GE
Security

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REMOTE AUTOMATIC MATERIAL ON-LINE SENSOR

FINAL REPORT

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1 Executive Summary

The Department of Energy (DOE) Industries of the Future (IOF) program seeks development and implementation of technologies that make industry more efficient – in particular, more energy-efficient. Quantum Magnetics, Inc. (QM), a wholly-owned subsidiary of GE Security, received an award under the program to investigate roles for low-cost Nuclear Magnetic Resonance (NMR) technology in furtherance of these goals.

Most NMR systems are designed for high-resolution spectroscopy applications. These systems use intense magnetic fields produced by superconducting magnets that drive price and operating cost to levels beyond industry tolerance. At low magnetic fields, achievable at low cost, one loses the ability to obtain spectroscopic information. However, measuring the time constants associated with the NMR signal, called NMR relaxometry, gives indications of chemical and physical states of interest to process control and optimization. It was the purpose of this effort to investigate the technical and economic feasibility of using such low-field, low-cost NMR to monitor parameters enabling greater process efficiencies.

The primary target industry identified in the Cooperative Development Agreement was the wood industry, where the moisture content of wood is a key process parameter from the time the cut tree enters a mill until the time it is delivered as pieces of lumber. Extracting the moisture is energy consuming, and improvements in drying efficiency stand to reduce costs and emissions substantially.

QM designed and developed a new, low-cost NMR instrument suitable for inspecting lumber up to 3 inches by 12 inches in cross section, and other materials of similar size. Low cost is achieved via an inexpensive, permanent magnet and low-cost NMR spectrometer electronics.

Laboratory testing demonstrated that the NMR system is capable of accurate (± 0.5%) measurements of the moisture content of wood for moisture ranging from 2% to over 140% (referenced to the wood's dry weight). Accuracy exceeded that offered by existing instrumentation when the moisture content was in excess of the fiber saturation point (~20%). Accuracy was independent of the wood form: solid wood, wood chips or sawdust.

The prototype NMR system was designed and built for incorporation and use in a beta test site. Beta testing is under way at the pilot plant operated by the Pulp and Paper Research Institute of Canada (PAPRICAN) in Vancouver, B.C.

Other industries were also investigated. For example, laboratory testing demonstrated that low-field NMR is capable of measuring the hydrogen content of calcium oxide (quicklime). Hydrogen content measurement can be done both rapidly (on the order of 1 second) and non-destructively. Measurement of moisture in quicklime affects energy consumption in the steel industry.

Further advances in system electronics, ongoing under DOD support, will enable yet more substantial system cost reductions over the prototype system, opening up a wider range of utility.

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LIST OF ACRONYMS

Alnico	Aluminum-Nickel-Cobalt alloy
ATC	American Technical Ceramics
AWG	American Wire Gauge
CaO	Calcium oxide (quicklime)
CT	Computerized (X-ray) Tomography
dB	Decibel
DOD	Department of Defense
DOE	Department of Energy
DRF-3	Digital RF Transceiver Board (QM part designation)
ID	Inner Diameter
IOF	Industries of the Future
GE	General Electric Company
GUI	Graphical User Interface
^{1}H	Hydrogen nucleus (also known as the proton)
ISA	Designation for a computer bus standard
LED	Light-Emitting Diode
LBNL	Lawrence Berkeley National Laboratory
LNA	Low-Noise Amplifier
MC	Moisture Content
MR-0	Magnetic Resonance Pulse Programmer Board (QM part designation)
NdFeB	Neodymium-Iron-Boron alloy
NMR	Nuclear Magnetic Resonance
NQR	Nuclear Quadrupole Resonance
OD	Outside Diameter
PAPRICAN	Pulp and Paper Research Institute of Canada
PC	Personal Computer
PGNAA	Prompt Gamma Neutron Activation Analysis
ppb	Parts per Billion
ppm	Parts per Million
PTFE	Poly-Tetra-Fluoro-Ethylene (Teflon®)
Q	Quality Factor
QM	Quantum Magnetics, Inc.
QNX	not an acronym, QNX is the brand name of a computer operating system
RF	Radio Frequency
SiC	Silicon Carbide
SII	SII Dry Kilns, Inc.
SNR	Signal to Noise Ratio
T	Tesla
VILNAD	Variable-Impedance, Low-Noise And Distortion

2 Interview of IOF Industry Staff to Determine Specifications

The sensor developed on this award was intended for use by at least two of the Industries Of the Future (IOF). In order to fulfill that requirement, the first phase of the award was to interview industry staff in order to develop specifications for a product that could be successfully used by two or more of the IOF's. Primary emphasis fell on the wood industry, which was the basis for the initial proposal.

