PROTON MAGNETIC RESONANCE OF WESTERN RED CEDAR

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ABSTRACT

The potential of proton magnetic resonance techniques, in particular magnetic resonance imaging, for analysis of western red cedar has been investigated. Proton magnetic resonance experiments were carried out on normal sapwood, heartwood and juvenile wood and on rotten juvenile wood from western red cedar logs at a range of hydration levels. Signals from the solid wood and the water were readily distinguishable, and the solid wood signal was characterized by its second moment, which was about 5×10^9 s^{-2} above the saturation point for all samples and increased by about 20% below the fiber saturation point. The water signal was separated into earlywood tracheid lumen water, latewood tracheid and ray lumen water, and bound water on the basis of spin-spin relaxation times. In the normal log, heartwood and juvenile wood had substantially less water and also shorter spin-spin relaxation times than the sapwood. The rot sample had considerably more water than normal juvenile wood. With proton NMR the sapwood/heartwood boundary of western red cedar can be distinguished easily, but the heartwood/juvenile wood boundary is more difficult to discern. Rot should be identifiable from surrounding normal wood, especially if in heartwood or juvenile wood. With current technology, magnetic resonance imaging facilities can produce cross-sectional images of whole cedar logs; however

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these images are mainly of earlywood tracheid lumen water and hence show only about 60% of the water in a normal western red cedar log.

Keywords: Western red cedar, proton magnetic resonance, heartwood, sapwood, moisture content.

INTRODUCTION

Proton magnetic resonance (^{1}H NMR) is a promising technique for the nondestructive investigation of wood structure on both the microscopic and macroscopic levels. ^{1}H NMR, which is responsive to all hydrogen nuclei in a wood sample, provides details on both structure and molecular motions (for an introduction to NMR, see, for example, Fukashima and Roeder 1981 or Slichter 1978).

It has recently been demonstrated (Menon et al. 1987) that in western red cedar sapwood the ^{1}H NMR signals from water in cell walls, water in latewood tracheids, and rays and water in earlywood tracheids can be differentiated on the basis of spin-spin relaxation time (T_2). Proton magnetic resonance can also be used to image the spatial distribution of water in wood. The water in earlywood tracheids, that in latewood tracheids, and the bound water have been imaged separately (Menon et al. 1989) by taking advantage of the differences on T_2 values for water in the different microenvironments. It therefore seems clear that ^{1}H NMR is the most detailed and direct technique available for the investigation of water in wood.

The signal from solid wood, which can readily be distinguished from that of water, contains information on the motional state of the wood polymer molecules. The second moment of the proton NMR spectrum for solid wood, M_{2r}, may be quantitatively related to the dynamic structure of the cell walls (MacKay et al. 1985, 1988).

The application of proton NMR to wood is not new. Several continuous wave broadline NMR studies (Odijama 1959; Swanson et al. 1962; Nannasy 1973, 1974, 1976, 1978; Rakos et al. 1984) and pulsed NMR studies (Sharp et al. 1978; Riggin et al. 1979; Hsi et al. 1977; MacGregor et al. 1983; Peemoeller et al. 1985; Byrne et al. 1986) have been carried out on wood. Also, recently, a number of magnetic resonance imaging (MRI) studies (Burgess 1984; Hailey et al. 1985; Hall et al. 1986; Hall and Rajanayagm 1986; Wang and Chang 1986) have been made on whole logs showing how the spatial distribution of water inside wood can be imaged by NMR. All of these studies have demonstrated how the water signal can be distinguished from the solid wood signal, but most failed to appreciate how the water signal could be quantitatively subdivided into contributions from the different water microenvironments, thereby providing much more information on wood water associations.

It seems likely that in the future MRI will play an important role in the quantitative measurement and understanding of the distribution of water in wood. The aim of this work was to discover, on a fundamental level, what information proton magnetic resonance can provide about wood. Such a study is essential before ^{1}H NMR can be fully utilized as a technique for the bulk internal scanning of wood. Here, we report on the detailed examination of ^{1}H NMR of western red cedar (*Thuja plicata* Donn) sapwood, heartwood, juvenile wood, and also rot in order to characterize quantitatively the NMR signal from the various types of wood. Since proton magnetic resonance has a potential application to studies on the

drying of wood, we have investigated the nature of the NMR signal of each type of wood at different hydration levels. Most of our measurements were made on small samples ($\approx$0.25 cm^3) using a solid state NMR spectrometer capable of detecting the signal from all the hydrogen nuclei in the wood. These results were then compared to cross-sectional magnetic resonance images obtained from the whole logs from which the small samples were cut. This comparison has enabled us to provide for the first time a quantitative assessment of the potential of MRI for internal scanning of cedar.

MATERIALS AND METHODS

Samples

The cedar sapwood, heartwood, and juvenile wood samples were cut from a 3-cm-thick cross-sectional slice of a fresh-cut sound western red cedar log. The rot sample, which contained brown cubical rot, was obtained similarily from a different log.

