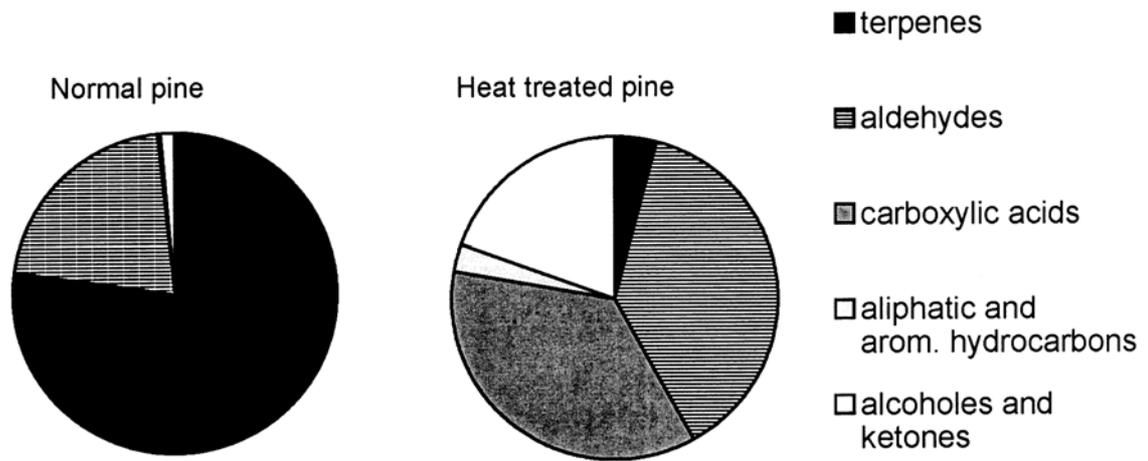


Figure 8: Emission of VOC's from untreated Pine wood (from: Kuopio University, in Thermowood 2002).