UiT The Arctic University of Norway

Department of Industrial Engineering

Investigation of moisture transport in branch wood of Norway Spruce using NMR

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Abstract

Two samples from a specimen of a Norway spruce (Picea abies (L.) Karst.) branch was prepared. One opposite wood (OW) sample and one compression wood (CW) sample. Several tests using nuclear magnetic resonance were performed on these specimens to study the motion of moisture through the branch wood. The T_2-experiment shows that the fibre saturation point is at 20% moisture content (MC) for OW and 25% MC for CW. The profile experiment shows that both samples have higher concentration of free water at side towards the bark, with the OW sample having a dry spot in the middle. The diffusion-T_2 experiment found the mean diffusion coefficient for the free water in the OW sample to be $10{,}19 * 10^{-10}$ m^2/s and the CW sample to be $9{,}9 * 10^{-10}$ m^2/s showing higher mobility than the water in Norway spruce, implying that the mobility of the bound water is significantly lower. As this test only tests one sample from one branch specimen further testing can increase the confidence in these results and testing OW and CW samples drilled out in other directions can give more data on the movement of moisture in branch wood of Norway spruce.

Sammendrag

To prøver fra en gren av Norsk gran ble preparert. En prøve av motstående tre (OW) og en av kompresjonstre(CW). Flere tester med NMR ble urførst for å studere bevegelsen av fukt gjennom grenveden. T_2-experimentet vise at fibermettningspunktet (FSP) er ved 20% fuktighetsinnhold (MC) for OW og ved 25% for CW. Profilforsøket viser at begge prøvene har en høyere konsentrasjon av fritt vann på bark siden av prøven, der OW prøven har et tørt punkt i midten av prøven. Diffusjon-T_2 eksperimentet fant en gjennomsnittlig diffusjonskoeffisient på $10{,}19 * 10^{-10}$ m^2/s i OW prøven og $9{,}9 * 10^{-10}$ m^2/s i CW prøven, som er høyere enn diffusjonskoeffisienten for vann i gran. Dette sier at det frie vannet har høyere mobilitet enn det bunde vannet i granen. Da denne oppgaven kun tester en OW og en CW fra en gren, kan ytligere testing øke tilitten til reultatene. Og OW- og CW-prøver boret ut i andre retninger kan gi mer data om bevegelen av fukt gjennom grenved av Norsk gran.

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Introduction

This project is started in collaboration with Uppsala university in Sweden and aims to describe the motion of moisture through branch wood of Norway spruce (Picea abies (L.) Karst.) using nuclear magnetic resonance and combine the experimental data in this report with a simulation model made at Uppsala university by master student Isac Norberg.

Wood is a major source of materials for construction and energy, and the distribution and behaviour of water in wood is therefore interesting. Wood has a complex and anisotropic structure, and the moisture content will influence the material's properties as well as the energy availability through combustion.

This work will reveal how water in wood is distributed through a branch, and between parts of the internal structure. The experiments were conducted on a plug drilled out of a Norway spruce (Picea abies (L.) Karst.) specimen sent from Sweden. The plug was separated into two pieces, one consisting of opposite wood and one consisting of compression wood. The tests performed was a T_2-relaxation experiment to find the moisture content and distribution of water between free water in the lumen and bound water in the cell walls. A profile experiment to find the concentrations of free water in height of the samples. And a diffusion-T_2 experiment to find the diffusion coefficients of the free water in the samples.

1 Theory

In this chapter theory about diffusion, wood properties and nuclear magnetic resonance will be covered.

1.1 Diffusion

Diffusion is the movement of mass from a place of higher concentration to a place of lower concentration by molecular motion. Diffusion can happen within a specific solid or form a liquid, gas, or another solid phase [1]. The process of diffusion is time dependent, and it is necessary to know the rate of mass transfer. This can be expressed as

$$J = \frac{M}{At} \tag{1.1}$$

where J is the diffusion flux, M is the mass, and A is the area over which the diffusion is occurring, and t is the time used for the diffusion. For steady state diffusion in a single direction, we have Fick's first law of diffusion.

$$J = -D\frac{dC}{dx} \tag{1.2}$$

Where D is the diffusion coefficient, and dC/dx is the concentration gradient. The diffusion coefficient is negative to take into account that diffusion goes from a high concentration to a low concentration [2].

For nonsteady-state diffusion the use of equation 1.2 is not practical and the partial differential equation 1.3 known as Fick's second law is used instead.

$$\frac{\partial C}{\partial t} = \frac{\partial}{x}\left(D\frac{\partial C}{\partial x}\right) \tag{1.3}$$

In cases where the diffusion coefficient is independent of the composition, equation 1.3 can be simplified to

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} \quad 1.4$$

1.1.1 Diffusion in polymeric materials

When looking at diffusion in polymeric materials, the focus is usually on the movement of a small foreign molecule. For example, molecules like O_2, H_2O, and CO_2. The diffusivity of the foreign molecule is dependent on the permeability and absorption characteristics of the polymer. The absorption of the foreign molecule can cause swelling in the polymer, and the size of the foreign molecule affects the diffusivity in the polymer. Smaller molecules and inert molecules that does not chemically interact with the polymer will see higher mobility than otherwise[1].

The diffusion through a polymer is often given in the form of a permeability coefficient, P_m. For steady state diffusion Fick's first law can then be written as

$$J = -P_m\frac{\Delta \mathrm{P}}{\Delta x} \quad 1.5$$

where J is the diffusion flux of gas through the membrane, P_m is the permeability coefficient, ΔP is the pressure difference across the membrane, and Δx is the membrane thickness[1].

1.2 Wood

Wood is a hygroscopic natural polymer composite material. The structure of wood consists of cellulose and hemicellulose in a lignin matrix[3].

1.2.1 Cellulose

Cellulose is a biopolymer, and polysaccharide. It is the most common biopolymer on earth and is used in many industries in different form. Such as structural building materials, packaging, paper, textiles, insulation and more. Cellulose is one of the main structural

components of the primary cell wall of plants, including wood. For wood cellulose makes up about 40% to 50% of the material[3, 4].

1.2.1.1 Molecular structure

The structure of cellulose consists of glucose monomers that are linked together in long linear chains to form a long polymer. As each time a glucose molecule is added to the to the cellulose chain one molecule of water is lost, the subunit within the cellulose is called a glucose anhydride unit.

The glucose units in the cellulose polymer are linked together in a β-configuration. The bonding structure is such that for each glucose molecule in the chain, the next molecule is rotated 180° relative to the previous molecule in the chain. Figure 1 illustrates the fundamental structure of the cellulose polymer, with the glucose anhydride monomers connected by β-1.4 glycosidic bonds[4].

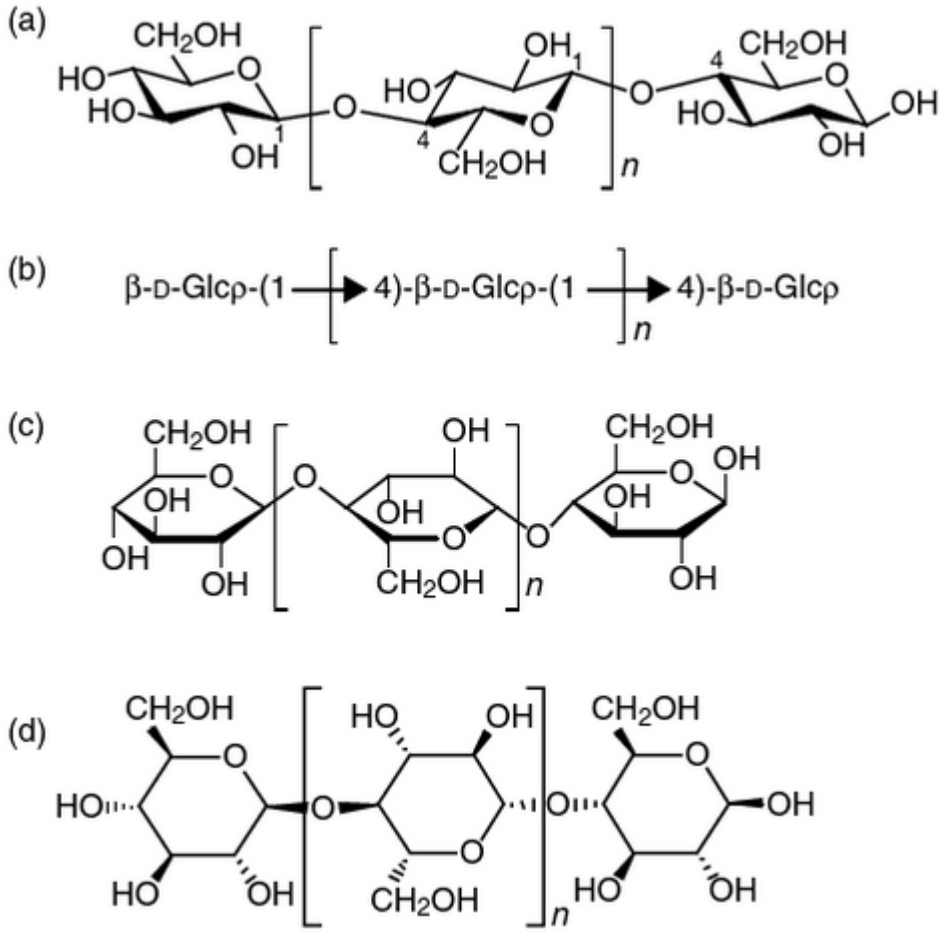

Figure 1 "Four typical representations of the fundamental structure of cellulose. (a) Sterochemical; (b) abbreviated; (c) Haworth perspective; (d) Mills'. Glcp = Glucopyranose (i.e., glucose in the form of a six-

membered ring containing five carbon atoms and one oxygen atom in the ring). Literature suggests n= 10 000 for wood cellulose" [4]

1.2.2 Hemicellulose

Hemicelluloses are natural polymers that consists of carbohydrate monomers. Unlike cellulose, hemicellulose does not consist of homopolysaccharides, are instead composed of different carbohydrate monomers like six-membered pyranose and five-membered furanose ring structures[3, 4].

The hemicelluloses in wood are usually a shorter and branched polymer. This structure allows the hemicellulose to branch around the cellulose fibres and provide strength to the cell walls in the wood. In wood hemicellulose generally stands for 25%-30% of the dry weight of the wood. The more open structure of the hemicellulose polymers compared to cellulose, makes it more hygroscopic, and more soluble. It also makes it more vulnerable to thermal degradation compared to cellulose[3, 4].

1.2.3 Lignin

Lignin an amorph an rigid polymer that plays a large role in the structural support of the cell walls along with cellulose and hemicellulose. In contrast to cellulose and hemicellulose, lignin does not consist of sugar monomers, but is instead composed of phenolic compounds. The structure of lignin is highly varied, even within the same plant due to the nature of the free radical polymerization during the biosynthesis of lignin. The effect of lignin is to be the glue, or matrix, of the wood, keeping the cells together and providing structure to the composite[3, 4].

1.2.4 Structure of wood

The wood is made up of a complex structure consisting mainly of cellulose fibres, hemicellulose, and lignin. For pine trees the sapwood on the inside is not clogged by resins, and it is here that the tree transports water up the tree. While the core wood is either filled with resins, or dead, and can therefore not transport water. The wood cells are like square tubes with four layers main layers and an outer layer called the middle lamella that mainly consists of lignin seen in figure 2

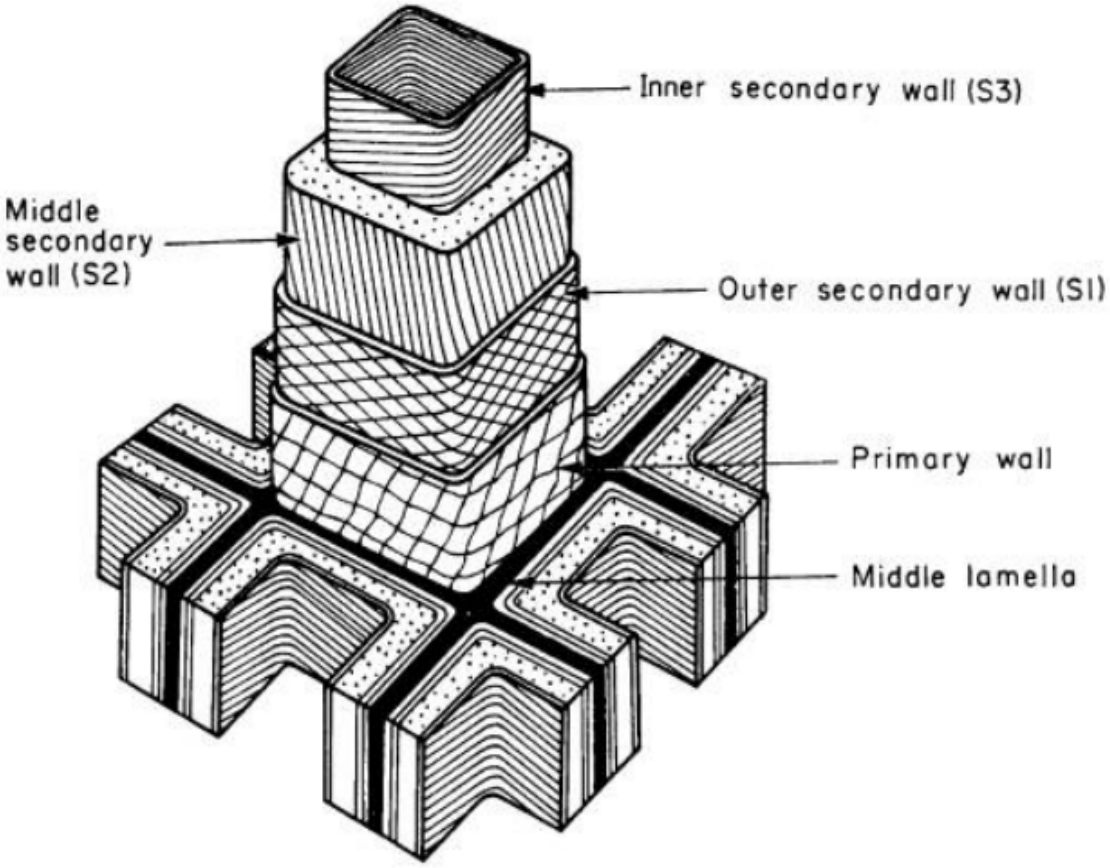

Figure 2 Illustration of wood cell structure[5].

