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NMR imaging of internal features in wood

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Abstract

This paper reports a nonmedical application of nuclear magnetic resonance (NMR) imaging that promises significant potential for large-scale industrial applications. Two white oak logs and one black cherry log were examined with an NMR scanner to view internal features of the wood. As a result of inherent moisture variations associated with various characteristics of the log, clear images were obtained to reveal not only normal features such as sapwood-heartwood, earlywood-latewood, and wood rays but also defects as varied as reaction wood, wetwood, gum spots, and knots. Further scanning of additional species, faster scanning methods, development of algorithms for image interpretation, and a lower cost for the NMR scanner would facilitate the early adoption of this technology that improves lumber production efficiency.

During the past decade, the field of diagnostic radiology in medicine has witnessed an explosion of new developments. In addition to improvements of traditional techniques, such as computerized tomography scanning (CT scan), diagnostic equipment based on entirely different principles has been developed. Among the new equipment is the innovative nuclear magnetic resonance (NMR) scanner. With its ability to differentiate between normal and abnormal cells, NMR scanners have produced images of the human body never seen before (12).

Prompted by the success of NMR imaging in medical diagnostics, researchers in other fields soon began to explore possible nonmedical applications of this technique. Early investigations include the imaging of wood (1,3,4,14) and fruit (16). With moisture variation inherent in wood, the NMR imaging technique is particularly suited for detecting internal features within wood. In this paper, we report our recent effort in scanning two commercially important hardwood species — white oak (*Quercus alba* L.) and black cherry (*Prunus serotina* Ehrh.).

Normally, in industrial practice, a log is graded based upon its external appearance. While this provides a good indication of possible internal defects, it often fails to identify all defects present in the log. During sawing, the sawyer must therefore make instantaneous decisions about the positioning and orientation of the log for the next cut. Inferior decisions are often made because of human errors and/or inaccurate knowledge of the defects contained within the log. If defects such as knots, rot, and worm holes are located and identified within a hardwood log prior to sawing, it is possible to determine in advance the optimal way to saw the log so that higher quality lumber can be produced. The advantage could be quite substantial. For example, in a simulation study, Richards (11) has shown that logs placed at their best rotational orientation for the first cut outproduce these same logs placed at their worst orientation, by an average of 11 percent in value.

In 1985, the hardwood lumber industry produced 6 billion board feet of lumber (13). Using $650 per thousand board feet for the No. 1 Common grade of Appalachian red oak lumber (5) as a bench mark,[1] an 11 percent increase in value would represent roughly a $430 million dollar increase in the value of the lumber produced. Thus, scanning hardwood logs could represent a very significant nonmedical application of the NMR imaging technique.

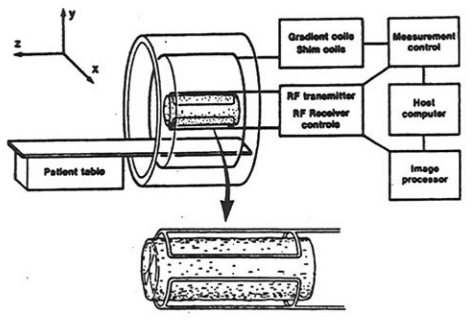

Figure 1. — Block diagram of an NMR scanner. A log section is positioned at the center of the magnet to produce scanning images.

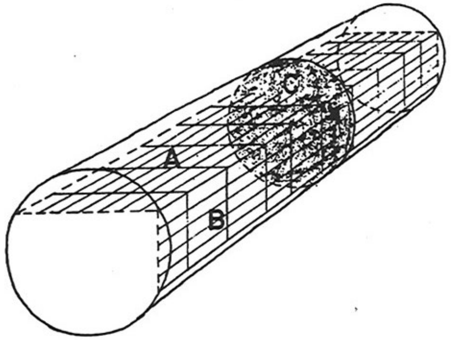

Figure 2. — The three NMR imaging views: A. coronal, from top to bottom; B. sagittal, from left to right; and C. transverse or cross-sectional views.