2.1 Forest Products

At the time the award was awarded, there was considerable interest in the company in pursuing applications in the Forest Products Industry. QM's parent company, InVision Technologies, was looking for new applications of its Computerized Tomography (CT) scanning technology developed for aviation security. This was before the events of September 11, 2001. One promising application was imaging of logs to look for internal defects. By knowing the location of defects, the cutting of the log could be optimized to maximize the value of the resulting lumber. As part of that strategy, InVision bought Inovec, a company that had considerable experience in selling laser-based equipment for the optimal cutting of hardwood lumber. In addition, InVision set up a subsidiary company, WoodVision, to pursue log imaging applications.

QM contacted Dr. Robert Little, Technical Director of SII Dry Kilns to ascertain where moisture content measurements would be of value in the drying process. A part of the conversation dealt with limitations of current technology. QM later hosted a meeting with Professor Joseph Denig of North Carolina State University and Dr. Eugene Wengert, Professor emeritus of the University of Wisconsin-Madison.

Wood moisture measurement is a critical parameter in the wood drying process. However, it is not the only parameter of importance. For example, the primary difference in drying hardwoods and softwoods is that the increased porosity of softwoods allows for a much more vigorous drying schedule. Hardwoods require slower drying: oak can take as long as one month, while an equivalent size softwood can be dried in eighteen hours.

The "gold standard" method of moisture content measurement is oven drying, where the wood is weighed, dried completely, and weighed again. Oven drying has two disadvantages: it is time consuming and it is destructive. Commonly used, rapid, non-destructive measurements include resistance gauges and capacitance gauges. Some work has been done on near infrared gauges.

A potential source of confusion for the novice is that the moisture content of wood is usually defined as the weight of the moisture divided by the weight of the dry wood. Hence it is possible to have moisture contents in excess of 100%, and it is not unheard of to have some samples of wood with moisture content in excess of 200%.

Some definitions may help with understanding the following discussion. "Green lumber" refers to cut lumber that has not been dried. "Fiber saturation point" is the moisture content at which the cellulose fibers are saturated with water; any additional water then accumulates in the pores of the wood. The dimensions of wood are generally not affected by moisture content above fiber saturation point, but will shrink when moisture content decreases below that point.

2.1.1 Hardwood lumber

The main limitation of current moisture content (MC) gauges is that accuracy is poor outside of the range of 5 to 25% moisture content for resistance gauges and 5 to perhaps 30% for capacitance gauges. The problem below 5% is of little concern, as wood is almost never intentionally dried below 5%. Typical accuracies for current technology are ±1% (MC between 5% and 25%), but some applications require ±0.5%. Current gauges do not give accurate readings for green lumber.