The NMR samples measured approximately 1 × 0.55 × 0.55 cm, with the long axis of the block parallel to the longitudinal tracheids in the wood. Each sample was placed at the bottom of a 18-cm-long, 10-mm OD NMR sample tube. A 16-cm-long glass dowel, 8 mm in diameter, was inserted in the tube, just above the wood, to minimize the air space with which the wood could equilibrate. The tube was sealed with a tight-fitting plastic cap.

Moisture was removed from the sample by drying for a few minutes at 70 C under 760 mm of vacuum with the cap removed. The tube was then removed from the oven, recapped, and left to equilibrate for 2 hours before the next NMR measurement. The sample tube, with sample, was weighed after each measurement.

The stepwise moisture removal process was continued for a varying number of steps until the sample was nearly dry. The sample was then removed from the tube and oven-dried to constant weight to determine the oven-dry MC at each point in the experiment.

NMR methods

Proton NMR measurements were carried out on a modified Bruker SXP 4-100 NMR spectrometer operating at 90 MHz. The data acquisition and analysis system, which is described in detail in the literature (Sternin 1985), included a MicroVax I and a National 32016 computer, a Nicolet 2090 digital oscilloscope, and a locally built pulse programmer.

The wood samples were always placed in the NMR probe in the same orientation with the longitudinal axis perpendicular to the magnetic field.

Moisture contents and second moments were measured using the solid echo pulse sequence:

$$(90_0 - \tau - 90_{90}) - \mathrm{TR} - (90_{180} - \tau - 90_{90}) - \mathrm{TR}$$

The τ value was 10 μsec, chosen to slightly exceed the 8 μsec recovery time of the receiver. The recycle time, TR, was 10 sec, which was more than 5 times the T_1 value for the samples. For each echo, 4,096 points were digitized with a dwell time of 0.5 μsec from a pretrigger point located 100 μsec before the first 90 pulse

of each solid echo sequence. One hundred echoes were signal averaged with alternate echoes being added and subtracted from the cumulative data memory.

To determine the water T_2 values and their populations, the Carr-Purcell-Meiboom-Gill (CPMG) pulse sequence (Carr and Purcell 1954; Meiboom and Gill 1958) was used:

$$90_0 - \tau/2 - (180_{90} - \tau)_n - TR$$

The recycle time was again 10 sec. For the sapwood sample, a τ value of 400 μsec was used and 100 μsec was used for the other samples that had shorter T_2 components. Four equally spaced points were digitized on each of the first 224 echoes and on every fourth echo of the next 2,048 echoes. One hundred scans were collected and signal averaged.

Magnetic resonance images were obtained using the 0.15 Tesla Picker Facility located at the Health Sciences Centre at the University of British Columbia. Cross-sectional images were taken from the sound and the rot containing logs with a 45-cm field of view, in both instances approximately 15 cm from where the previously described samples were removed. Multiple spin echo images were obtained using 256 views, 8 repetitions, a TR value of 500 msec and echo times (TE) of 26, 52, 78, 104, 130 and 156 msec.

Anatomical methods

Samples for scanning electron microscopy were taken from just above each of the four NMR samples. Cross and tangential sections were cut from these new sample blocks, mounted on buttons and sputtercoated with gold. Photomicrographs of these sections, at 25 power magnification, were acquired by a Cambridge Stereoscan 250 scanning electron microscope (SEM) operating at 20 kV. This SEM was located in the Department of Biological Sciences at the University of British Columbia. The anatomical dimensions were measured using a four-times enlargement of each of the original negatives.

The specific gravity of each of the samples was determined using the green volume and the oven-dry weight.

The hydrogen contents of each sample were measured by Canadian Microanalytical Service Ltd. (New Westminster, B.C.) using a Carlo Erba Model 1106 Elemental Analyser.

RESULTS

In Fig. 1, the ^1H NMR signals following a solid echo pulse sequence are illustrated for the undried sapwood, heartwood, juvenile wood, and rot samples. Two distinct components are obvious: a rapidly decaying signal from the relatively immobile protons in the solid wood and a slowly decaying signal from the mobile protons in the water.

All moisture contents used in the results are oven-dry moisture contents. NMR moisture contents were monitored during the experiment by multiplying the ratio of water to wood signal intensities by the ratio of the hydrogen content of wood to that of water. Hydrogen contents for the sapwood, heartwood, juvenile wood, and rot samples were 6.28%, 6.14%, 6.13% and 5.27%, respectively. When compared to the oven-dry values, the solid echo moisture contents, which we have