Principle of NMR imaging

Under the influence of a strong external magnetic field, nuclei with an odd number of protons and/or neutrons that normally scatter their magnetic moments randomly would align these moments with the direction of the external field. At the same time, these nuclei would precess or wobble about at their Larmor frequencies $\omega(x)$, which depend on the specific gyromagnetic ratio of the nuclei γ, are proportional to the strength of the magnetic field $B(x)$, and can be expressed as $\omega(x) = \gamma B(x)$. To image an object, the specific nucleus of interest is singled out for excitation by piping in radio-frequency (RF) waves at its Larmor frequency. As the nuclei absorb the energy of the RF wave, they realign their magnetic moments away from the direction of the magnetic field in proportion to the amplitude and duration of the RF wave. Once the excitation RF wave stops, the nuclei will precess to their initial equilibrium alignment within the magnetic field and release the absorbed energy in the form of RF signals at their Larmor frequency during the process. To spatially encode the emitted signal, a small magnetic field gradient (7,10,15) is imposed with a coil during the relaxation process (Fig. 1). Such a gradient causes nuclei at unlike positions to emit signals at different frequencies. Analyzing the received RF signals (2,6) yields the spatial distribution of the imaged nucleus to construct a two-dimensional NMR image of the studied object.

Theoretically, any kind of nucleus with an odd number of protons and/or neutrons can be imaged. Indeed, equipment now under development will soon be able to scan multiple nuclei of the object at the same time. Today's commercial scanners, however, focus primarily on hydrogen because of its sensitivity and abundance. In wood imaging, only water protons are chosen due to their relatively long relaxation times, as compared to the rapid relaxation of protons associated with the wood components. An NMR image, therefore, is actually a profile of water content with the lighter area relatively wet and the darker area relatively dry. Most of the scanners have a magnetic field strength of .15 to 1.0 tesla (1 tesla = 10,000 gauss), while few experimental instruments operate at 1.5 or 2.1 tesla. Recently, research NMR scanners with a magnetic field strength as high as 4.7 tesla have become available.

Procedure

The NMR unit used in this study was a Siemens 0.5 tesla Magnetom whole body scanner located at the Montgomery Imaging Center of Georgetown University. Two white oak logs 15 and 25 cm in diameter, respectively, and one black cherry log 25.5 cm in diameter were scanned. They were chosen for two reasons. First, both species are commercially important. Second, the ring-porous white oak and semidiffuse porous black cherry provide sufficient contrast in order to study if different types of wood would affect the quality of log scanning images.

When the log was laid on the gantry of the magnet with its length parallel with the main magnetic field, three different types of scanning images (Fig. 2) could be generated: A. coronal image, by moving the imaging plane from the top to the bottom (in human equivalence from chest to back) of the log; B. sagittal image, from the left to the right; and C. transverse or cross-sectional image, from one end of the log to the other. At present, the NMR scanners can only image from one direction at a time. Medically, all three views are often needed to provide a detailed look into a patient's body.

For wood imaging, a combination transverse and coronal or transverse and sagittal will usually suffice. With the multislice spin-echo method (7,15) of varying echo time and repetition time, we were able to scan 15 images simultaneously, each 16 mm apart. Image data requisition required 7.5 minutes and another 7.5 minutes was required for image reconstruction, during which time the log remains stationary. Two different coils were used to scan the logs. A smaller head coil for a maximum log

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[1] In the calculation of the 1985 producer price index for rough sawn hardwood lumber, 81.48 percent of the weight was assigned to No. 1 Common red oak and other valuable hardwood species such as cherry, ash, and black walnut.

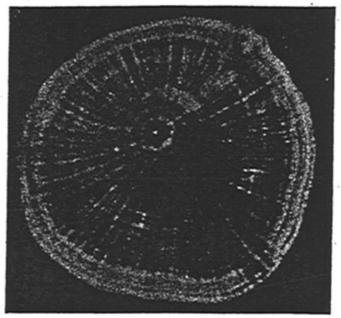

Figure 3. — Head coil image of the cross-sectional view of a white oak log, 15 cm in diameter. The image shows the darker heartwood surrounded by a brighter ring of sapwood, the annual growth rings, and wood rays emitting from the pith (shown in the image as the small bright dot in the middle). Also visible is the live branch at the 1 o'clock position.