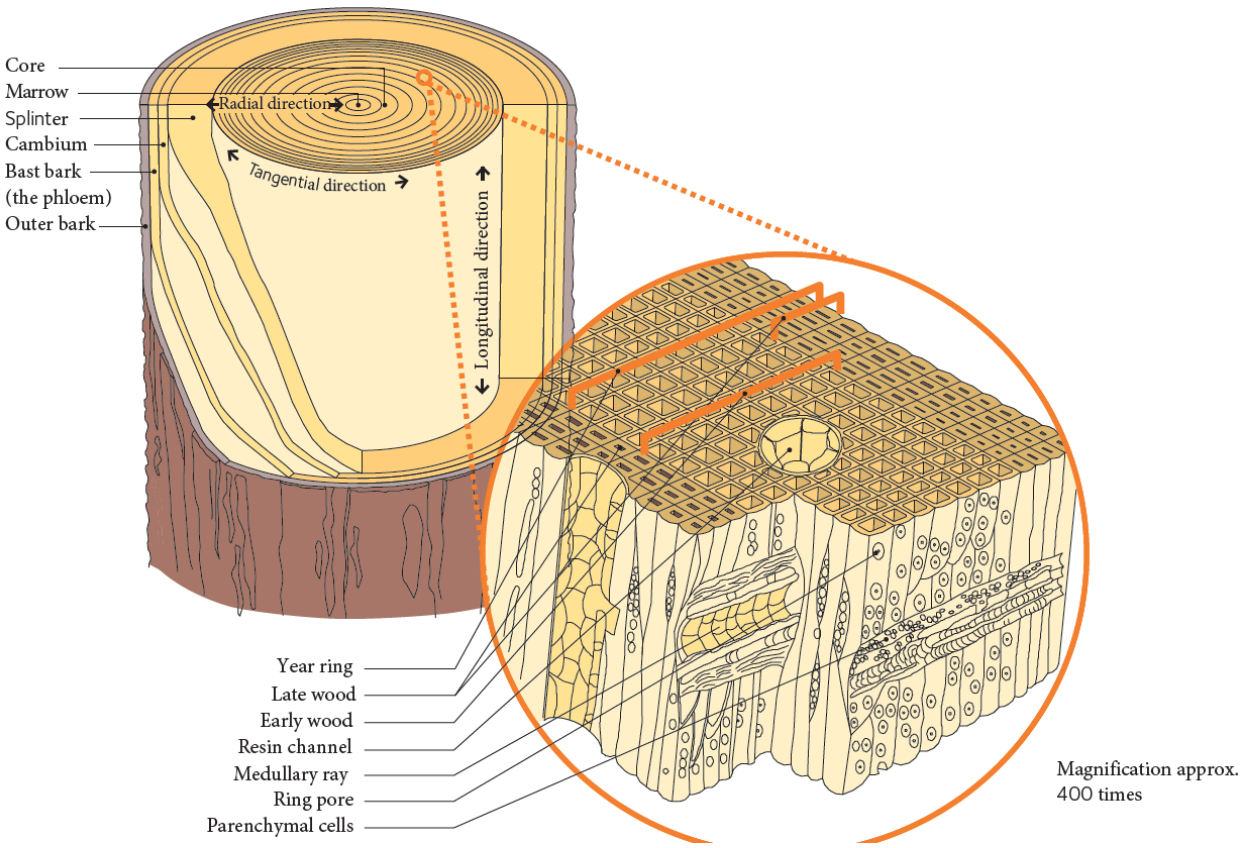

Figure 3 Illustration showing the structure of a tree[6].

Figure 3 Illustrates the structure of a tree, with bark on the outside and wood on the inside, and it also illustrates the cell structure of the wood. The year rings are caused by differences in the growth cycle. During the start of the growth season the tree produces wide thin-walled early wood, at the end of the growth season late wood is produced. Figure 3 also illustrates the difference in the wall thickness of the early wood and late wood[6].

1.2.4.1 Structure of branches

Branch wood is a type of reaction wood, affected by gravity, and the structure will be different from normal stem wood. The pith will be lower than the centre of the branch, and on the underside of the branch compression wood (CW) will be formed. Compression is characterized by thicker tracheid walls compared to stem wood. On the top side of the branch opposite wood (OW) is formed, with thinner tracheid walls [7, 8]

1.2.5 Moisture and drying

Fresh timber has a considerable amount of free water in the lumen of the wood. And after felling this water will start to evaporate. The evaporation of the free water does not have any significant impact on the structure of the timber or the strength of the timber. The point where the free water has evaporated and all that's left is the bound water in the cell walls is called the fibre saturation point (FSP). The bound water that is trapped in the cell walls at the FSP is around 25-30% of the dry weight of the material[5].

When using wood as a construction material or as a fuel material, the moisture content influences the properties of the wood. The moisture content **(MC)** is given by moisture ratio. The moisture ratio is given by the amount of dry material, after drying the wood at 103°C. So, 100% moisture ratio, would mean that a 100 kg piece of lumber will contain 50 kg water, and 50 kg dry material[9].

The moisture concentration is not homogenous in the wood, with heartwood often being dryer than the surface wood. This makes drying the wood a challenge, as it can easily cause the wood to crack during drying due to introduced stress, making it unfit as a construction material. During drying below the FSP the wood will start to shrink and experience densification[5]. When going from wet to dry wood generally shrinks 8% in the tangential direction, 4% in the radial direction, and 0,2-0,4% in the longitudinal direction illustrated by figure 4[9].

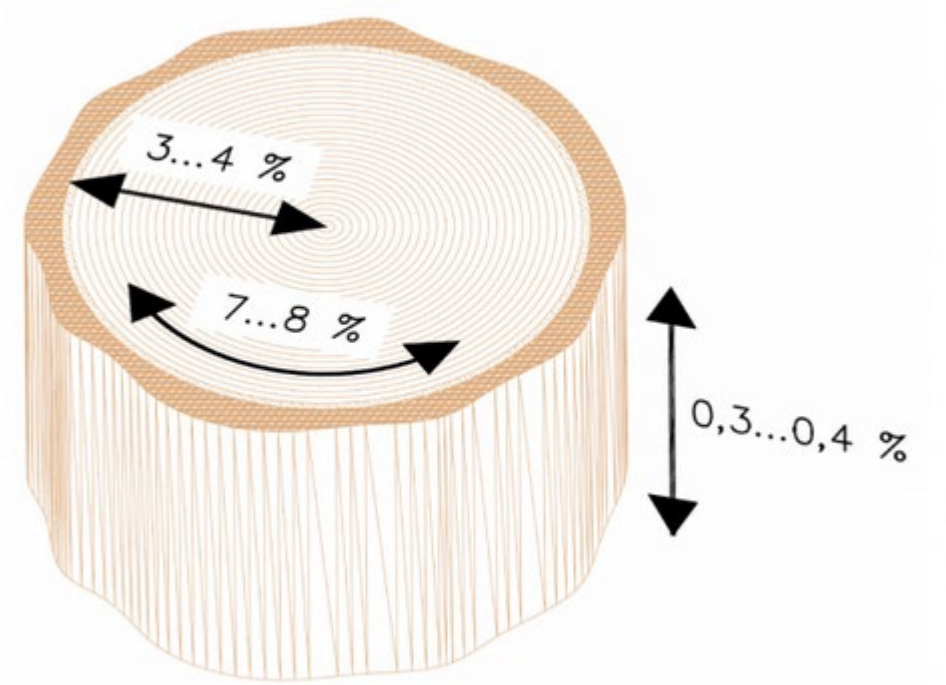

Figure 4 The shrinkage of wood during drying in the radial direction, tangential direction and longditudal direction[9].

If the moisture content of the wood remains too high for a long period of time, the material will start to degrade. This typically happens if the MC stays above 20 % with a high relative humidity, typically above 80%. At this humidity level the wood will start to mould, and if the relative humidity goes over 90% the wood will start to rot[9].

As a fuel source the MC also has an effect. Evaporating the moisture requires energy to perform the phase change. But the heated water vapour in the smoke also helps with the heat transfer from the burning. Controlling the MC and drying the wood to an optimal MC can therefore increase the efficiency of wood as a fuel source. Commercial wood for wood stoves in Norway is sold with a max moisture content of 25% according to the Norwegian standard for wood[10].

The strength properties of wood increases when the wood is dry, and this might be because cellulose has greater strength in dry conditions. Another contributing factor can be that the higher moisture concentrations can act as a lubricant in the middle lamella, and this will allow some slip between the microfibrils. Reducing the moisture will increase the friction and

thereby increase the stiffness of the wood. At the same time the stiffness is increased the wood also becomes more brittle[5].

1.2.5.1 Relative humidity

Relative humidity is a percentage of the amount of water in the air compared to the max soluble amount of water in the air at the a given temperature. The relative humidity ϕ is given by equation 1.5

$$\phi = \frac{p_v}{p_*} \qquad 1.5$$

Where is p_v the partial pressure of the water vapor p_* and is the saturation vapor pressure.[11]

1.3 Norway spruce (Picea abies (L.) Karst.)

Norway spruce is a common species of softwood in the pine family that is native to central and northern Europe. It has many uses such as Christmas trees, construction of houses and furniture, paper production, and as a tonewood for string-instruments[12].

1.3.1 Composition of Norway spruce

As all other types of wood Norway spruce also consists mainly of cellulose, hemicellulose, and lignin. The content of cellulose and hemicellulose is slightly higher in the heartwood compared to the sapwood. While the lignin content is higher in the sapwood. Table 1 shows the composition of heartwood, sapwood and the transition wood between the heartwood and sapwood [13]

Table 1 Main chemical composition of Norway Spruce [13]

Component	Heartwood	Transition wood	Sapwood
Cellulose	32,4% ± 1,7%	29,5% ± 0,5%	30,9% ± 0,8%
Hemicellulose	25,7% ± 1,4%	25,3% ± 1,4%	47,1% ± 1,6%
Lignin	45,5 ± 1,7%	46,9% ± 1,4%	47,1% ± 1,6%

1.3.2 Reaction wood of Norway spruce

Branches of Norway spruce produces CW and OW as expected for softwood. Figure 6 shows a microscope picture of an annual ring of Norway spruce. This sample is not from a branch but shows the structure of both CW and OW. The early wood at A has small tracheid walls, while the late wood at D has thicker tracheid walls. CW as seen in C has thicker tracheid walls because of a force acting on the wood during the growth [14].