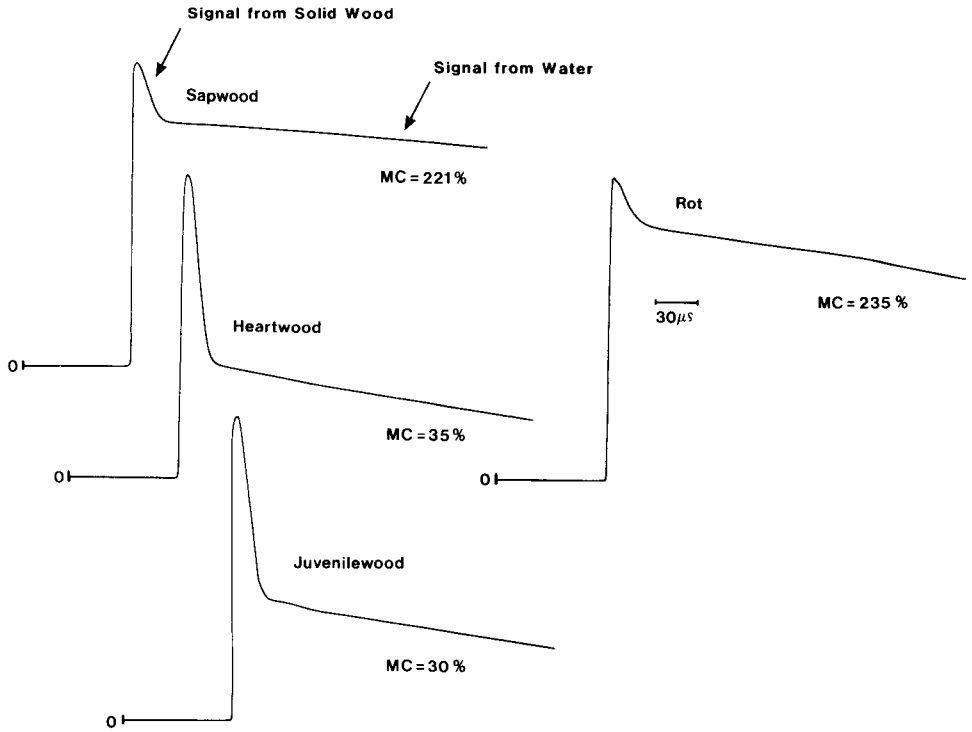


FIG. 1. The Free Induction Decay Curves for the undried cedar (a) sapwood, (b) heartwood, (c) juvenile wood and (d) rot samples. In each case the solid wood signal decays to zero within 30 to 50 μsec.

not reported here, tended to be overestimates at the higher moisture contents and underestimates at the lower moisture contents.

The CPMG curves for each of the undried samples are shown in Fig. 2. For the T_2 calculations, about 130 echoes were used corresponding to times, from the 90° pulse, increasing approximately geometrically from the first echo to the time at which the echo height had decayed to less than 1% of its initial amplitude. For T_2 analysis where several components are present, it was extremely important to use the full range of the CPMG decay; otherwise serious systematic errors could occur. The CPMG echo peaks, S(t), were fitted using a χ^2 minimization routine (MINUIT, James and Roos 1975), to the function:

$$S(t) = I_{cw}e^{-t/T_{2cw}} + I_{lw}e^{-t/T_{2lw}} + I_{ew}e^{-t/T_{2ew}} \quad (1)$$

where the fit parameters were the populations, I, and the spin-spin relaxation rates, $1/T_2$, for cell-wall water, latewood tracheid and ray lumen water, and earlywood tracheid lumen water, respectively, and t is the time after the initial 90° pulse. Each data set was fitted to the minimum number of terms, starting from the left in Eq. (1), which were required to give a satisfactory fit. Confidence limits of 68% were estimated for each parameter and found to be typically a few percent. In Figs. 3 to 6, respectively, the T_2 values and corresponding populations are plotted as a function of hydration level for the sapwood, heartwood, juvenile wood, and rot samples.