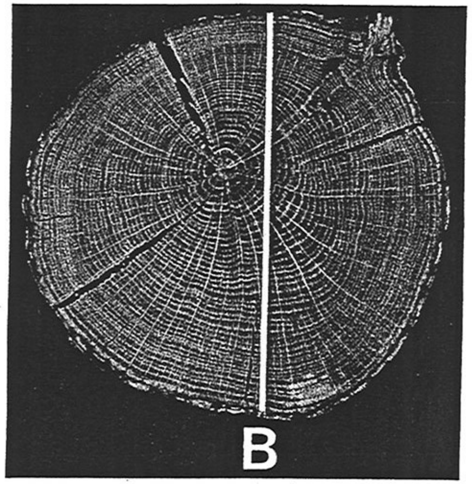

Figure 4. — Actual photo of the cross section shown in Figure 3. The checks developed from drying after the white oak log was scanned.

diameter of 20 cm was used to obtain high resolution images of the 15-cm white oak log (image area 30 by 30 cm, spatial resolution 1.2 by 1.2 mm). We experimented with the head coil mainly to see just how detailed a scanning image one can get. A body coil with a gantry opening of 100 cm was used to obtain lower resolution images of the two larger logs (image area of 50 by 50 cm, spatial resolution 1.95 by 1.95 mm). As will be shown, for all practical purposes, this lower resolution is more than sufficient.

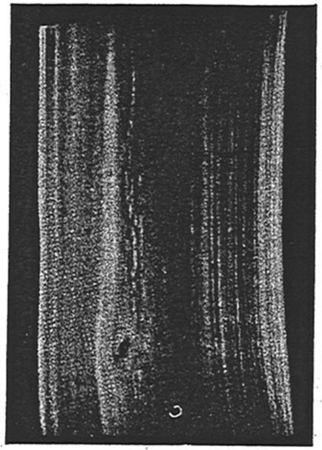

Figure 5. — Head coil sagittal image of the 15-cm white oak log taken along line B drawn in Figure 4.

Results and discussion

A head coil cross-sectional image of a white oak log 15 cm in diameter is shown in Figure 3. It should be noted that because of the low amount of moisture contained in it, the bark never showed up in this or any of the images we scanned. This fact may prove to be very helpful later on when processing the log images because one never has to worry about separating the bark from the wood. On the other hand, one recognizes in the image the separation of the sapwood and heartwood, the delineation of the growth rings, the pith, the rays, as well as a live branch, and this image compares favorably with the actual photo of the cross section taken after the log was cut (Fig. 4). More importantly, the NMR image also reveals some features of the wood that cannot be detected with the naked eye. For example, the eccentricity of the growth rings on the cross section suggests the existence of tension wood, which is formed on the upper side of a leaning stem. Yet, the exact boundary of such wood would be hard to determine in Figure 4. In Figure 3, the region of the tension wood is depicted on the upper part of the log in a lighter shade, indicating higher amounts of moisture contained there. Furthermore, the bright strip above the pith in Figure 3 indicates the presence of wetwood, known to be difficult to dry. The knowledge of the location and size of these defects might prove to be important considerations in the orientation and positioning of the log during the sawing process. For example, if the log were sawn sagittally, along line B drawn in Figure 4, the lumber produced would appear as the NMR image in Figure 5. The left side of the lumber would contain both tension wood and wetwood (shown as the bright strip near the middle) with higher moisture content, while the right side of the lumber would contain normal wood with lower moisture content. Such an uneven distribution of moisture could cause uneven shrinkage and excessive warping during wood drying.

While the head coil has the advantage of providing high resolution images, it is limited to smaller logs of up to 20 cm in diameter and is mainly for research purposes. For practical purposes, sawlogs are never smaller than 20 cm in diameter and therefore body coil imaging is required. In Figure 6, the body coil image of a 25-cm diameter white oak log is presented. With a resolution that is only 36 percent of the head coil image, one can still identify the separation of sapwood and heartwood, as well as some of the growth rings in the heartwood. The rays in this case are barely visible and the pith is just a small white dot in the middle. It should be noted that due to scheduling delays the log was scanned after it was taken out of the plastic storage bag and stored inside the building for 21 days. The dark bands around the sapwood showed areas of sapwood where moisture has escaped through checks on the bark. As it is, the image provides an important reminder of what might happen in an industrial production environment when logs are not scanned immediately after they are harvested. The images of the smaller white oak log reported earlier and the cherry log reported later do not have the dark bands because they were scanned as soon as they were taken out of the plastic storage bag. In Figure 7, the cross-sectional image of a 25.5-cm diameter black cherry log reveals both the sapwood and heartwood, as well as some of the growth rings. The pith and the rays cannot be seen on this image because they are too small. More importantly, the image also reveals the existence of gum spots as dark spots scattered around the sapwood. A sagittal image of the gum spots is shown in Figure 8. It should be pointed out that gum spots exist in both the sapwood and heartwood. Because of the low amount of moisture contained in both the heartwood and the gum spots, the latter are not revealed in the heartwood. Gum spots do not finish very well and are not visually appealing, as Figure 8 suggests. Logs containing gum spots are therefore less valuable.