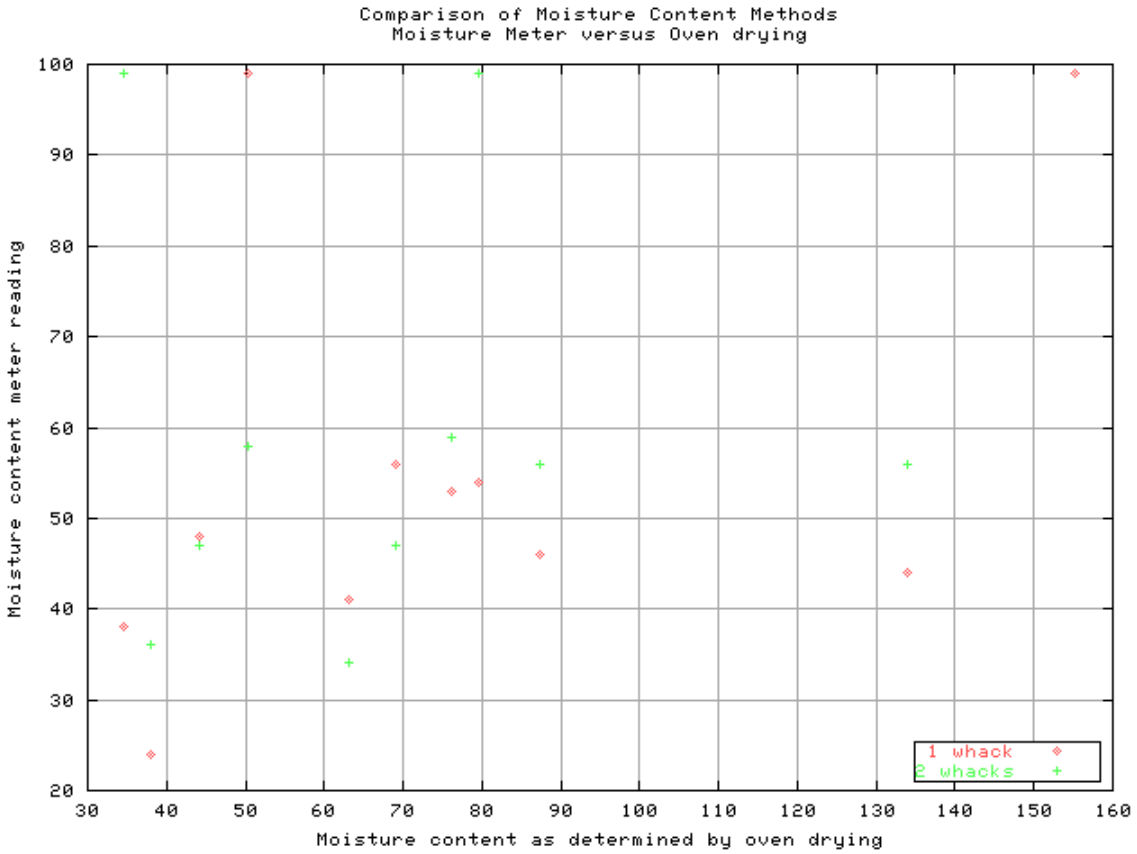

Figure 1. Moisture content of green hardwood lumber (cypress, poplar, red oak) measured with a resistance meter, compared to moisture content as determined by oven drying. Note the very poor correlation between the meter readings and oven drying results. "Whacks" refer to the number of times the meter's pins have been struck to drive them into the wood.

Potential applications for NMR moisture content measurement include sorting of green lumber before drying, monitoring of the drying process (especially oak), and verification of moisture content after kiln drying. Sorting prior to kiln drying and monitoring during drying are important to ensure uniformity of product emerging from the kiln. Verification after drying is important for quality control: if the wood is too dry, it is dimensionally unstable; if it is too wet, it can support growth of mold and fungus.

A distinct advantage of using NMR for monitoring drying is that it is possible to determine when the wood has reached the fiber saturation point. A further advantage is the ability to do depth profiling of the moisture content.

Discussions were held with hardwood kiln operators regarding the size of lumber that would need to be accommodated by the moisture content gauge. They preferred to have the capability of measuring boards up to three inches thick and being able to measure the center of a twelve-inch (30 cm) wide board. There was not much resistance to the idea of having a single gauge outside of the kilns, as current practice in many kiln operations is to remove sample boards for weighing on a daily basis.

Several energy savings modes are expected when moisture content is known accurately. One is that the airflow through the stacks of lumber in the kiln can be reduced when the wood has reached fiber saturation point. Drying can be stopped when the wood has reached the desired moisture content, typically 10 to 12% MC. Better control of the drying schedule will also reduce damage to wood and thus reduce the amount of wood that must be harvested to yield a given product.

One vendor of alder has an unusual problem. The logs are stored in a salt-water mill-pond resulting in an increased conductivity of the wood for a given moisture content. Their customers typically use a resistance meter to verify moisture content, and those meters gave an erroneously high reading. This results in the vendor having to defend their wood drying process.