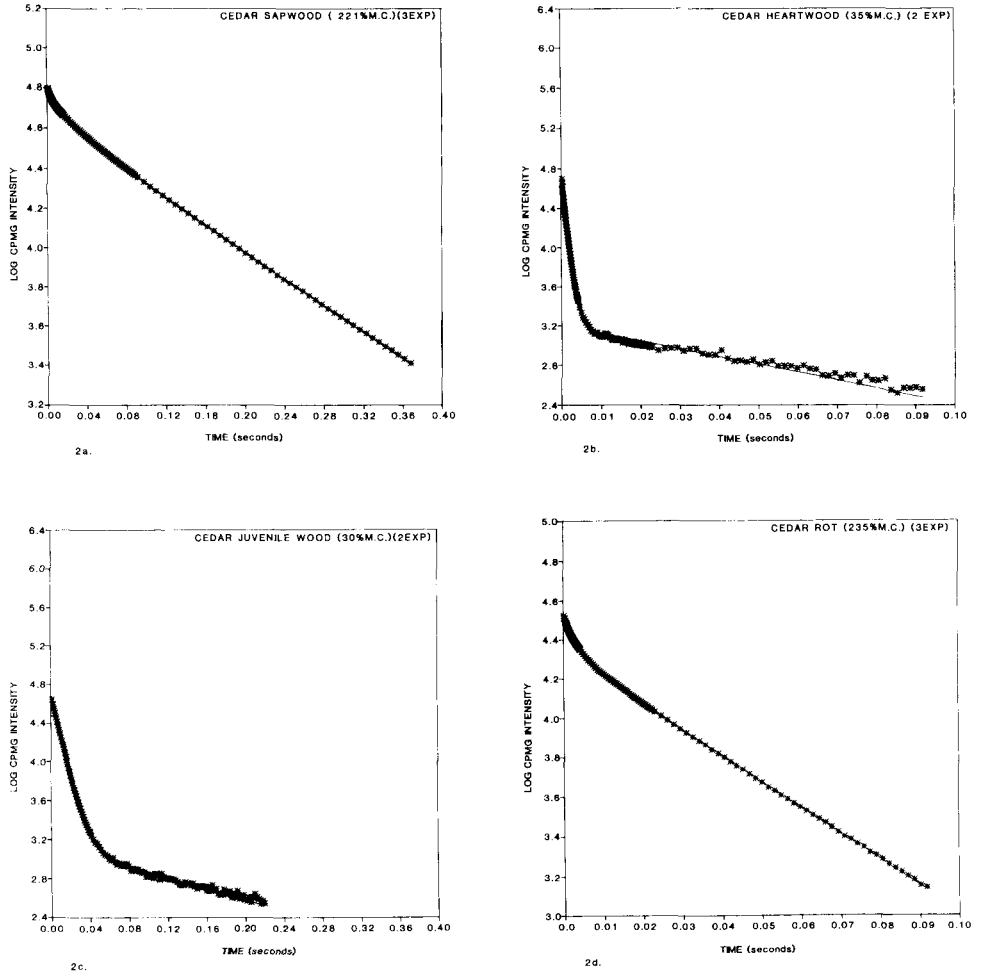


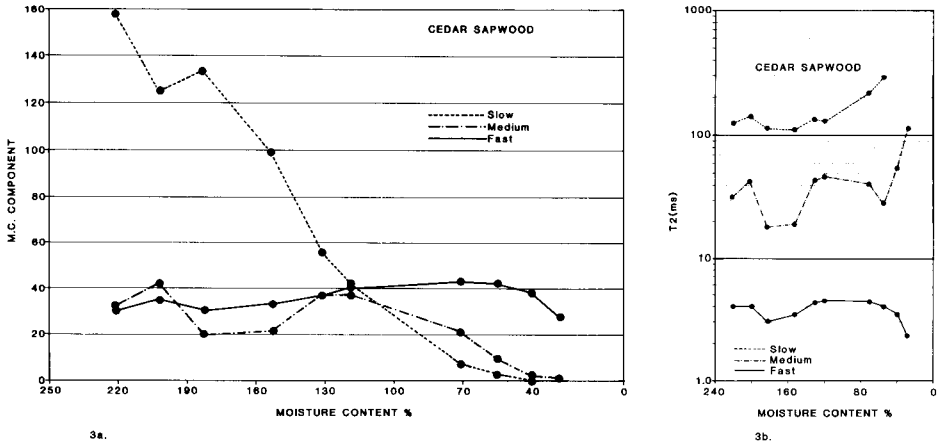
FIG. 2. The Carr-Purcell-Meiboom-Gill pulse train echo heights as a function of time from the initial 90° pulse for the undried cedar (a) sapwood, (b) heartwood, (c) juvenile wood and (d) rot samples.

Second moments were calculated by fitting the solid echoes, SE(t), starting from the echo peak, to the function:

$$SE(t) = SE(0)\left(1 - \frac{(M_{2ave}t^2)}{2}\right) \quad (2)$$

The M_{2r} values for the solid wood signal were then obtained by dividing the average second moment of the wood and water combined, M_{2ave}, by the fraction of the solid echo contributed by the wood. This assumes that the water has a negligible second moment. For all samples above the fiber saturation point, the M_{2r} values were around 5×10^9 s^{-2}. Below the fiber saturation point, the M_{2r} values were found to increase. At the lowest moisture contents, this increase was 20%.