In terms of the detection of other hidden defects, three cross-sectional views and one sagittal view of a buried knot in the black cherry log are presented in Figure 9. Similarly, three cross-sectional views and one coronal view of a buried knot in the big white oak log are shown in Figure 10. Furthermore, in the white oak image shown earlier (Fig. 6), the dark shadow at the 1 o'clock position reveals the existence of a covered knot and the shadow at the 5 o'clock position reveals another buried knot. Compared with the dark shadow of a buried scar caused

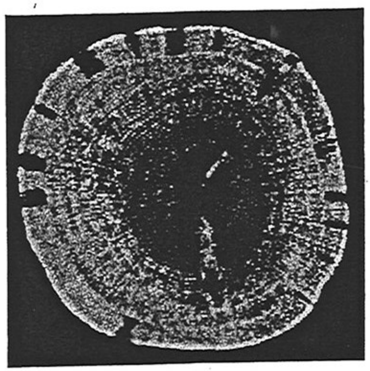

Figure 6. — Body coil cross-sectional image of a white oak log 25 cm in diameter. The covered knot is at the 1 o'clock position and the buried knot is at the 5 o'clock position. Dark bands in the sapwood are areas where the wood has dried.

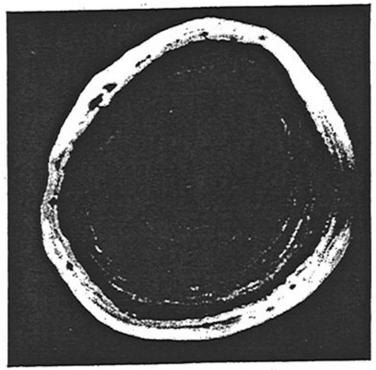

Figure 7. — Body coil cross-sectional view of a black cherry log 25.5 cm in diameter. The sapwood-heartwood, annual rings, and gum spots are visible.

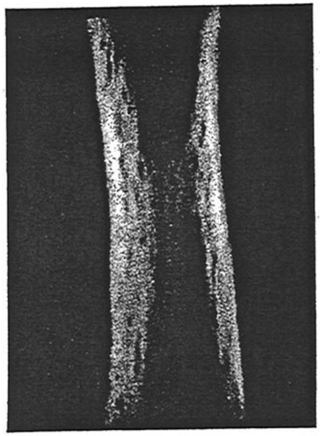

Figure 8. — Body coil image of a sagittal view showing the gum spots found in Figure 7.