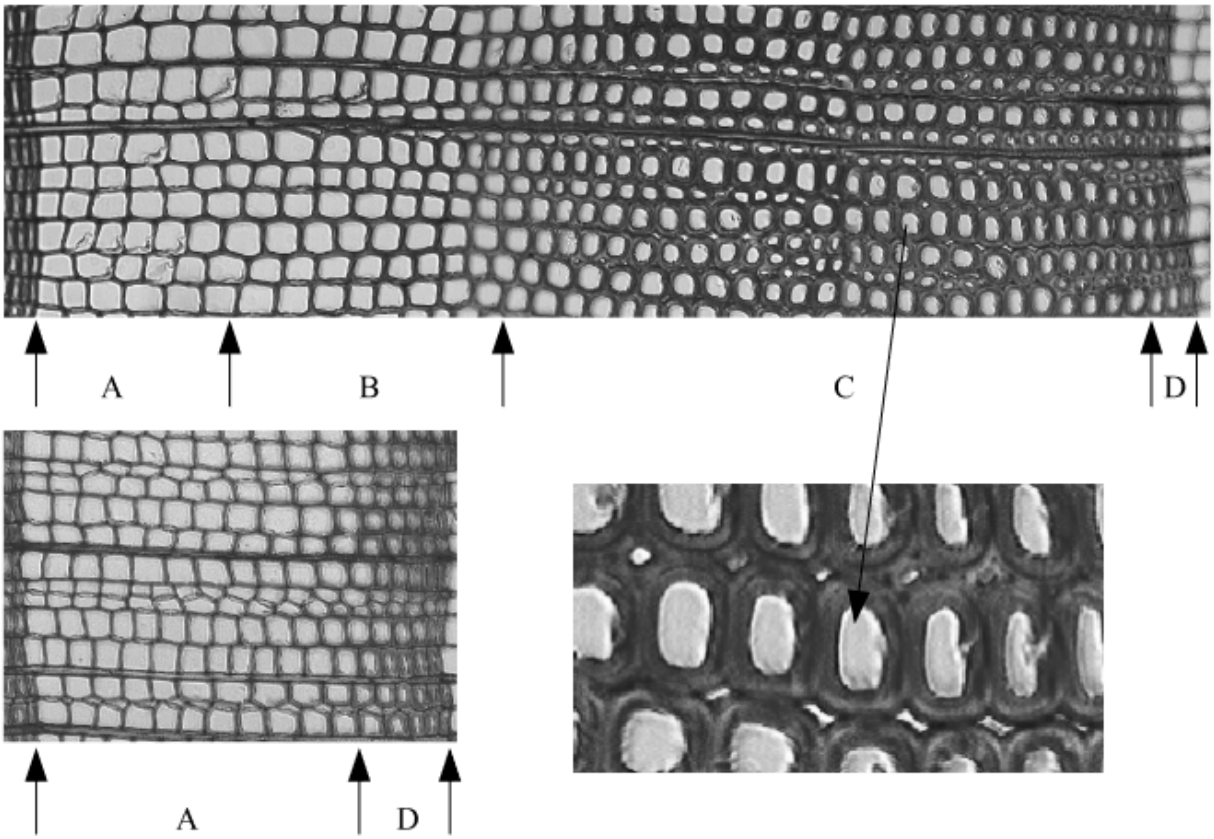

Figure 5 "The microscopic photograph of an annual ring with the occurrence of compression wood from the CW zone (A – early wood, B – transitional wood, C – reaction compression wood, D – late wood) and with normal wood from the OW zone (A – early wood, D – late wood)" [14]

1.3.3 Diffusion in Norway spruce

A study conducted at Luleå university in Sweden has compared the diffusion coefficients of heartwood and sapwood of Norway spruce with and without extractives. The study found that the diffusion coefficient of the unextracted wood was significantly higher than the unextracted wood, in both heartwood and sapwood. But density has a higher impact on the moisture transport, with a linear relation between the diffusivity and density. Table 2 shows the diffusion coefficients of water in extracted and unextracted wood, and figure shows the relation between density and diffusivity[15].

Table 2 Diffusion coefficient D_w and standard deviation s of unextracted and extracted Norway spruce [15].

	Norway spruce			
	Heartwood		Sapwood	
	Unextracted	Extracted	Unextracted	Extracted
$D_w\,(10^{-10})(m^2/s)$	6,5 s 1,6	5,4 s 1,1	6,8 s 1,1	5,4 s 1,0

1.4 Nuclear magnetic resonance

Nuclear magnetic resonance is a non-destructive and non-invasive method that can be used to measure moisture content and diffusion coefficients. It uses an external magnetic field to align the nuclear magnetic spin of the nuclei and by sending a transverse magnetic pulse the direction of the spin will change. The time the nuclei uses to realign with the external magnetic field is called the relaxation time, and this can be recorded by the change in magnetic flux[16].

Different pulse sequences can be used to detect different things using NMR. The Carr-Purcell-Meiboom-Gill (CPMG) sequence is used to find the T2 relaxation time distributions for different components in a sample. And these results can be used to calculate the moisture content for a sample[17].

NMR can also be used to get a profile of the water content of a sample. To do this the pulse sequence in figure 7 is used. This sequence combines the profile experiment with the CPMG experiment to get a profile of the sample[18].

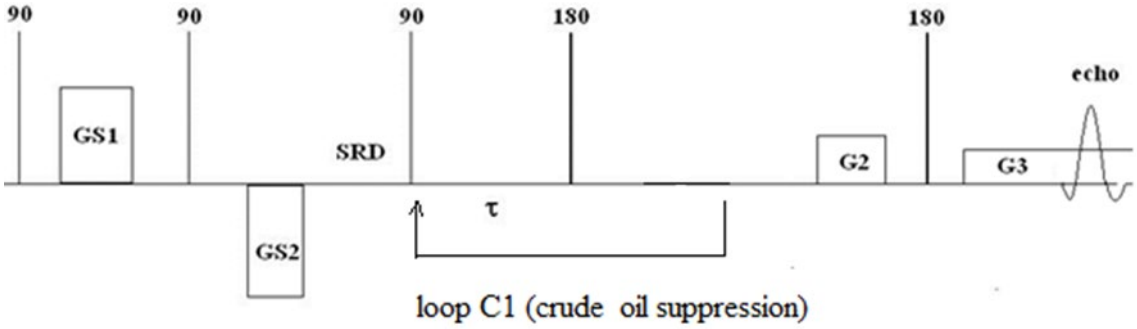

Figure 6 NMR profile experiment pulse sequence.

NMR can also be used for 2-Dimensional tests to measure T_1T_2 relaxation using the sequence in figure 10. And in a diffusion-T_2 experiment using the SR-11-interval PFGSE-CPMG sequence in figure 9. With the diffusion-T_2 experiment diffusion coefficients for the sample being tested can be measured and found[16].

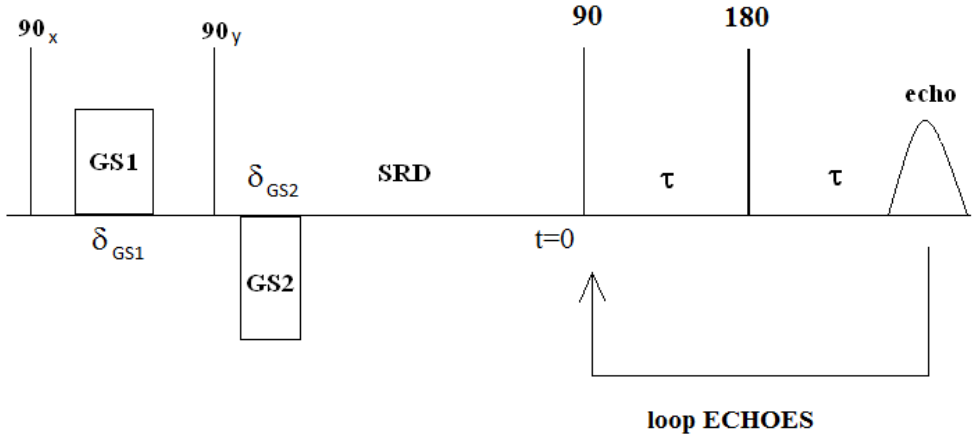

Figure 7 Combined SR-T1-T2 pulse sequence.

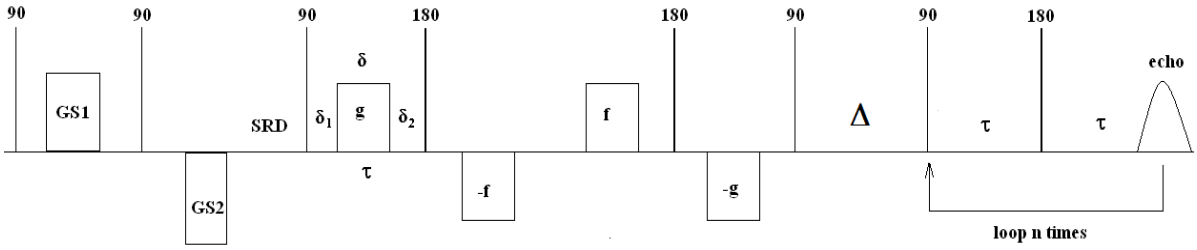

Figure 8 The SR-11-interval PFGSE-CPMG sequence.

2 Materials and method

In this chapter the methodology for the experiments will be described alongside the equipment and material used to measure the moisture content and movement of moisture in Norway Spruce.

2.1 Equipment

This project consists of several NMR experiments. For these experiments the equipment used is listed below.

R4 Benchtop NMR System, manufactured by Advanced Magnetic Resonance Ltd.

Ae Techron 2105 Gradient amplifier

Ø 15 mm tap drill

Kern ALT 310AM scale.

Test tube.

KNF LABOPORT N 938 vacuum pump and chamber

Measuring beaker

Branch specimen of Norway spruce provided by Uppsala university.

2.2 Software

The software used in this project will be covered here with a short introduction of the use of each program.

2.2.1 OpenNMR

This software is used to interface with the NMR system to perform NMR experiments spectrometers from Advanced Magnetic Resonance Ltd

2.2.2 Microsoft Excel programs provided by Anvendt Teknologi

These programs are used to control the OpenNMR software and perform the different experiments and collect the data.

2.2.2.1 CPMG.xls

The CPMG.XLS program runs the CPMG sequence with acquisition parameters being controlled by the document and acquired data processed with the 1-dimensional inverse Laplace transformation (1D-ILT) and saved for further post processing.

2.2.2.2 11PFGSE_CPMG.xls

This program runs the 11-interval Pulse Field Gradient Spin Echo (11PFGSE) sequence. The different parameters for the experiments are controlled using this program, and the data is processed using the 1D-ILT routine and saved for further post-processing.

2.2.2.3 Brine_profiling_100khz.xls

This program runs a profile experiment by combining the CPMG sequence with a profile experiment. This experiment shows the water cut of the sample and how the moisture is distributed along the Z-axis of the sample. The program is originally made to get the profile of a brine emulsion but has been tweaked for this project to work with a porous wood sample. This was done by Geir H. Sørland from Anvendt Teknologi AS.

2.2.2.4 Profile_Processing.xls

The Profile_Processing.XLS program takes the data from the profiling experiment and removes the noise to give a cleaner profile to evaluate.

2.2.3 Anahess1D

Anahess 1D is used to process one dimensional NMR data. The software has different kernels to be used depending on the experiment.

2.2.3.1 Anahess 1D Discrete

Anahess 1D Discrete is used to process the data gathered in the CPMG experiment. The data is processed with until a fit with the minimum number of components according to the stop criterion, in this case the Bayesian Information Criterion (BIC).

After the data has been processed by Anahess 1D discrete the result with the lowest BIC number is showed first, followed by the fit for all number of components. The result can then be saved as an html file and an NCO file used in Anahess 1D distribution to probe the distributivity of the solution.

2.2.3.2 Anahess 1D Distribution

Anahess 1D Distribution is used to probe the distribution found using Anahess 1D Discrete. The software does most of the work automatically after loading the NCO file produced by Anahess 1D Discrete.

To produce the distribution a broadening factor can be changed by the user until a good fit is achieved. This is in part a qualitative job dependent on the user's knowledge and experience with the software and experiment being performed.

2.2.4 Anahess2D

Anahess 2D is used to process the NMR data from the two-dimensional experiments. The software has several kernels to choose from depending on the tests that have been performed.

2.2.4.1 Anahess2D Discrete

Anahess 2D Discrete works similarly to Anahess 1D discrete and will process the data until the stop criterion, the Bayesian Information Criterion (BIC) is met with the least number of components necessary.

To process the data, the data is loaded, a kernel is chosen, and dataset type is selected. The dataset can be either time-time or time-diffusion. Then the software runs until a fit with the

lowest BIC is found. The output can then be saved in an NCO file to be further probed using Anahess2D Distribution.

2.2.4.2 Anahess 2D Distribution

Anahess 2D Distribution is used to probe the distributivity of the data processed using Anahess 2D Discrete. After loading the NCO file from the discrete program, the software produces the input parameters based on the NCO file without a need for user input.

When the NCO file is loaded, and the program is run it will show a proposed distribution. Here the components may be loaded together or separately, and it's up to the user to evaluate how the components should be grouped.

Mean diffusion coefficients of the detected components in the sample can also be found using Anahess 2D distribution.

2.2.5 NCO PeakEditor

NCO PeakEditor is used to edit NCO files made by Anahess 2D Discrete. Sometimes the best fit will show a component that is not there. This can be because of noise in the signal and give a false distribution. The NCO PeakEditor software can then be used to remove components that are out of place, to give "fix" the distribution. This must be used with caution and will help with a qualitative evaluation but not a quantitative evaluation of the data.

2.3 Method

In this section the preparations and methods for the tests will be described.