2.1.2 Softwood

The main interest from softwood mills is the ability to measure moisture content of green lumber to allow for pre-sorting. This would allow for a more uniform moisture content of the dried lumber. Discussions indicated that accuracy of ±5% would be sufficient; however, the sensor must be capable of measuring lumber in motion on a conveyor.

Energy savings are expected from reduced drying times for the lots of green lumber with less than average moisture content.

2.1.3 Engineered wood

The engineered wood industry can be split into two broad groups. One produces laminated wood, with the most common example being plywood but also including other forms available in panels and beams. The other produces products such as particleboard or fiberboard.

The producers of laminated wood products are most interested in knowing moisture content of the wood immediately prior to lamination. Accuracy is not as much of a concern as being able to spot wood chips or strips with excessive moisture content. The wood is typically heated above 100°C to cure the resin used for lamination, and excess moisture can lead to a small steam explosion damaging the product. If excessively wet samples could be diverted, then the process could operate with higher average moisture content, which would then reduce the energy consumed in drying. Running with a higher moisture content before curing may improve the quality of the product as the wood would soften more during the cure, producing a tighter fit between the individual pieces and, thus, a better bond.

The producers of fiberboard would like to measure moisture content in the received material, during the drying process and immediately before curing.

2.1.4 Paper and Pulp

The paper and pulp industry is interested in measuring moisture content above the fiber saturation point. Drying the wood below fiber saturation point will tend to decrease porosity and make chemical treatment of the wood more difficult. Some sources state that the desired accuracy is 6%. Interest in improved moisture content accuracy is driven by the ability to assay the amount of fiber in delivered wood chips: paper companies pay for wood chips by weight, and prefer to pay for fiber, not water.

2.1.5 Paper recycling

Paper recycling companies expressed interest in moisture content measurement as a way of assaying fiber content. Since the most common method of paying for recycled paper feedstock is by weight, it sometimes happens that recycled paper is watered down before delivery to the recycling plant.

2.2 Mining

2.2.1 Coal

The first non-wood industry application to be investigated was measuring water content in coal. Gamma-Metrics had approached QM in 1999 to ask about the feasibility of developing an NMR system capable of measuring water content in coal that was being transported on a conveyor, to be used in conjunction with their own prompt gamma neutron activation analysis (PGNAA) analyzers. The opinion of QM's staff was that such an instrument was technically feasible.

PGNAA systems are useful for giving an elemental analysis of a sample but say nothing about the chemical composition of the sample. For example, PGNAA can give an accurate measurement of the hydrogen content of a sample, but doesn't say if the hydrogen is in the form of water or hydrocarbons. Hydrocarbon content is the source of the coal's energy value, but water represents "negative energy", since it absorbs energy in evaporation.

Existing technology relies on microwave attenuation to measure the water content of coal. There are three areas of concern with using that technique. First, the signal declines exponentially with the amount of water present, and accuracy would decline with higher water content (whereas NMR provides a linear measurement). The second area of concern is that the system assumes either a constant thickness of coal or a precisely known thickness. Errors in knowing the true thickness, for example, due to air pockets in the coal bed, then yield errors in the water content measurement. The third area of concern is that the microwave gauge cannot detect bound water. The microwave absorption technique relies on the water molecule rotating such that the molecular electric dipole moment would follow the oscillating electric field of the applied microwave radiation. If the molecule is bound, it cannot rotate and therefore cannot absorb energy.

Gamma-Metrics supplied QM with some coal samples that were used to perform feasibility studies. The results of the tests were encouraging, with a decrease in NMR amplitude that correlated well with mass loss when the samples were dried in a vacuum oven. The desired water content accuracy was ±0.25%.