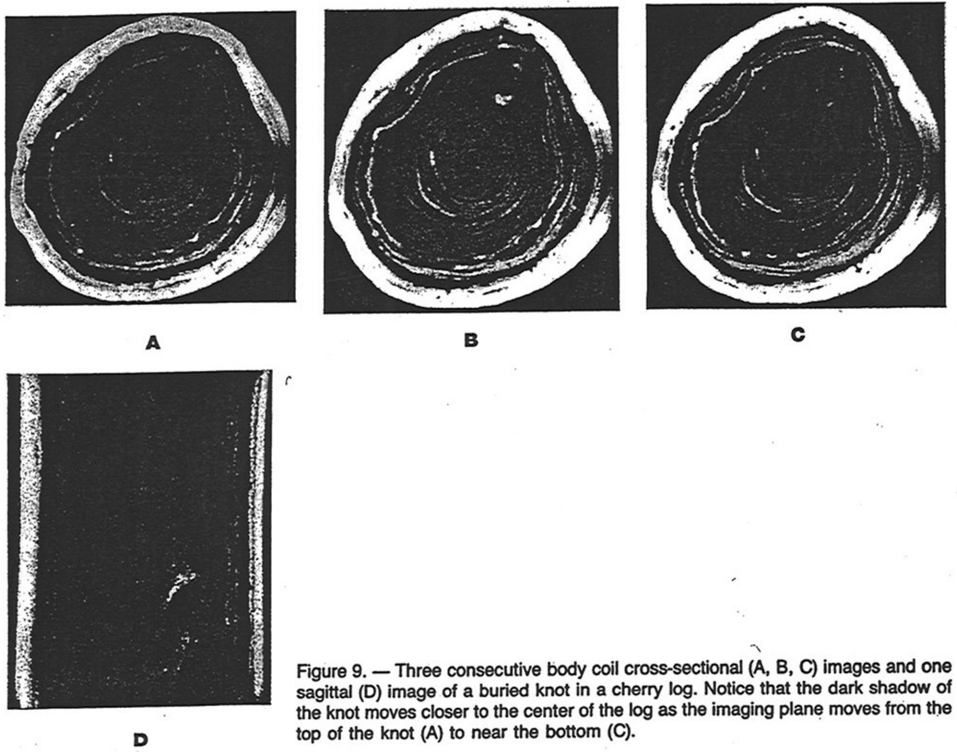

Figure 9. — Three consecutive body coil cross-sectional (A, B, C) images and one sagittal (D) image of a buried knot in a cherry log. Notice that the dark shadow of the knot moves closer to the center of the log as the imaging plane moves from the top of the knot (A) to near the bottom (C).

by an injury to the bark (Figs. 11A and B), knots can be differentiated by noting that usually the dark shadow of a knot is surrounded by the bright image of a band of wood (Fig. 10) with higher moisture, and on successive images, the shadow moves either closer to the pith or away from it.

In addition to the various defects just mentioned, earlier work by Wang and Chang (14) has shown that a worm hole will appear on the NMR image as a bright strip if it is filled with water. If it is free of all water, the worm hole will appear as a dark strip similar to the background because of its lack of any moisture. As for decay, usually it appears as a dark shadow with a jagged bright band around it. The exact reason why the higher moisture is bordering the decay is not yet clear. A typical example of wood decay was shown in a study by Hall et al. (4).

Defects like knots and scars are major concerns in the wood utilization process. The existence of these defects limits the length and width of the clear wood that can be obtained from a piece of lumber (Figs. 5, 9, and 10). Since the rotation and positioning of the log would affect the spatial distribution of various defects on each piece of lumber, which in turn affects the amount of usable clear wood available, the ability of the NMR scanner to produce clear images of features inside the log represents an important first step. Eventually, such images would permit either human or machine to identify and locate the various defects and form the basis for the more efficient sawing of logs.

Conclusions and recommendations

In this paper, we have attempted to demonstrate the feasibility of using the NMR scanner to image various defects in hardwood logs. The results of both white oak and black cherry studies have shown that NMR images can detect defects such as knots, worm holes, and ring shake, plus decay and nonstructural defects such as gum spots, wetwood, and tension wood. Scanning logs to determine the location and size of both external and internal defects represents the first step in the pursuit of building an automated sawmill. Ultimately, the goal is to develop a system that will scan the log, process the image to locate and identify defects, determine the optimal sawing sequence for the log, and then actually control the sawmill to carry out the sawing instructions. Before such a system can become a reality, progress in the following areas must be obtained:

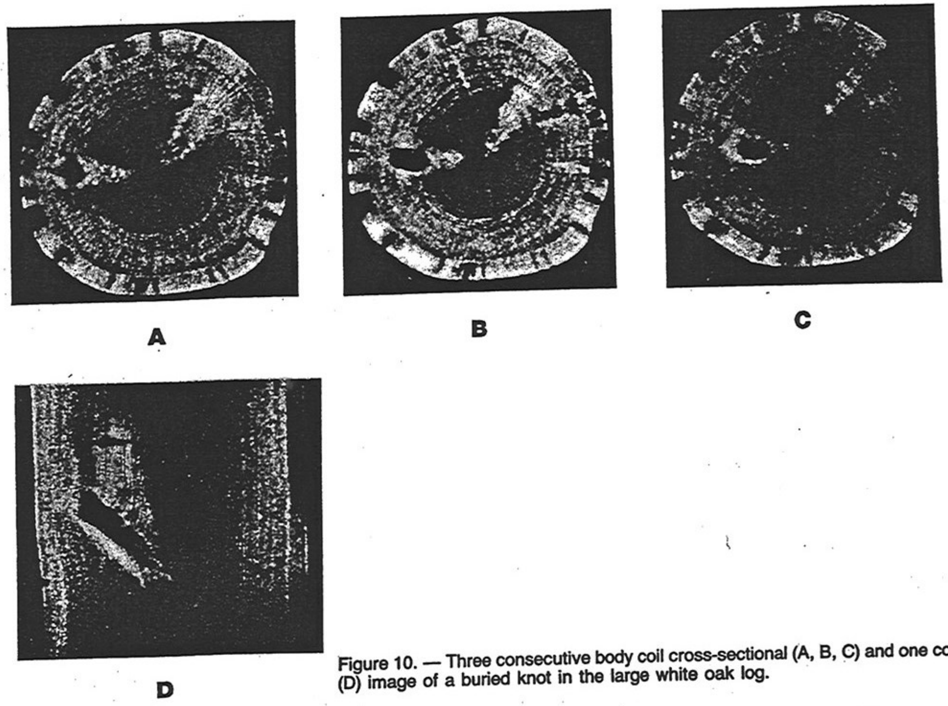

Figure 10. — Three consecutive body coil cross-sectional (A, B, C) and one coronal (D) image of a buried knot in the large white oak log.

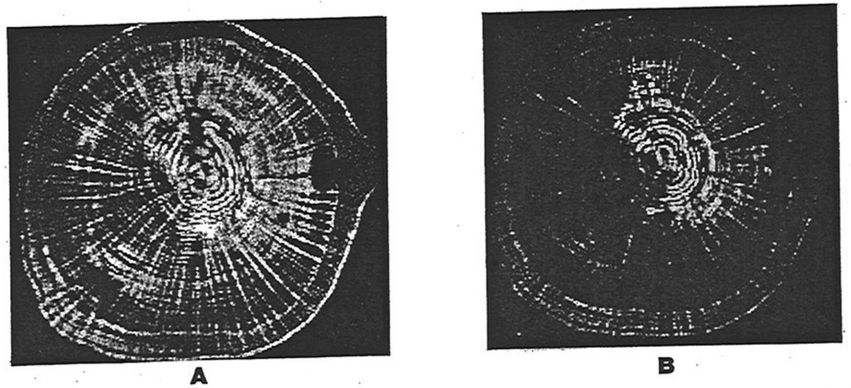

Figure 11. — Two head coil cross-sectional images, 6 cm apart, of a scar tissue at the 3 o'clock position in the small white oak log.

1. Additional samples and species must be scanned to establish the limitations of the NMR scanner.

2. Fast scanning techniques such as the echo-planar method (9) need to be explored so that commercial-size sawlogs can be scanned at a rate of about 1 to 2 minutes per log to match the production rate of the sawmill.

3. More powerful, less expensive scanners, perhaps employing recent developments in superconductivity

research, need to be developed. Current cost figures of 2 to 2.5 million dollars for medical scanners are unacceptable.

4. Interpretive algorithms must be developed to permit rapid identification and precise location of various defects.

Accomplishment in these areas would then facilitate the early adoption of the automated sawmill system (8) to improve lumber production efficiency.