2.3.1 Preparation of the equipment

The NMR equipment needs to be calibrated before the experiments start. For this project the calibration of the equipment was performed by Geir H. Sørland from Anvendt Teknologi, using a sample of tap water for the calibration. This calibration is done to ensure that the equipment will pick up the moisture signals in the sample and not a signal from other components in the sample.

2.3.2 Preparation of the sample

The samples in this project are some pieces of Norway spruce, provided by our collaborators at Uppsala university in Sweden. To send the sample to Norway it was packed in plastic and frozen to avoid moisture disappearing from the wood. After receiving the samples, they have been kept in a plastic container in a refrigerator.

To make a sample for the test a tap drill was used to make a plug. The plug was made in the radial direction, through the pith, to get a plug with both CW and OW. The bark was then removed, and the ends were cut flat. Due to the length of the plug, it had to be split into two pieces. The split was through the pith to make one CW plug and one OW plug.

After the samples have been made, each sample is weighed, and the series of tests is performed on each of the samples before saturating each sample with water using distilled water and a vacuum chamber. The samples are put in a beaker with distilled water and put under vacuum for several hours until visible bubbles stop forming on the surface. After saturation the sample is then weighed again.

2.3.3 Experiments

The initial test ran is a CPMG test on a sample of pure water at a known weight. This gives an NMR signal that can be used as a baseline to later calculate the amount of moisture in the wood samples.

$$\frac{I_0}{m} = \frac{NMR}{g} \qquad 2.1$$

To do the calculation the NMR signal per gram is needed and is calculated using I_0 the NMR signal from the pure water sample divided by m the mass of the water sample.

To start the testing the NMR machine is set to 25 degrees Celsius, and the sample is removed from the refrigerator to reach ambient temperature. After the sample has been warmed up it is then weighed using the Kern ALT 310AM scale to 0.001 g. After weighing the sample is then placed in the test tube with the pith towards the top and inserted into the NMR equipment. When everything is ready all the experiments are run after each other.

There were four experiments performed on each both wood samples. The first experiment is a T_2 experiment using the CPMG sequence with the acquisition parameters shown in table 3. The second experiment is a profile experiment using the profile sequence shown in figure 7 with the acquisition parameters shown in table 4. The third experiment is a T1T2 experiment using the sequence in figure 8 with the parameters shown in table 5. The last experiment is a diffusion-T_2 experiment using the SR-11-interval PFGSE-CPMG sequence shown in figure 9 with the acquisition parameters shown in table 6.

Table 3 Parameters for the CPMG experiment.

Parameter	**Setting**	**Explanation**
NS	32	Number of scans
RG	5	Receiver gain
SF	21,33	
P90	8,6	Duration of the 90-degree RF pulse
Dead	7	Dead time used in the sequence
Filter	1 mhz	The acquisition filter used
RD	5000	Recycle delay in milliseconds
SI	5	Number of averaging points for each echo in the CPMG train
RFA	1023	Power level of RF amplifier
DS	0	Number of dummy scans run before the actual recording of the data
TAU	150	The half of the inter echo spacing in the CPMG, given in milliseconds
Echoes	1000	Number of echoes acquired

Table 4 Parameters for the profile experiment.

Parameter	Setting	Explanation
Number of experiments	1	Number of brine profile acquisition
Number of scans	512	Number of scans used in the acquisition
Dummy scans	0	Number of dummy scans in the acquisition
Receiver gain	1	Receiver gain
SRD / ms	500	Spoiler recovery delay
Time between experiments / s	1	Desired time between the profiles measured
C1 Echoes for suppression	10	The suppression value

Table 5 Parameters for the T1-T2 experiment.

Parameter	Setting	Explanation
Echoes	1000	Number of echoes acquired
TAU	150	Half if the inter echo spacing in the CPMG part of the sequence
NS	8	Number of scans
SI	20	Number of averaging points for each echo in the CPMG train
Number of SRD's	32	Number of spoiler recovery delays for recording of the T_1 recovery
RD	100	Recovery delay

Table 6 Parameters for the 11PFGSE-CPMG experiment.

Parameter	Setting	Explanation
Number of gradients	16	Number of gradient values used in the experiment
SI	20	Number of datapoints for each echo
NS	16	Number of scans for each echo
D11 (SRD)	1000000	Spoiler recovery delay for each echo
DEAD	5	Dead time used in the sequence
RD	100	Recycle delay in milliseconds
DS	1	Number of dummy scans
Filter	1 mhz	The acquisition filter used
Receiver Gain	10	
TAU	150	Half if the inter echo spacing in the CPMG part of the sequence
Echoes	1000	Number of echoes acquired
D2 (δ)	1500	The gradient pulse length duration
D1 (δ_1)	200	The pre-gradient pulse duration

D3 (δ_3)	800	The eddy current dead time
G_increment	1500	The incrementing value of the gradient strength
C1	3	The number of pair of preparatory gradients.

After all the NMR experiments have been completed, the weight of the sample is then measured again. After measuring the weight, the sample is then dried about 0,030 g before continuing with all tests. This process is then repeated until the profile experiment only produces noise due to the sample being too dry.

After completing all tests on the OW sample the same steps were then followed with the CW sample. Both samples were dried until the scale showed about 0,030 g less than the end of the previous run.

2.3.4 Data treatment

When all experiments are completed, and all the data has been gathered it is ready to be processed. This will be done using the Anahess software suite and the profile processing excel program.

2.3.4.1 CMPG Data

The CPMG experiment produced text files with t-data and data. These are then loaded into Anahess 1D discrete and processed with the *e(-t/T)* kernel until the solution with the lowest BIC number is reached. From this result the moisture content of the sample can be calculated using formula

$$MC\% = \frac{\left(\frac{I_0}{NMR_{water}}\right)}{m_{wood}} * 100 \quad 2.2$$

Where I_0 is the NMR signal from the wood sample NMR_{water} is the constant calculated using formula 2.1 and m_{wood} is the mass of wood sample. This can then be used to calculate the total mass of water in the specimen using formula 2.3.

$$m_{water} = m_{wood} * \frac{MC\%}{100} \quad 2.3$$

The NCO file saved after the processing the data using Anahess 1D discrete is then loaded into Anahess 1D distribution. Using Anahess 1D distribution the broadening parameter is changes until a good fit is reached. For the wood samples this gives two peaks in the distribution. The relative area under each peak can be found by marking the area, and at the same time the average relaxation time for each peak is found. Using formula 2.4 the mass of each component can be calculated.

$$m_{WC} = m_{water} * \frac{A_{rel}}{100} \quad 2.4$$

Where m_{WC} is the mass of the water component m_{water} is the mass of the total amount of water in the sample and A_{rel} is the relative area under the peak for the component.

This can then be done for all tests to see the effect of drying.

2.3.4.2 Profile Data

The profile data found using the profiling program is copied into the Input_data sheet in the profile processing excel program. The input parameters are showed in table 7 where the water cut parameter is changed for each test as the sample dries.

Table 7 Parameters for the profile processing.

Parameter	**Setting**	**Explanation**
Resolution / mm	0,39	The distance between measuring points in the specimen
Threshold (%)	3	Set s the threshold value in % in the sample
Water cut (%)	Changes per experiment	The water content in the specimen of the detected water component
Number of profiles	1	The number of profiles in the application
Number of datapoints	127	The number of datapoints in the profile
Sample length / mm	Changes per test specimen	The length of the sample

The post processing removes noise that was picked up during the experiment. The profiles from each experiment can then be used to make a 3-D Area chart to show the distribution of water within the specimen, alongside the change of distribution during drying.

2.3.4.3 T1-T2 Data

The data for the T1-T2 experiment contained too much noise and did not give any clear signals so this data has not been processed. This decision was made together with Geir H. Sørland from Anvendt Teknologi after looking at the results in Anahess 2D discrete and distribution.

2.3.4.4 11PFGSE-CPMG Data

The11PFGSE-CPMG experiment produced a time file, a gradient file, and a data file. These are loaded into Anahess 2D discrete, with the time file as the tx-file, and the gradient file as the ty-file and the data file as the data-file. The dataset type is set to Time-Diffusion and the *e(-ty/Ty)*e(-tx*Tx)* kernel is used. The data is then processed until a solution with the lowest BIC number is reached. The solution with the lowest BIC number is then saved as an NCO file and imported into Anahess 2D distribution.

After loading the NCO file in Anahess 2D distribution the input parameters are produced automatically based on the NCO-file. The components are grouped together based on the diffusion coefficient, where components are placed in different groups if the diffusion coefficient is one order of magnitude away from other components. To get an average diffusion coefficient all components are grouped together, and the diffusion coefficient can be found.

3 Results and discussion

3.1 CPMG results.

Before saturation the OW piece had a mass of 3,307 g, with a moisture content of 21,32% and a length of **21** mm. The CW piece had a mass of 0,852 g, a moisture content of 29,76% and a length of **9** mm. After saturation the mass of the OW piece was 3,675 g, and a moisture content of 29,34%. This is an increase of 11,13% in mass. The CW piece had a mass of 1,112 g after saturation, a 30,52% increase in mass.

One of the reasons why the initial free water content is so low can be due to time it took from the felling, sending it to Norway and the start of testing. This may have impacted the results, and further experiments with a known felling date should be considered.

From the T_2 experiment with the CPMG sequence there are two components found in both OW and CW. One with a relaxation time at about 10 ms and one at about 0,4 ms shown in figure 10 for OW and figure 11 for CW. In a sample of water, the relaxation time is 2s shown in figure 12. This shows that the component with the longer relaxation time is likely free water in the lumen, while the other component with the shorter relaxation time is likely bound water in the cell walls.

Figure 13 and figure 14 shows the distribution of mass of the water for each component in the OW and CW samples respectively. The first column for each sample is before saturation and shows that the 10 ms component is significantly smaller than the 0,4 ms component. The next column shows the sample after saturation and the 0,4 ms component has not significantly increased, while the 10 ms component has had a significant increase. This strengthens the claim that the 10 ms component is free water in the lumen of the wood. And that the 0,4 ms component is bound water in the cell walls of the wood.

After saturation there is a difference between the OW and CW. The 10 ms component in the CW sample increases more than in the OW sample. This happens even though OW has thinner cell walls than OW and should therefore be able to take in more water than CW. Reasons for this might be that the OW sample has parts that are more similar to heartwood

closer to the pith. This will be covered more in the next section with the profile experiment data.

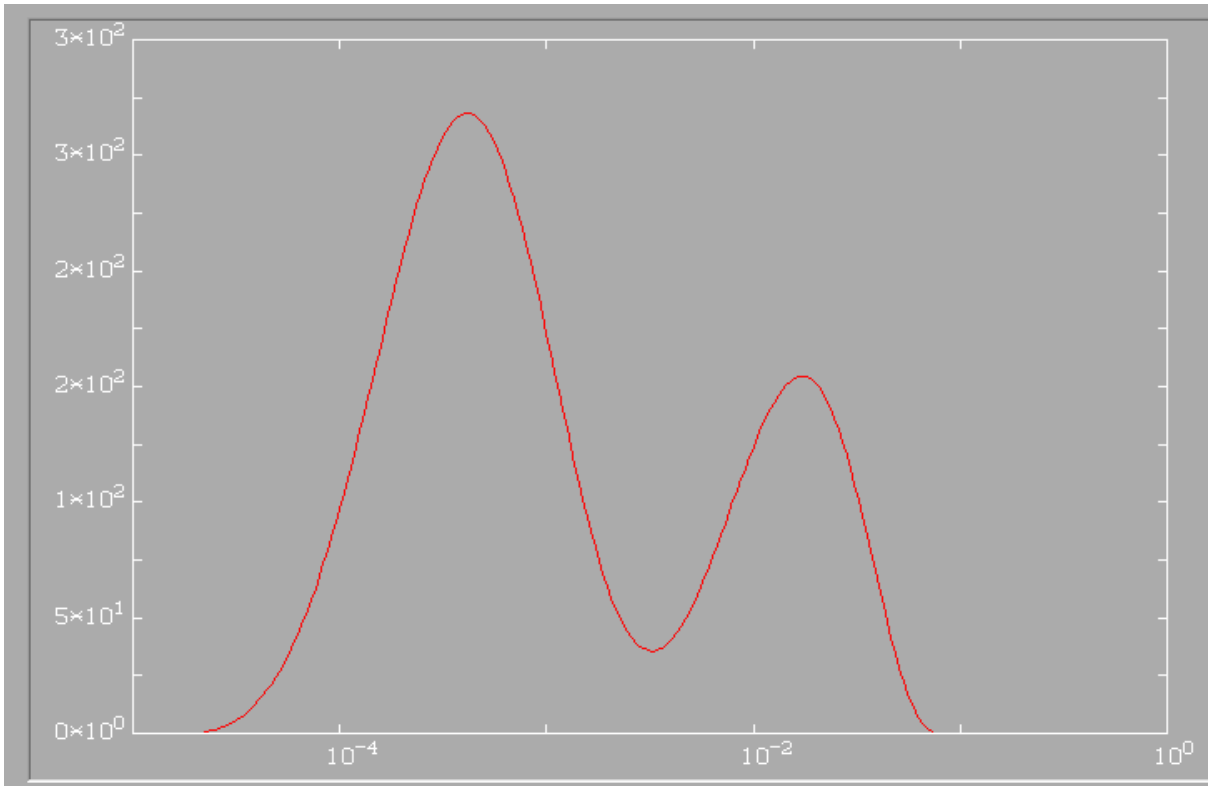

Figure 9 T2 distribution from the CPMG experiment of the saturated OW sample.