Anatomical data measured from scanning electron photomicrographs of each



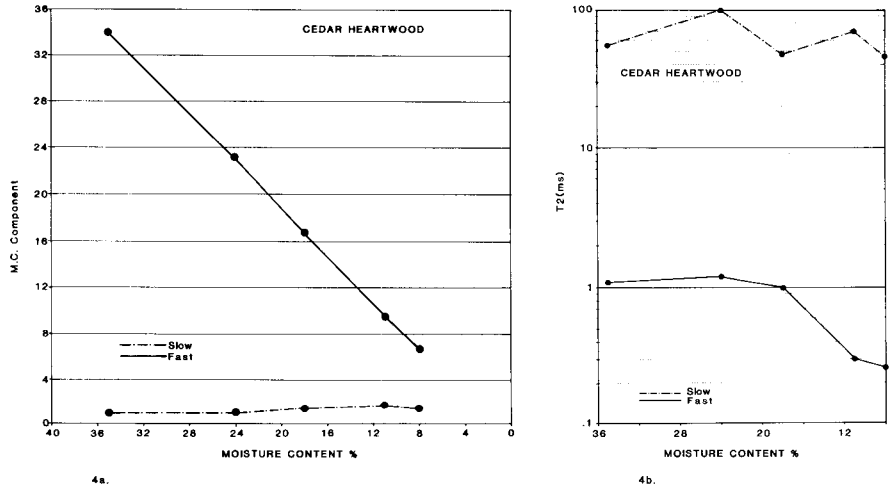
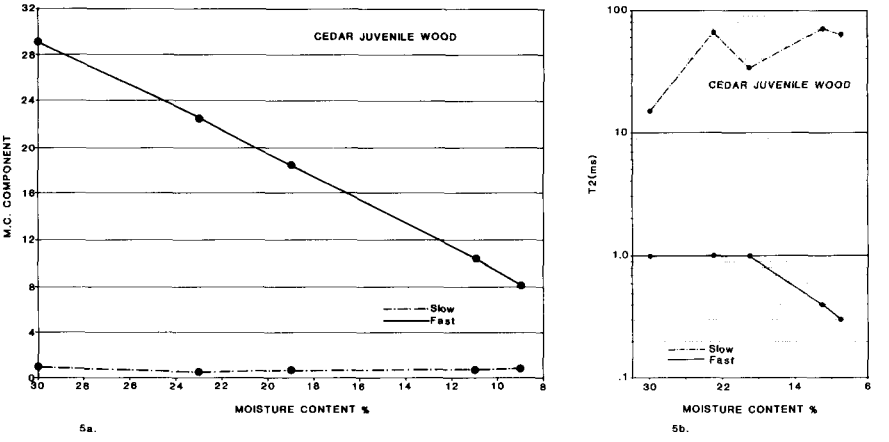


FIG. 3. The moisture contents (a) and T_2 values (b) for water in the normal cedar sapwood sample as a function of moisture content from 221 to 28%. The slow, medium and fast relaxation rates have been assigned to water in earlywood lumens, latewood and ray lumens and cell walls respectively.

FIG. 4. The moisture contents (a) and T_2 values (b) for water in the normal cedar heartwood sample as a function of moisture content from 35 to 8%. The faster relaxation rate has been assigned to the bound water.

of the 4 samples are tabulated in Table 1. The cell diameters listed in Table 1 are the average of more than 100 representative cells for each group, i.e., earlywood tracheids, latewood tracheids, and ray parenchyma.

In Figs. 7 and 8, cross-sectional magnetic resonance images (with echo times of 26 msec) are displayed for both the sound log and the rot containing log, along with photographs of the same cross-sectional views of the same logs after cutting. Practically all the intensity for the sound log is in the sapwood, and the rotten



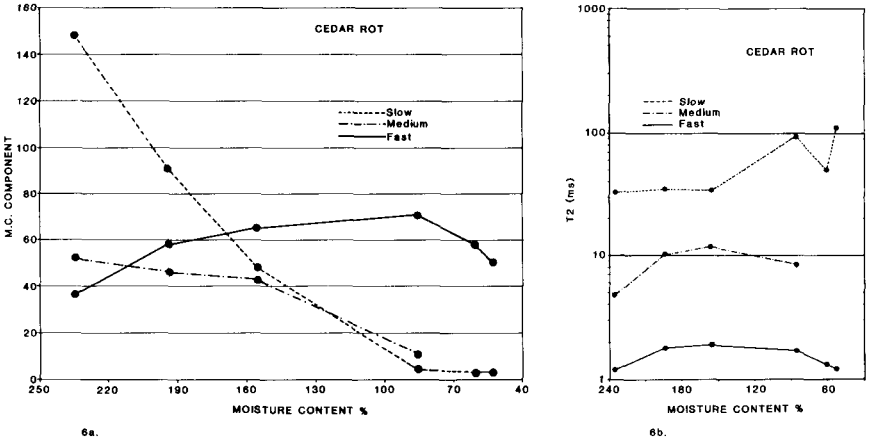


FIG. 5. The moisture contents (a) and T_2 values (b) for water in the normal cedar juvenile wood sample as a function of moisture content from 30 to 9%. The faster relaxation rate has been assigned to the bound water.

FIG. 6. The moisture contents (a) and T_2 values (b) for water in the rotten cedar juvenile wood sample as a function of moisture content from 235 to 53%. The slow and medium relaxation rates have been assigned to water in earlywood lumens and latewood and ray lumens.

areas of the other log show up as regions of higher moisture content. The variation of signal intensity versus echo time for the sapwood of the sound log was similar to that obtained at 90 MHz with the small samples. For the times the images were acquired, the relaxation curve was approximately exponential with a T_2 value of about 130 msec. Water associated with the rotten areas of the second log possessed a shorter decay time of about 50 msec.