Literature cited

1. Chang, S.J., P.C. Wang, and J.R. Olson. 1987. Nuclear magnetic resonance imaging of hardwood logs. *In:* Proc. of the Second Inter. Conf. on Scanning Technology in Sawmilling. Oakland/Berkeley Hills, Ca. pp. IX1-IX9.
2. Edelstein, W.A., J.M.S. Hutchison, G. Johnson, and T. Redpath. 1980. Spin warp NMR imaging and application to human whole-body imaging. Phys. Med. Biol. 25:751-756.
3. Hall, L.D., V. Rajanayagam, W.A. Steward, and P.R. Steiner. 1986. Magnetic resonance imaging of wood. Can. J. of Forestry Res. 16:423-426.
4. ———, ———, ———, ———, and S. Chow. 1986. Detection of hidden morphology of wood by magnetic resonance imaging. Can. J. of Forestry Res. 16:684-687.
5. Hardwood Market Report. 1988. Memphis, Tenn. 66(1):4.
6. Kumar, A., D. Welti, and R.R. Ernst. 1975. NMR Fourier zeumatography. J. Magn. Reson. 18:69-83.
7. Mansfield, P. and P. Morris. 1982. NMR Imaging in Biomedicine. Academic Press, N.Y.
8. McMillin, C.W., R.W. Conners, and H.A. Huber. 1984. ALPS — A potential new automated lumber processing system. Forest Prod. J. 34:13-20.
9. Morris, P.G. 1986. NMR-Imaging in Medicine and Biology. Clarendon Press, Oxford.
10. Pykett, T.L. 1982. NMR imaging in medicine. Scientific American 246:78-88.
11. Richards, D.B. 1980. Lumber values from computerized simulation of hardwood sawing. Res. Pap. FPL-356. USDA Forest Serv., Forest Prod. Lab., Madison, Wis.
12. Sochurek, H. 1987. Medicine's New Vision. Nat. Geog. 171:2-41.
13. USDA Forest Service. 1987. U.S. timber production, trade, consumption and price statistics. 1950-85. Misc. Publ. No. 1453. USDA Forest Serv., Washington, D.C.
14. Wang, P.C. and S.J. Chang. 1986. Nuclear magnetic resonance imaging of wood. Wood and Fiber Sci. 18: 308-314.
15. ———, S.K. Moon, S.J. Chang, and J.R. Olson. Technology of NMR imaging in wood. J. of Appl. Polymer Sci. (in press).
16. Wang, S.P., P.C. Wang, and M. Faust. NMR imaging of water-cored apple. J. of Hort. Sci. (in press).

SAF develops fire policy recommendations

The Society of American Foresters (SAF) released a recently developed position statement on fire management with nine policy recommendations as a part of its testimony during congressional oversight hearings held in January.

The position statement affirms the ecological role of fire in forested wildlands. The statement also describes conditions in which fire should be suppressed or allowed to burn within strict prescriptions.

SAF is the largest organization of forestry professionals in the world. The position statement reflects the best thinking within the profession about the role of fire in natural and human-inhabited ecosystems and is based on findings of an independent task force of leading fire researchers and managers.

"SAF recognizes that fire is an important and useful ecological process in many forest types," SAF Executive Vice President William Banzhaf told members of the U.S. House of Representatives. However, he also said, "Although natural fires may be appropriate in some areas, strong measures must be taken to ensure that they do not escape predetermined prescription."

SAF calls for suppression of fires to protect commercial timber, range, watersheds, and human-made facilities within a wildland environment.

Although suppression is often necessary in the short term, repeated suppression activities may result in the gradual buildup of fuel, thereby increasing the probability of large, catastrophic, and costly fires. This was a partial cause of the Yellowstone-area fires in the summer of 1988.

To avoid this risk, SAF supports the use of human-ignited prescribed fire, stressing that such activity only be carried out by skilled professionals under strictly controlled conditions. Prescribed fire should also continue to be used to achieve other land management objectives, according to the SAF position statement.

SAF also recognizes the role of managed natural fires (the so-called "let burn" type) in wilderness and other natural areas. However, SAF recommends case-by-case analysis to determine what suppression steps should be taken when the fire appears to be escaping the natural area's boundaries.

The January hearing was held by the House Agriculture Committee's Subcommittee on Forests, Family Farms and Energy and the House Interior and Insular Affairs Committee's Subcommittee on Parks and Public Lands.

Du Pont tallies cost of injuries

A disabling injury cost the lumber and wood industry an average of $23,500 in 1987, according to a study by Du Pont Safety and Environmental Services, which offers consulting, training, and seminar products to industry. This is 22 percent greater than the $19,300 cost-per-injury estimate found in 1986.

Data used in the study came from the National Safety Council and a performance review of selected companies from more than 500 of the group's consultation clients.

The 1,800,000 disabling injuries recorded in 1987 cost a total of $42.4 billion. Of this amount, $12.5 billion went for management and productivity losses and accident-related equipment damage.

"A lumber and wood products company with 1,000 employees could expect to have 42 lost workday injuries in 1987," says Anthony Cantarella, product manager for Safety and Environmental Services. "At a profit margin of 3.7 percent, it would need about $26.5 million in sales to offset these injuries.

"Clearly, safety makes good business sense. Even an average safety record can sap a company's financial health. And since the cost per injury is increasing faster than inflation, the fiscal importance of safety will continue to grow."