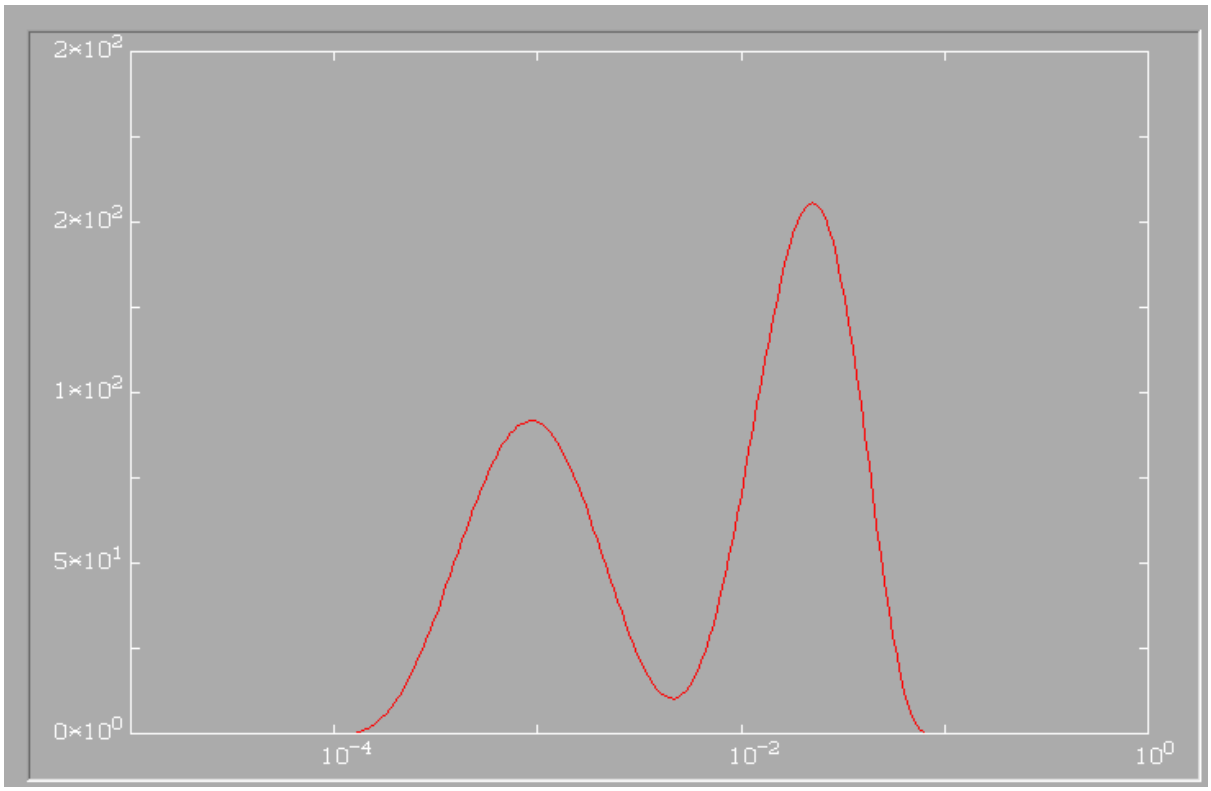

Figure 10 T2 distribution from the CPMG experiment of the saturated CW sample.

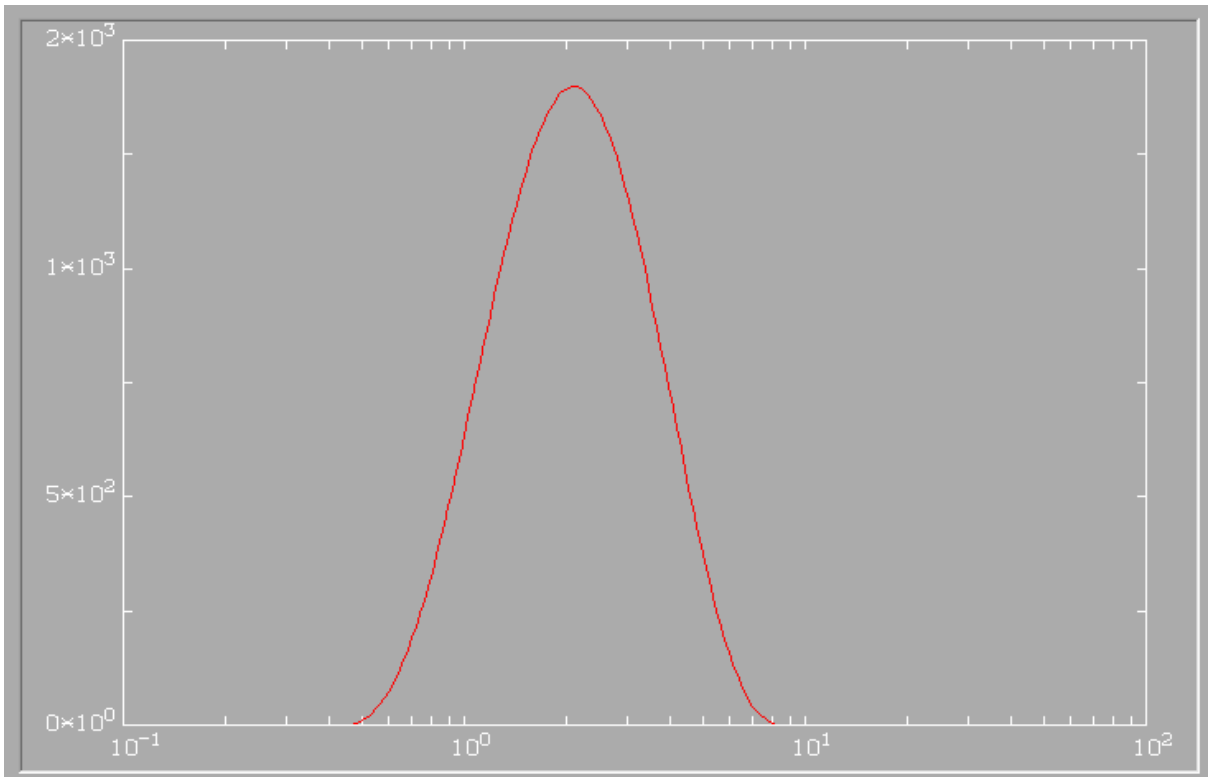

Figure 11 T2 distribution from the CPMG experiment of a pure water sample.

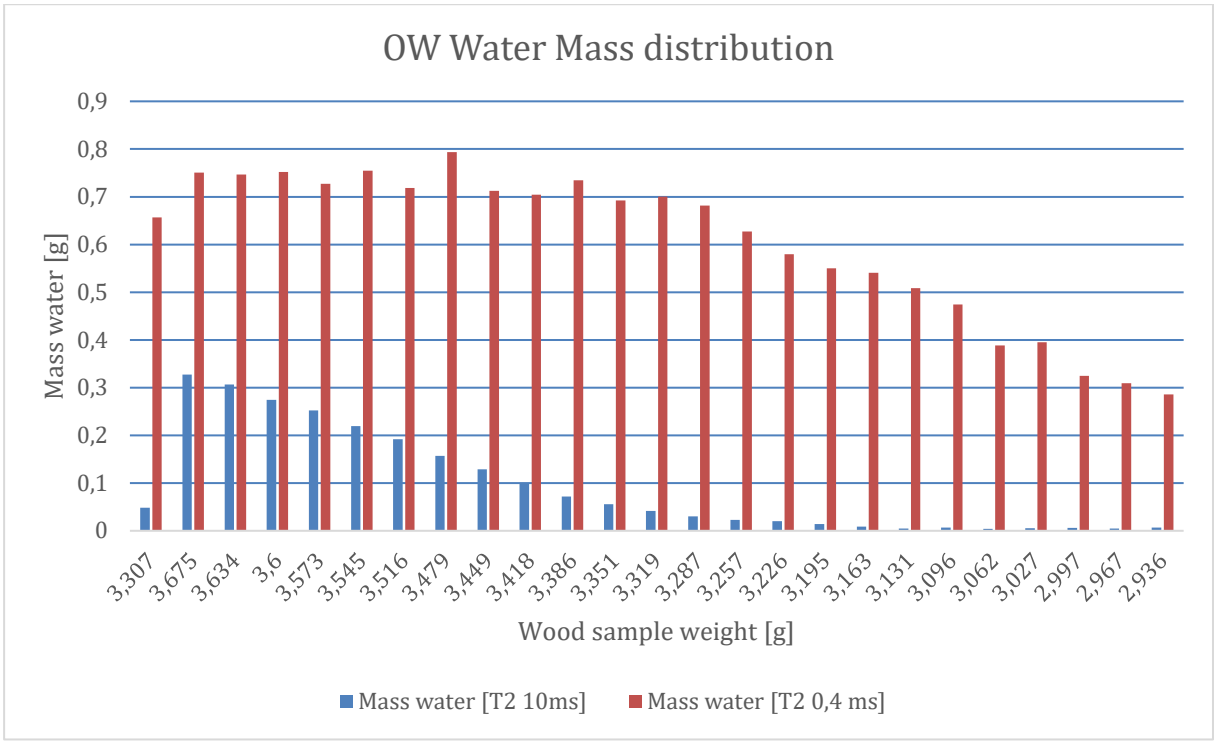

Figure 12 Distribution of mass of water in the sample for each experiment during the drying of the OW sample.

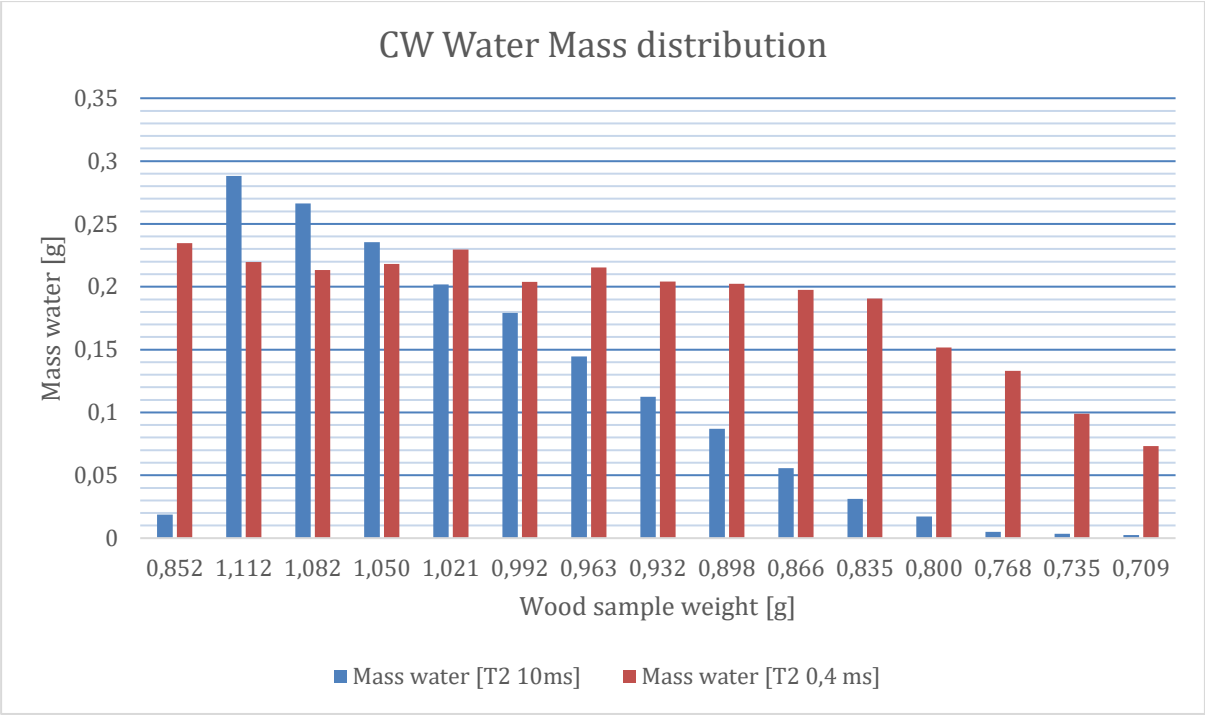

Figure 13 Distribution of mass of water in the sample for each experiment during the drying of the CW sample.