DISCUSSION

NMR moisture content measurement

By comparing the intensity of the solid wood free induction decay with that from the water, it is possible to measure directly the moisture content of wood

TABLE 1. *Anatomical data for western red cedar samples.*

	Sapwood	Heartwood	Juvenile wood	Rot
Early tracheids				
Cell lumen diameter	27 (4)	25 (5)	15 (4)	15 (3)
Cell wall thickness	4	4	4	4
Percent total lumen volume	83	82	84	84
Latewood tracheids				
Cell lumen diameter	11 (3)	9 (3)	6 (2)	6(2)
Cell wall thickness	4	5	4	4
Percent total lumen volume	9	8	6	13
Ray parenchyma				
Cell lumen diameter	8 (2)	8 (2)	8 (2)	7 (2)
Cell wall thickness	3	4	4	3
Percent total lumen volume	8	10	10	3
Specific gravity	0.376	0.358	0.464	0.215

Sizes are in micrometers.
Numbers in brackets indicate standard deviations in size distributions.

by ^{1}H NMR (Menon et al. 1987). For this study we used the solid echo pulse sequence to monitor moisture content during the experiment; however, because of the rather complex nature of the evolution of the solid echo intensity at short pulse spacings (Boden and Levine 1978), it would be more accurate to use the simple single pulse free induction decay. For this reason, all moisture contents reported in this study are oven-dry moisture contents.

Water

Water in normal wood.—For western red cedar sapwood, the spin-spin relaxation time, T_2 for water in the cell lumens has been found to be roughly proportional to the cell lumen diameter (Menon et al. 1987). This can be understood in terms of a crude model in which free water in the lumen interior exchanges rapidly with a layer of bound water on the surface of the cell wall. Then:

$$\frac{1}{T_{2\text{lumen}}} = \frac{f}{T_{2\text{cell wall}}} + \frac{(1-f)}{T_{2\text{free water}}} \tag{3}$$

where f, the fraction of surface water is proportional to the lumen radius. This implies that there is little physical exchange of water between lumens on the millisecond time scale and makes it possible to monitor separately the moisture contents of cells of earlywood and latewood.

More detailed interpretation of spin-spin relaxation for water in wood is complicated since there is actually a distribution of cell sizes within earlywood and latewood and also since the relatively slow diffusion of lumen water plays a role in the rate of exchange between free and surface water for larger cell lumens. A more sophisticated treatment (Brownstein and Tarr 1979), accounting for the finite diffusion time of water to the cell lumen surface predicts that T_2 scales as the cell radius for smaller radii and as the square of the radius for larger cell radii. Eq. (3) represents the fast diffusion limit where T_2 scales as the radius. From the anatomical results for the cedar sapwood sample, the ratio of earlywood lumen

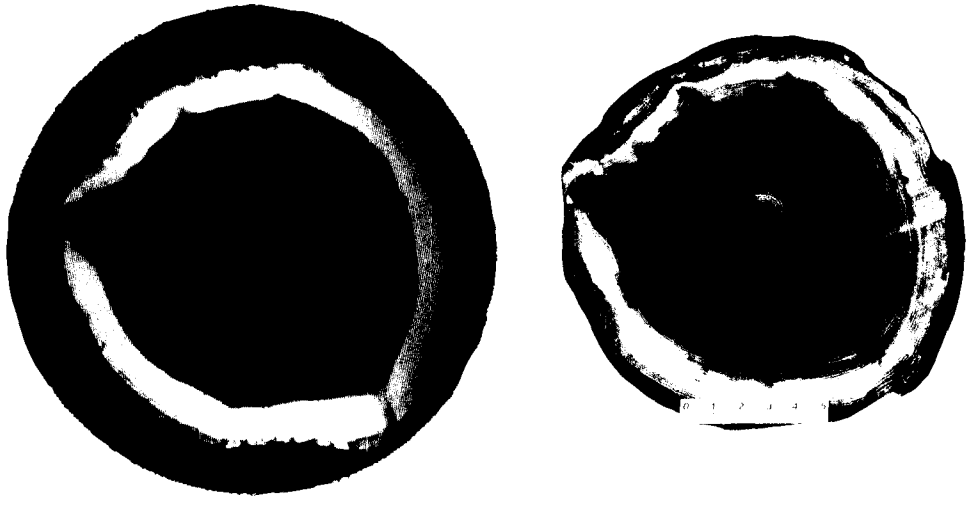


FIG. 7. A spin echo (TE = 26 msec) cross-sectional magnetic resonance image of the normal cedar log and a photograph of the corresponding image plane.

cell radii to latewood and ray cell radii is about 3. This may be compared to the ratio of earlywood to latewood and ray lumen water T_2 values from Fig. 3(b), which is just slightly larger than 3. We note also from Table 1 that the ratio of earlywood lumen volume to that of the latewood and rays is about 5. At the