During the drying process figure 13 and figure 14 shows that the free water will disappear first, with most of that component disappearing before any significant reduction in the bound water component. Table 8 and table 9 shows the weight of the OW and CW samples at each step during the testing along with the MC and the distribution of moisture by percent and mass. From test 2 to 14 of the OW sample the bound water component does not change, and all the drying comes from the free water component. When the free water component is less than 4% of the total moisture component the bound water component starts to reduce. This gives the OW sample a FSP at about 20% MC. The CW sample is smaller than the OW sample and doesn't have as many steps. Here the bound water component does not significantly decrease until after test 11. And this gives the CW a FSP at about 25% MC.

Table 8 T2 results of the OW sample showing the moisture content at each step and the distribution between free and bound water at each step.

Test number	Weight wood	Moisture content [%]	Relative area T_2 10 ms [%]	Relative area T_2 0,4 ms [%]	Mass water T_2 10 ms [g]	Mass water T_2 0,4 ms [g]
1	3.307	21.31968	6.848	93.152	0.048281	0.656761
2	3.675	29.33526	30.343	69.657	0.327119	0.750952
3	3.634	28.98217	29.08	70.92	0.306274	0.746938
4	3.6	28.50817	26.733	73.267	0.274359	0.751935

5	3.573	27.41438	25.771	74.229	0.252431	0.727085
6	3.545	27.47191	22.515	77.485	0.219269	0.75461
7	3.516	25.8962	21.106	78.894	0.192172	0.718338
8	3.479	27.32615	16.546	83.454	0.157299	0.793378
9	3.449	24.39485	15.293	84.707	0.128672	0.712707
10	3.418	23.49505	12.309	87.691	0.098849	0.704212
11	3.386	23.81189	8.889	91.111	0.071669	0.734601
12	3.351	22.32285	7.474	92.526	0.055908	0.69213
13	3.319	22.34556	5.581	94.419	0.041391	0.700258
14	3.287	21.65624	4.279	95.721	0.03046	0.681381
15	3.257	19.96594	3.527	96.473	0.022936	0.627355
16	3.226	18.5881	3.386	96.614	0.020304	0.579348
17	3.195	17.64078	2.449	97.551	0.013803	0.54982
18	3.163	17.36061	1.58	98.42	0.008676	0.54044
19	3.131	16.4052	0.976	99.024	0.005013	0.508634
20	3.096	15.54538	1.391	98.609	0.006695	0.47459
21	3.062	12.82994	1.11	98.89	0.004361	0.388492
22	3.027	13.21941	1.304	98.696	0.005218	0.394933
23	2.997	11.02333	1.745	98.255	0.005765	0.324604
24	2.967	10.5876	1.487	98.513	0.004671	0.309463
25	2.936	9.96388	2.238	97.762	0.006547	0.285992

Table 9 T2 results of the CW sample showing the moisture content at each step and the distribution between free and bound water at each step.

Test number	**Weight wood**	**Moisture content [%]**	**Relative area T_2 10 ms [%]**	**Relative area T_2 0,4 ms [%]**	**Mass water T_2 10 ms [g]**	**Mass water T_2 0,4 ms [g]**
1	0.852	29.75768	7.397	92.603	0.018754	0.234781
2	1.112	45.66055	56.745	43.255	0.28812	0.219625
3	1.082	44.33746	55.529	44.471	0.26639	0.213341
4	1.05	43.20365	51.927	48.073	0.235561	0.218078
5	1.021	42.24554	46.793	53.207	0.201831	0.229496
6	0.992	38.60169	46.781	53.219	0.179138	0.203791
7	0.963	37.37288	40.151	59.849	0.144504	0.215397
8	0.932	33.98193	35.542	64.458	0.112566	0.204146
9	0.898	32.22204	30.058	69.942	0.086974	0.20238
10	0.866	29.22376	21.965	78.035	0.055589	0.197489
11	0.835	26.55853	14.044	85.956	0.031144	0.190619
12	0.8	21.11215	10.247	89.753	0.017307	0.15159
13	0.768	17.95367	3.553	96.447	0.004899	0.132985
14	0.735	13.9504	3.397	96.603	0.003483	0.099052
15	0.709	10.68914	3.377	96.623	0.002559	0.073227

3.2 Profile experiment results.

The profile experiment can only pick up one of the components due to the relaxation times. So, when evaluating the profiles the only component being evaluated is the 10 ms component. The OW profile in figure 15 clearly show that most of the moisture is close to the bark, there is a dry spot at the middle of the specimen at around 10 mm, before it goes up again towards the pith. This can be seen in figure 17 where profile of at different heights are looked at. But the moisture content is still lower close to the pith like in stem wood, where there is less moisture in the heartwood compared to the sapwood. Figure 16 is a picture of the OW sample, oriented the same direction as the profile in figure 15 with the bottom axis being the height of the sample.

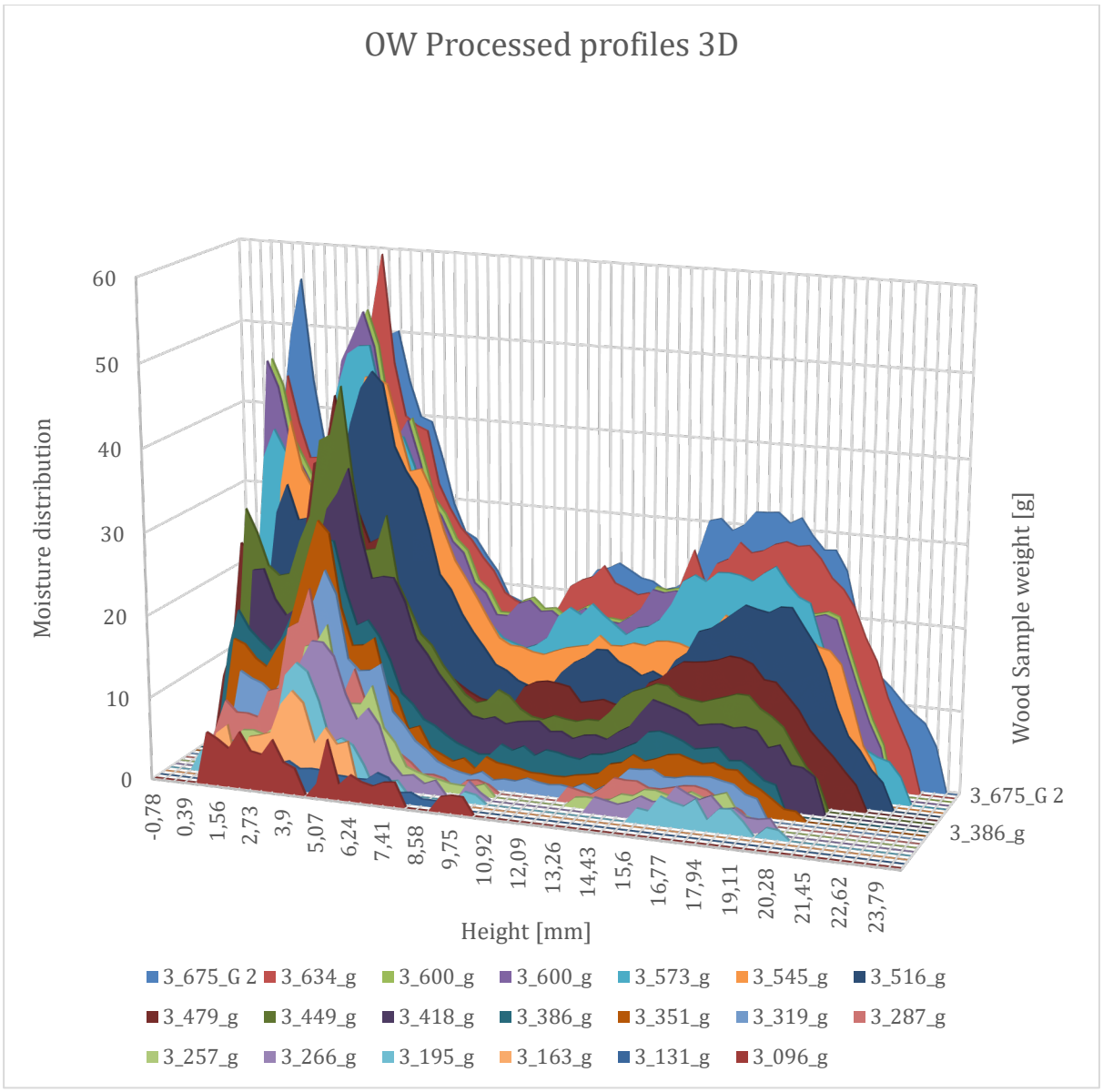

Figure 14 Water content profiles of the OW sample. The bark is at 0 mm and the pith is at 21.5 mm

Figure 15 OW sample oriented in the same direction as the profile with the bark to the left at z=0 mm and pith to the right at z=21,5 mm

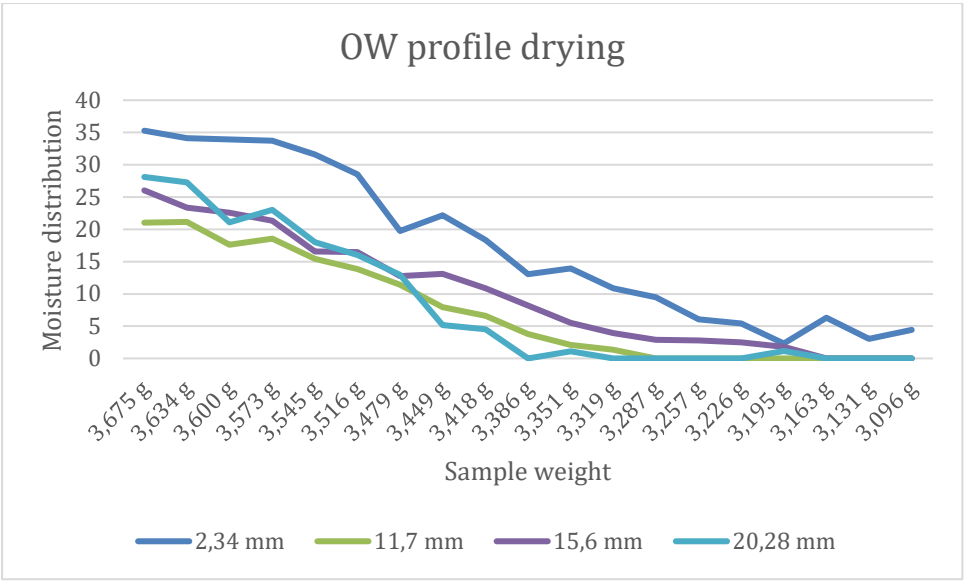

Figure 16 water content at different heights of the OW sample during drying.

In CW there the profile is similar to the OW profile, with more water at the bark, and less at the pith. But unlike OW there isn't a dry spot in the middle in the CW as seen in figure 16. This can be either because of the difference in structure in the wood, or due to the size difference of the samples. With the OW sample being over twice the length of the CW sample. figure 20 shows the water distributions at two different heights of the CW sample, with the lower height closer to the bark containing significantly more water than the height closer to the pith. figure 19 shows the CW plug oriented the same direction as the CW profile figure, with the bark side at 0 mm to the left and pith side at 9 mm to the right.

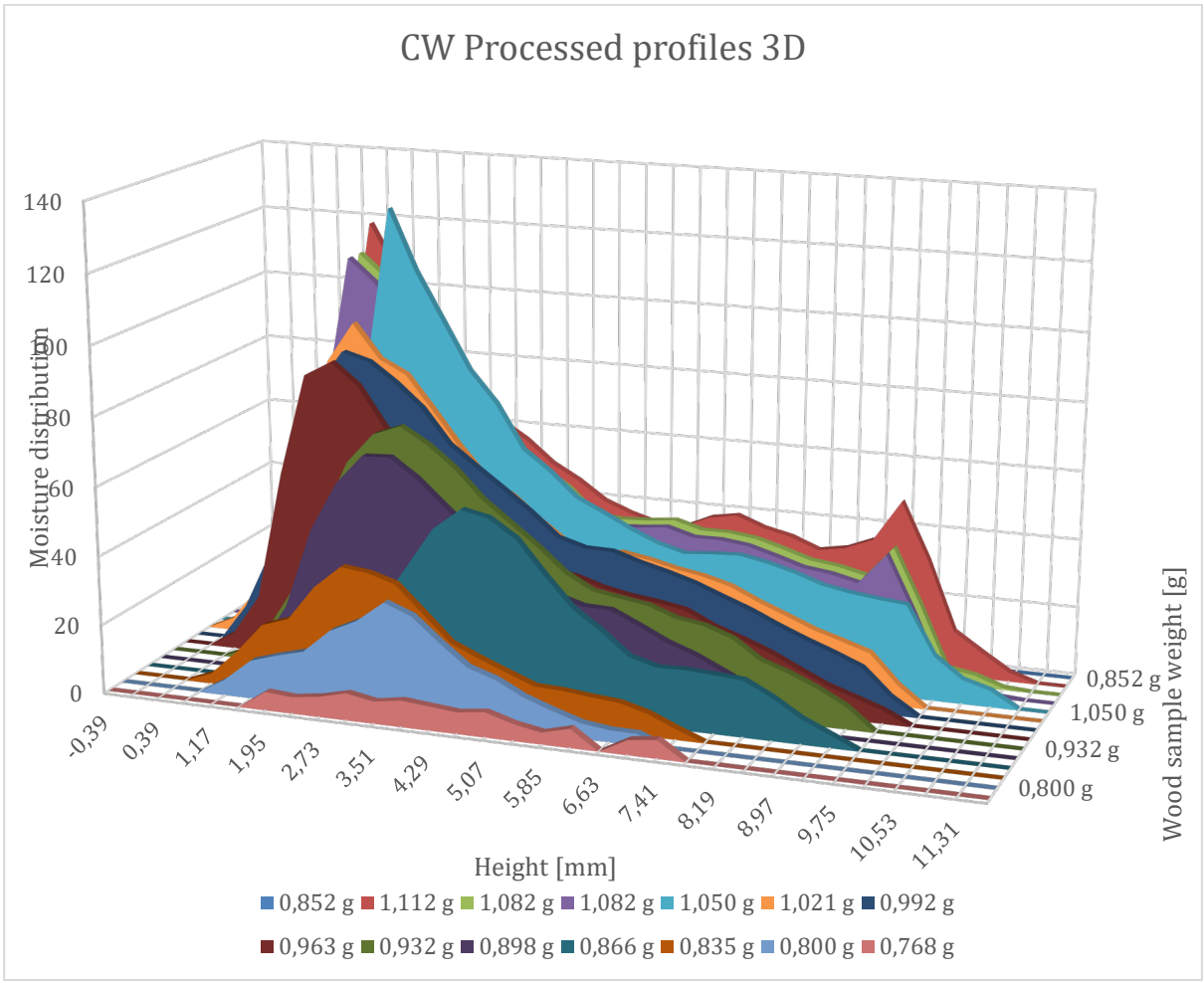

Figure 17 Water content profiles of the CW sample during.

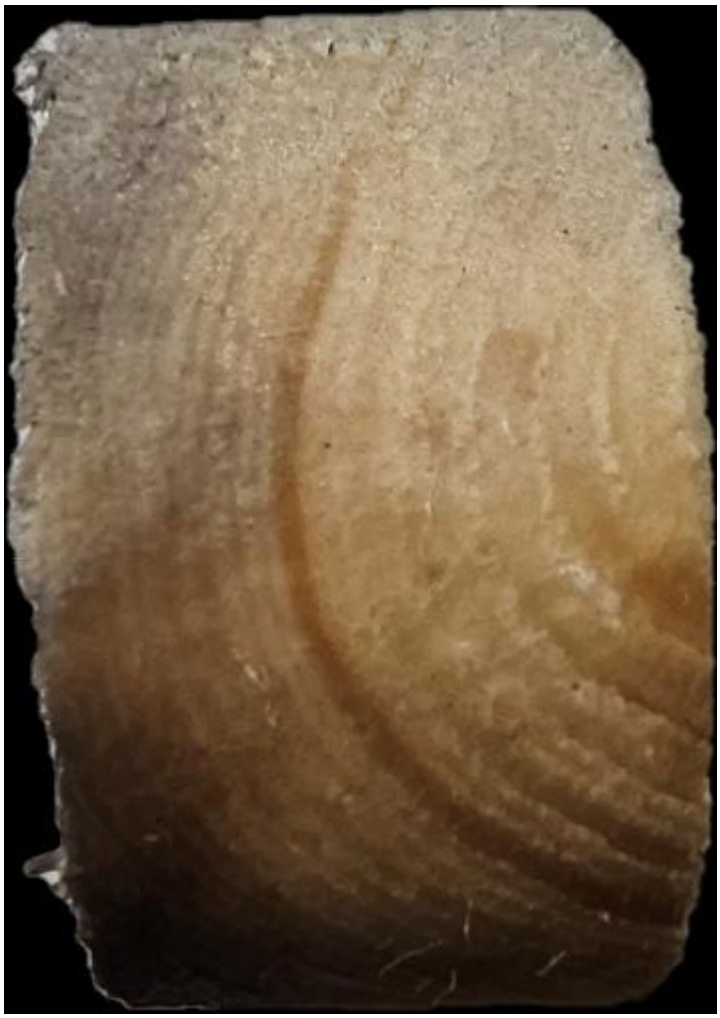

Figure 18 CW sample oriented in the same direction as the profile with the bark to the left at z=0 mm and pith to the right at z=0,9 mm

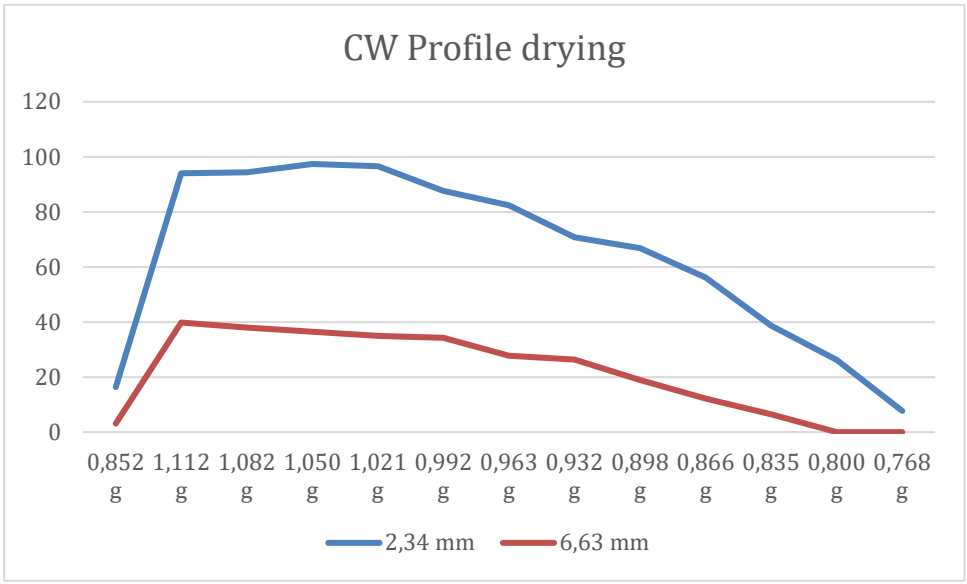

Figure 19 water content at different heights of the CW sample during drying.

3.3 11PFGSE-CPMG Results.

The diffusion-T_2 experiments give the diffusion coefficients for the 10 ms free water component at each step during the drying until the signal is too weak, and the equipment pics up too much noise. The 0,4 ms bound water component is not detected in this experiment due to the relaxation time being too fast to acquire a signal. Table 10 shows the mean diffusivity coefficient obtain at the different drying stages for the OW sample. The diffusivity found when the sample has a considerable amount of free water is higher than the diffusivity of heartwood and sapwood as seen in table 2. Except for the last couple of experiments where the diffusion coefficient is close to the ones for heartwood and sapwood in table 2.

Table 10 Mean diffusion coefficients for the OW sample.

Weight wood [g]	Mean diffusion coefficient $[10^{-10}\ m^2/s]$
3,307	10,7
3,675	12,1
3,634	10,3
3,6	11,5
3,573	9,43
3,545	11,6
3,516	10,8
3,479	9,56
3,449	11,3
3,418	10,3
3,386	9,9
3,351	10,8
3,319	11,1
3,287	12,4
3,257	10,9
3,226	6,51
3,195	4,68

The diffusion coefficients for the CW sample are shown in table 11. Here the diffusion coefficients are close to the ones found for the OW sample, and a bit higher than for the heartwood and softwood. This confirms that the mobility for free water is considerably higher than the mobility for bound water in Norway Spruce.

Table 11 Mean diffusion coefficients for the CW sample.

Weight wood [g]	Mean diffusion coefficient [10^{-10} m^2/s]
0,852	9,22
1,112	11,4
1,082	11,4
1,050	11,3
1,021	11
0,992	9,18
0,963	9,17
0,932	9,79
0,898	9,49
0,866	7,78
0,835	8,89
0,800	9,44

The mean diffusion coefficient of all the steps during drying is 10,19 * 10^{-10} m^2/s in the OW sample and 9,9 * 10^{-10} m^2/s in the CW sample. The diffusion coefficients found for the free water of both samples show a higher mobility than the diffusion coefficients for Norway spruce. And implies that the mobility of the bound water is lower than the mobility of the free water.

3.4 Further thoughts

The experimental data found in this project are promising, but a few factors need to be taken into consideration. The branch specimen was frozen and sent from Sweden to Norway. There were several delays with the shipment, and the freezing and long transport time may have had an effect on the wood. There was also only performed experiments on one OW sample and one CW sample drilled out from the branch in the radial direction. Further testing on wood from other branches with OW and CW samples made in the tangential and longitudinal directions can give more information and increase the confidence in the results found in this project.

4 Conclusion

Through this work it has been shown that water in wood can be studied by nuclear magnetic resonance. Both the water fraction bound to cell walls and the free water in the cell lumina have been observed through varying wood moisture content. It was also possible to observe the water profile throughout the branch stem, and the self-diffusion coefficient of water in the cell lumina.
The one-dimensional T_2-experiment shows that the free water component evaporates before the bound water component in both samples. The FSP for the OW sample is at a MC of about 20%. With the free water component being 4% of the remaining water and the bound water being 96% of the remaining water. In the CW sample the FSP is at a MC of about 25%. With the remaining water being distributed as 14 % free water and 86% bound water. Showing a difference in the FSP between the two regions of branch wood in Norway spruce.
The profile experiment shows how the concentration of free water is distributed throughout the sample. Both samples contain more water closer to the bark, and less towards the pith. The OW sample has a dry spot in the middle of the sample, with the water concentration increasing a bit towards the pith. The water distribution shows that branch wood share similarity to stem wood by exhibiting traits similar to heartwood and sapwood. The diffusion-T_2-tests gives the mean diffusion coefficient for the free water in each sample. The OW sample has a mean diffusion coefficient of $10{,}19 * 10^{-10}$ m^2/s. And the CW sample has a mean diffusion coefficient of $9{,}9 * 10^{-10}$ m^2/s. The free water of both samples has higher mobility than all moisture in Norway spruce implying that the bound water has a lower mobility than the free water. These tests are conducted on a single sample of OW and CW, and more research using the same method with plugs made in the tangential and longitudinal directions of the wood can reveal more data about the mobility of water in Norway spruce.

Bibliography

1. Callister, W.D. and D.G. Rethwisch, *Materials Science and Engineering*. 2014: Wiley.
2. Theodore, L. and F. Ricci, *Mass transfer operations for the practicing engineer*. 2010, Wiley: Hoboken, N.J.
3. Fengel, D. and G. Wegener, *Wood : chemistry, ultrastructure, reactions*. 1989, Walter de Gruyter: Berlin ;,New York.
4. Stokke, D.D., et al., *Introduction to Wood and Natural Fiber Composites*. 2013, Newark, UNITED KINGDOM: John Wiley & Sons, Incorporated.
5. Silvester, F.D., *Timber : its mechanical properties and factors affecting its structural use*. 1967, Pergamon Press: Oxford, England ,London, England.
6. Fröbel, J. and P. Bergkvist, *Att välja trä*. 2020, Svenskt Trä.
7. Tarmian, A., et al., *Inter-Tracheid and Cross-Field Pitting in Compression Wood and Opposite Wood of Norway Spruce (Picea abies L.).* Notulae scientia biologicae, 2011. **3**(2): p. 145-151.
8. Mayr, S. and H. Cochard, *A new method for vulnerability analysis of small xylem areas reveals that compression wood of Norway spruce has lower hydraulic safety than opposite wood.* Plant, cell and environment, 2003. **26**(8): p. 1365-1371.
9. *Moisture properties of wood*. 2020 [cited 2024 02.02]; Available from: https://puuinfo.fi/puutieto/wood-as-a-material/moisture-properties-of-wood/?lang=en.
10. Larsen, Ø.S. *Norsk Standard 4414 – Ved til brensel i husholdninger*. 2021 [cited 2024 06.02]; Available from: https://www.norskved.no/norsk-standard-4414.
11. Grøn, Ø., *Termodynamikk for høgskole og universitet*. 2015, Oslo: Cappelen Damm akademisk.
12. Bremaud, I., *Acoustical properties of wood in string instruments soundboards and tuned idiophones: Biological and cultural diversitya: Musical Acoustics.* The Journal of the Acoustical Society of America, 2012. **131**(1): p. 807-818.
13. Bertaud, F. and B. Holmbom, *Chemical composition of earlywood and latewood in Norway spruce heartwood, sapwood and transition zone wood.* Wood science and technology, 2004. **38**(4): p. 245-256.
14. Gryc, V.M.Z.a.L.U.B.U.N.o.D. and H.M.Z.a.L.U.B.U.N.o.D. Vavrcik, *Effects of the position in a stem on the variability of tracheids in spruce (Picea abies /L./ Karst.) with the occurrence of reaction wood.* Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis, 2014. **58**(2): p. 77-86.
15. Sehlstedt-Persson, M. *The effect of extractive content on moisture diffusion properties for Scots pine and Norway spruce*. in *European Cost E15 Workshop on Wood Drying (2001): 11/06/2001-13/06/2001*. 2001. VTT Building and Transport.
16. Sørland, G.H., *Dynamic Pulsed-Field-Gradient NMR*. 2014, Springer Berlin Heidelberg : Imprint: Springer: Berlin, Heidelberg.
17. Sørland, G.H., et al., *Improved Methods for Characterizing Emulsions by Low-Resolution Nuclear Magnetic Resonance via Surface Relaxation and One-Dimensional Images.* Applied Magnetic Resonance, 2023. **54**(6): p. 619-635.
18. Sørland, G.H., *Manual brine profile*. 2020, Anvendt Teknologi AS.