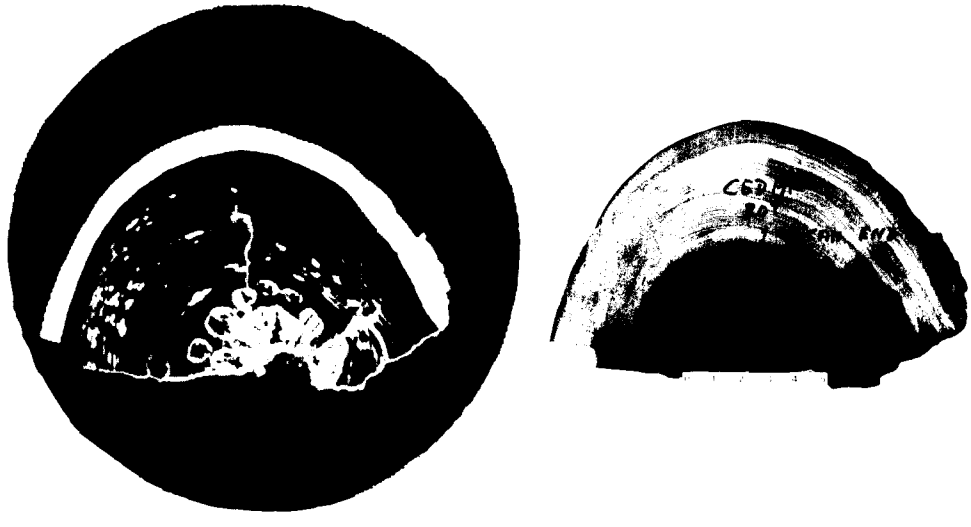


FIG. 8. A spin echo (TE = 26 msec) cross-sectional magnetic resonance image of the rotten cedar log and a photograph of the corresponding image plane.

highest moisture content (221%), the ratio of earlywood water signal to latewood and ray water signal [Fig. 3(a)] was also about 5. We therefore conclude that when we fit the data to 3 or fewer discrete T_2 components and deal with average lumen diameters determined by scanning electron microscopy, Eq. (3) gives an adequate description of the T_2 data for western red cedar.

The distribution of water in western red cedar sapwood as a function of moisture content was discussed in detail in a previous work (Menon et al. 1987) and is presented here only for comparison with results from heartwood and juvenile wood from the same log. The three T_2 components have been unambiguously assigned to water in earlywood tracheids, water in latewood tracheids and rays, and the bound water (Menon et al. 1987, 1989). When the wood dried, the water was observed to leave the lumens with the larger diameters first; i.e., the earlywood tracheid lumen water disappeared first, then the latewood tracheid and ray lumen water, and finally the bound water. This was expected from surface tension arguments. It is worth pointing out that ^1H NMR may be the only technique capable of independently monitoring the moisture contents of earlywood, latewood, and the cell walls. In this experiment the wood samples equilibrated for 2 hours between measurements at different moisture contents. Qualitatively similar results have been found (Quick et al. 1990) when the equilibration time between measurements was only a few minutes.

In a normal western red cedar log, the heartwood and juvenile wood have considerably less water than the sapwood. Our heartwood and juvenile wood samples were first measured at 35% and 30% moisture contents, respectively. At these moisture contents, practically all of the water was bound within the cell walls. Heartwood and juvenile wood cell-wall water had a relatively low T_2 value of about 1 msec compared to 4 msec for the sapwood cell-wall water. This effect, which may be due to the presence of extractives, is not understood quantitatively. The dependence of the amount of bound water upon moisture content is particularly simple (i.e., linear with unit slope) for the heartwood and juvenile wood samples since this is the only water that can be removed. This behavior occurs for cedar sapwood also (Menon et al. 1987).

In the heartwood and juvenile wood, an additional component with a T_2 of about 50 msec was observed which made up about 1% of the wood weight. Two possible assignments for this minor constituent could be nonvolatile extractives or water in sealed compartments.

Water in western red cedar rot.—The brown rot sample, which was obtained from the juvenile wood of a western red cedar log, had a relatively high moisture content of 235%. As a result it was possible to distinguish between earlywood lumen water, latewood and ray lumen water, and bound water. The T_2 values measured for the lumen waters were consistent with Eq.(3) using the cell wall T_2 value of 1.8 msec and the anatomical data in Table 1. The rot sample possessed a large amount of water with a short T_2 (usually assigned to the bound water component); almost twice that associated with the bound water in the other three samples. It is not obvious why a region of brown rot would possess more water binding sites than normal wood; in fact since the carbohydrate component has been selectively degraded, one might expect the opposite. It is conceivable but not substantiated that some cell walls of the rot sample have collapsed as the water was removed, thereby resulting in a lowering of the T_2 values for remaining

lumen water. This hypothesis could account for the anomalous increase of the short T_2 component as the moisture content was decreased from 235% to 90%.