Appendix

Appendix A – Task Description

Appendix B - Pre-study report

UiT
THE ARCTIC
UNIVERSITY
OF NORWAY

Faculty of Engineering Science and Technology
Department of Industrial Engineering
Date: 30.10.2023

Industrial Engineering, Master Thesis 2023/2024, part I
INE-3900

Stud. Techn. Henrik Rødal Ler

Title

1. Introduction

The moisture content of woodchips plays a decisive role when used as biomass for district heating systems. This project aims to describe the physical process of vaporization of confined water in wood used in district heating systems. The project is part of a twin project with Uppsala University. One master student in Uppsala will focus on the three-dimensional finite element modelling of the diffusion process in wood during drying using the actual microstructure of wood based on X-ray computed tomography scans. The master student here in Narvik will investigate the diffusion of water confined in the wood experimentally with NMR. The determined diffusion coefficient will be used in the Uppsala twin-project as material input parameters.

The student's work tasks during phase I will mainly consist of making a survey of the theory and literature related to NMR and diffusion of moisture in wood.

The work should be based on the requirements to perform the practical work for phase 2

2. Scope

1. Conduct a literature review on
    a. Pulsed field gradient NMR
    b. Mass transport by molecular diffusion
    c. Microstructure of softwood such as Norway spruce and Scots pine
2. Prepare a Report on the findings.
3. Prepare a PowerPoint presentation and give an oral presentation of the work performed.

3. General

Master thesis at Industrial Engineering is divided into two parts where the total allocated time is limited to 27 weeks fulltime work, corresponding to 45 study points.

Part I

In general, this part is an introduction to the project and is often a literature review especially adapted to meet the challenges within the project as well as to strengthen the competence of the candidates in a given field or direction. Part I study counts for 1/3 of the total time allocated to the project. This part has to be finished with a PowerPoint presentation and a written report after approximately 9 weeks fulltime work. Any written documentation of the thesis part I has to be enclosed or integrated in the final thesis reporting.

Part II

This is the main part of the master thesis within the Industrial Engineering education, and is a R&D project. The part II study counts for 2/3 of the total time allocated to the project. The final report with all accompanying documentation has to be handed in after approximately 18 weeks full-time work.

Within three weeks (full-time work) after the start of Part I, a pre-study report shall be prepared. The report has to include the following (a pre-study report template exists):

- An analysis of the work task's content specifically emphasizing the areas where new knowledge has to be gained.
- A description of the work packages that have to be performed. This description shall lead to a clear definition of the scope and extent of the total task to be performed.
- A time schedule for the project. The plan shall comprise a Gantt chart with specification of each individual activity/work package, their scheduled start and end dates, and a specification of project milestones.

The pre-study report is a part of the total thesis reporting and has to be enclosed with the final report. This includes also all progress reports made during the working period as well as the original task description. (A progress report template also exists.)
The final report should be edited as a research report with a summary, table of contents, conclusion, list of references, list of literature etc. The text should be clear and concise, and include the necessary references to figures, tables, and diagrams. It is also very important that exact references are given to any external sources used in the text.
All documentation developed during the work, e.g. computing programs, measuring results, drawings and models are parts of the final report and have to be enclosed.
The final report will be evaluated and basis for the grade of the master thesis.

If the work is performed in cooperation with an external organization, the candidate has to comply with the actual organization’s company regulations and possible other relevant orders from the company’s management. The candidate has no opportunity to interfere with the organization’s information systems, manufacturing equipment or the like. If this should be relevant in connection with the execution of the tasks, it has to be authorized by the organization’s management.

Any travel, copying, phone or other expenditures have to be covered by the students themselves, unless other agreements have been established.

If the candidate encounters unforeseen difficulties during the work, and if these difficulties warrant a reformulation of the tasks, these problems should be addressed immediately to the supervisor at the faculty.

4. Deadlines and participants

Date of hand out part I:	8th November 2023
Date of progress report:	8th December 2023 Progress report to be submitted to the Principal supervisor before the deadline.
Date of hand in part I	12th January 2024.
Presentation in part I:	PowerPoint presentation and give an oral presentation of the work in mid-January 2024.
Date of hand-out part II:	After presentation and approval of part I.
Date of hand in part II (final report):	15th May 2024.
Student(s):	Stud. techn. Henrik Rødal Ler, address: Sildretunet 15B 8515 Narvik, mobile phone: 98499119, E-mail: hle043@uit.no ler.henrik@gmail.com
Supervisor:	Professor Espen Johannessen, Faculty of Engineering Science and Technology, office phone: +4776966263, mobile phone: 95054969, E-mail: espen.johannessen@uit.no
Co.-supervisor:	Dr Sara Florisson, Postdoctoral researcher, Uppsala University, Division of Applied Mechanics, Uppsala, Sweden, sara.florisson@angstrom.uu.se
Company liaison:	
Obligations and acceptance:	By signing this task document I am/we are fully aware of the consequences of not following the respective delivery dates defined above. I also accept the obligations this task description implies. I /we have received this task description: Date:30.10.2023 Students' signatures: Henrik R. Ler .....

Faculty of Engineering Science and Technology

Espen Johannessen

Professor

(sign.)

5. Cooperation agreement in connection with the master thesis work

The following agreement has been entered into by the following master students:

Xx and Zz

Amount of work: A total work load of about 1200 hours for each participant during the whole project period (27 weeks) is assumed. This means that each participant should have a work load of about 45 hours per week.

Planning: Activities have to be defined and a time schedule has to be prepared for both part I and part II (see the description of part II above).

Progress meetings: Progress meetings together with the supervisor will be held by the end of each month during the whole project period. Date and time has to be decided in agreement with the supervisor. The students have to prepare a progress report before each meeting, and it is recommended to write minutes of meeting afterwards.

Evaluation of progress and working methods: This has to be a permanent item on the agenda in each status meeting. Any project delay has to be reported and justified, and actions to make up for lost time must be clarified.

Obligation to inform: Absence of any of the participants has to be notified immediately to the supervisor and possible actions taken.

Working environment: A friendly and open attitude has to be present among the participants throughout the project. If any of the participants is dissatisfied with anything this should be addressed in the status meeting. An open and positive communication that will encourage and inspire the participants should be endeavoured.

Common grade: The result of the master thesis work (the final report) will be evaluated as a whole, and a common grade will be given.

Through their signatures, it is confirmed that the participants have read and accepted the content of this agreement:

…….. ……..

Sign. Sign.

Master Thesis - the Pre Study Report

The objective of the pre study report is to make sure that the student understands what kind of tasks she/he is going to perform, and that she/he is able to show how they will be fulfilled.

The pre study report shall include a project definition, analysis and description of the project tasks and scope, activity lists and Gantt chart. The Gantt chart specifies different tasks/activities, their scope, scheduled start and end dates, dependencies, milestone meetings and progress reports.

A project definition template may be used (see attachment 1).

Use the front page shown in attachment 2.

A suggested content of the pre study report - see attachment 3.

An activity description template (see attachment 4) may be used to describe each activity.

MS Project (or any other simpler software) may be used to construct the Gantt chart.

Use Times New Roman 12 for the normal text, and use Times New Roman Fat 14 for main headings.

Use spellchecker.

Do not forget to specify any references!

Project definition template:

Elements	Descriptions
Project title (4 – 12 words):	Short, descriptive, official project title.
Project sponsor(s):	Supervisor. (Possible external organization's liaison.)
Project manager:	Name and % of time committed to this project.
Project team:	Individual names and % of time committed to this project. (It is supposed that a total workload of part II is about 800 working hours per student.)
Problem statement:	The problem to be addressed and resolved.
Project description/benefits:	Project context, background and expected benefits.
Theory/hypothesis:	Identify/define/describe.
Assumptions:	Identify/define/describe.
Risks/constraints:	Obstacles to achieving the project objectives.
Specific objectives:	What will be achieved?
Scope:	What is and is not included in the project? (Possible external organization's liaison has agreed.)
How status will be reported:	How information will be exchanged with supervisor (and external organization's liaison) throughout the project cycle.
Start date /Est. timeline:	Start date and planned schedule (Gantt-chart). (With normal progress and full time work you will have a total of 21 weeks (included eastern) to complete the thesis work part II. This means from the official start date until the date of hand in of the final report.)
Completion target date:	Final report delivered and presented, and project team is disbanded.

UiT
THE ARCTIC
UNIVERSITY
OF NORWAY

Faculty of Engineering Science and Technology
Department of Industrial Engineering

Attachment 2

Master of Science – Industrial Engineering

Master Thesis – Pre Study Report

(INE-3900)

Diffusion of Water in Wood

Author(s):
Stud. Techn. Henrik Rødal Ler

01/11/2023

Title: Investigation of Diffusion of Water in Wood using Nuclear Magnetic Resonance	*Date:01/11/2023* *Classification:*
Author(s): Henrik Rødal Ler	*Number of Pages:* *Number of Attachments:*
Subject Name: Master Thesis - Pre Study Report	*Subject Code:* INE-3900
Faculty: Engineering Science and Technology	
Master Program: Industrial Engineering	
Supervisor: Espen Johannessen	
Co-supervisor: Sara Florisson	
External Organization/Company:	
External Organization's/Company's Liaison:	
Keywords (max 10): Diffusion, PFG-NMR, Mass transport	
Abstract (max 150 words):	

Table of Contents (suggested)

1. Introduction

The moisture content of woodchips plays an important role when used as a biomass for heating systems. To ensure smooth operation and efficient heating from the woodchips controlling the moisture content is important.

2. Background

3. Problem statement

UiT and Uppsala university in Sweden have a twin project that aims to describe the physical process of vaporization of confined water in wood used in district heating. The master student in Uppsala will focus on the three-dimensional finite element modelling of the diffusion process of wood during drying using the actual microstructure of wood based on X-ray computed tomography scans.
To be able to accurately simulate the diffusion process experimental data is required and the goal for this project is to determine the diffusion coefficient of porous water in wood samples experimentally by using nuclear magnetic resonance. Verification of the observed diffusion and the simulation of the diffusion in the tomography scans will provide a basis for industrial application of the method.

4. Project description/benefits

Using simulation to estimate the drying process can

- Relate wood material properties with water content
- Wool lumber industry can monitor the material during drying
- Improve the understanding of wood combustion with varying degrees of water content
-

5. Theory/hypothesis

- The NMR water diffusion test will result in a diffusion coefficient for the diffusion of moisture in water that can be used for accurate simulation of drying wood.

6. Assumptions

7. Risks/constrains

Lack of knowledge on NMR and unfamiliarity with the use of equipment to perform the experiment is a challenge. This can result in bad data, making the simulation inaccurate.

8. Objectives

a. To perform a NMR water diffusion test on wood samples to determine the diffusion coefficient of Norway Spruce and Scots Pine during the drying process.
b. Use observed diffusion coefficients for interpretation of the wood cellular structure
c. Correlate the observed diffusion with the corresponding simulations of diffusion

9. Scope

- Work on Scots Pine and Norway Spruce
- Water molecular diffusion measured
- Water content in samples varying from saturated to when water is no more detectable

10. Organization

Main activities

Milestones

Progress monitoring

Status reporting

11. Costs

12. References

13. Attachments

1. Activity description number 1
2. Activity description number 2
3. .....
4. ……..
5. Gantt-chart

Activity description:

Project title:		*Date:*	*Sign:*
Activity no:	*Activity name:*		
Responsible:			
Task description/intention:			
Scope:			
Method:			
Dependency:			
Documentation/results:			
Written by:		*Duration (days/weeks):*