Solid wood

The polymeric molecules of solid wood are well known to have a rigid structure. For such a system the ^1H NMR spectrum, which is dominated by the dipolar interactions between neighboring protons, is broad and featureless. Spectra of this type can be characterized most quantitatively by their spectral moments, in particular, the second moment, M_2. For a rigid solid the measured second moment, M_{2r}, is equal to the rigid lattice M_2 which can be calculated from knowledge of the spatial distribution of protons in the sample. In the presence of molecular motion, the NMR spectrum is narrowed and M_{2r} is lower than M_2. For molecules undergoing isotropic motion, for example, most of the water, M_{2r} is zero. For all the cedar samples above the fiber saturation point, the M_{2r} values were just under 5×10^9 s^{-2}. Since the rigid lattice M_2 for cellulose and hemicellulose is 7.3×10^9 s^{-2} (MacKay et al. 1985) and for lignin we expect it to be similar, the molecular constituents of wood clearly undergo only a small amount of highly restricted motion. This cedar M_{2r} value is similar to that measured in a previous study for the primary cell walls of *Phagulus vulgaris* bean hypocotyls (MacKay et al. 1988). Above the fiber saturation point M_{2r} was, within experimental error, independent of moisture content but for measurements below the fiber saturation point, the M_{2r} values increased; at the lowest moisture content the increase was about 20%. Since many macroscopic physical properties of solid wood (e.g., wood strength) are dependent upon moisture content (Bodig and Jayne 1982), it is not surprising that the microscopic physical properties (i.e., molecular motion) should also be affected by changes in the amount of bound water.

Potential application of ^1H NMR for western red cedar

Identification.—Since western red cedar sapwood has a high moisture content, the sapwood/heartwood boundary is easily visualized by ^1H NMR as a decrease in water signal intensity. The longer T_2 components from earlywood water are present only in the sapwood. A more subtle difference is the observed change in the bound water T_2 from 4 msec in sapwood to 1 msec in heartwood.

The heartwood/juvenile wood boundary in western red cedar is not easily detected by ^1H NMR on the basis of T_2 since the bound water T_2 values were similar for both types of wood. If the moisture content were well above the fiber saturation point, the smaller cell lumina of the juvenile wood would have lumen water with shorter T_2 values. Also if the bound water were imaged by ^1H NMR then the heartwood/juvenile wood boundary could probably be identified by the change in spacing and diameter of the growth rings.

The rot sample was readily identifiable from the surrounding wood because of its much higher moisture content. The smaller T_2 values of the observed water signal were representative of the distribution of cell lumen radii at the rot location. Another feature of the ^1H NMR signal from rotten wood was the substantial increase in the intensity of the short T_2 component.

The second moment of the solid wood lineshape was, within error, the same for all types of western red cedar investigated. It was observed that M_{2r} increased

with decreasing moisture content below the fiber saturation point, but this would not be an accurate measure of moisture content.

Magnetic resonance imaging of cedar.—We wish to emphasize that in the preceding we have discussed some of the information ^{1}H NMR can potentially provide about western red cedar. The technological requirements for carrying this out on whole logs or lumber are considerable.

A convenient and useful way to present the ^{1}H NMR signal from whole logs or lumber is a two-dimensional cross-sectional image. In fact, large bore 'whole body' magnetic resonance imaging (MRI) facilities have already been used to image whole logs (Burgess 1984; Hailey et al. 1985; Hall et al. 1986; Wang and Chang 1986). We have displayed here in Fig. 7 and 8 representative cross-sectional images of the two western red cedar logs from which our samples were taken.

At present, most large bore MRI facilities are incapable of imaging protons with T_2 values shorter than a few msec. Therefore the log images displayed here and also in the literature referenced above show none of the solid wood and do not show all of the water in the wood—in particular the bound water. Since the actual amount of water contributing to the image depends upon a number of different factors including the imaging pulse sequence, the measurement frequency, and the type of wood being imaged, 'whole body' MRI images of wood are qualitative in nature. To interpret the images meaningfully, it is necessary first to characterize the entire ^{1}H NMR signal using a spectrometer that is responsive to all the protons in the wood. This has been accomplished in this work.

We note that the T_2 values measured from the multiple echo images acquired at 0.15 Tesla (6.4 MHz) were not substantially different from those measured at 2.1 Tesla (90 MHz), indicating that the lumen water spin-spin relaxation had practically no frequency dependence.

The contribution of the various types of water to the images follows Eq. (1); our spin echo images with the echo peak at 26 msec should contain no bound water (T_2 between 1 and 4 msec) and a diminished contribution from the latewood and ray lumen water (T_2 about 35 msec). We note from Fig. 7 and with reference to Figs. 3 to 5 that for the normal cedar log the only imageable water is in the sapwood tracheid lumens and in the knot, which apparently contains appreciable water with longer T_2 values. In our spin echo images with TE = 26 msec, roughly 60% of the water in the normal log is imaged. (A softwood species with a less moist sapwood would have substantially less imageable water.) In the rot-containing log, the rotten regions show up as areas of increased moisture content in the earlywood lumina. We note that although the moisture content of the rotten wood is similar to that of that of the sapwood, it has substantially less contribution to the MRI image due to its shorter T_2 values.

It is technically possible, using shorter echo times, to image most, if not all, of the water in wood. This has been accomplished in one dimension in two separate studies by our group (Menon et al. 1989; Quick et al. 1990). Such facilities will be very valuable in obtaining a complete understanding of the spatial distribution of water in wood and the associated characteristics of wood.

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