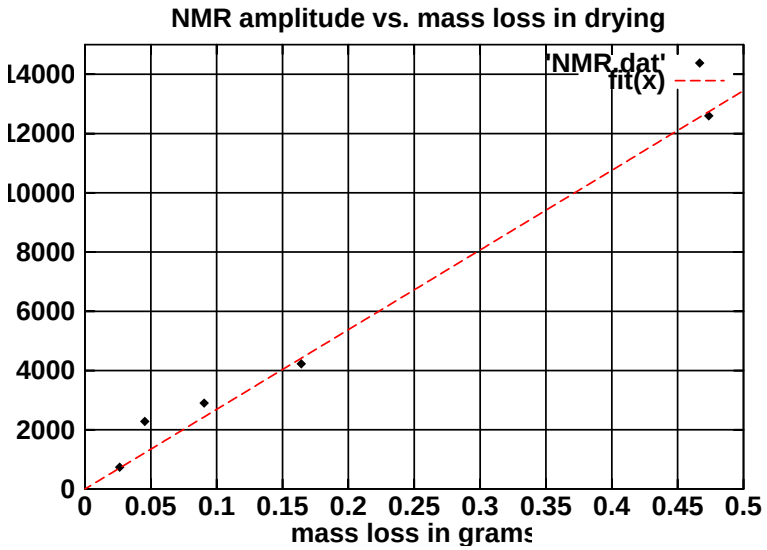

Figure 2. Coal samples. The graph shows a good, linear correlation between the NMR amplitude (in arbitrary units) and the mass loss (in grams). Drying was accomplished by placing samples in a vacuum oven maintained at 100°C.

Discussions then turned to potential system pricing. Gamma-Metrics was hoping for a price about the same as the existing microwave gauges ($50,000 or less), but the cost for a system that could handle coal on a conveyor belt would be substantially more than that. At that point, Gamma-Metrics did not feel that the advantages of the NMR instrument outweighed the cost of the system.

2.2.2 Gold

Professor Jeffrey Reimer of the University of California at Berkeley and Lawrence Berkeley National Laboratory (LBNL) contacted QM in regard to acting as a collaborator on a award to measure water content of gold ore. The intent was for QM to supply equipment of a design similar to that developed under this award. The motivation is that water content affects ore processing and, thus, energy consumption. Preliminary discussions with industry personnel failed to yield follow-up interest, however.

2.3 Bauxite Processing

QM personnel had held discussions with Raymond Proctor of Gamma-Metrics and Frank Kimmle of Alcan on the application of NMR for bauxite ore analysis. The motivations were measuring water content and hydration state of bauxite. Processing bauxite to extract aluminum is extremely energy-intensive, and driving off the water takes a large share of the energy budget. Improved water and hydration state measurement stands to save significant energy costs.

Unfortunately, raw bauxite contains iron, leading to concerns that would interfere with the NMR signal.[1] Frank Kimmle graciously supplied bauxite samples to QM. As expected, the iron in the

[1] The presence of iron particles in bauxite cause local disturbances in the static magnetic field. These disturbances result in local frequency offsets which then causes a rapid loss of coherence in the NMR signal.

bauxite caused a rapid de-phasing of the NMR signal. Water residing in the mineral pores could be detected because enough water resides far enough from the iron to be measurable. However, water hydrating the bauxite crystals is tightly bound inside the crystals, close to the iron. While it was possible to measure water content, the iron prevented the measurement of hydration state. A gauge that fails to measure both quantities does not address the industry's pressing need.

2.4 Petroleum

QM had engaged the services of Dr. Suresh Menon of Menon and Associates to look into possible applications of NMR to the petroleum industry. He discovered that many refineries were using NMR systems made by Foxboro for refinery control; he set up discussions with a contact person at Chevron, Donald Nettles.

The presence of the Foxboro units in the petroleum industry is both encouraging and discouraging. On the one hand, the petroleum industry has already accepted NMR as a means of process control. On the other, an established player appears to have a secure hold on the market.

The Foxboro system is significantly different than the system being developed under this award. The Foxboro system has a relatively small sample volume and typically measures a side stream of the product flow. This enables the key difference: namely, that the NMR measurements are done at a much higher static field (approximately 1 T) and the magnet is designed for high-resolution spectroscopy (the field is homogeneous to better than 1 ppm), using chemical shift to determine the constituents of the process stream.

The QM system developed under the present award uses a much lower field (0.14 T), has a larger sample volume, and is intended for measuring physical properties rather than chemical constituents. Properties of interest include fluid viscosity, and the fraction of material that has undergone polymerization.

Discussions with Mr. Nettles indicated several potential applications of a low-field, low-cost NMR system. These included measuring the water content of oil, determination of the end of well life, and analysis of petroleum coke. One significant requirement is that the equipment must meet the safety requirements for operation in and about a refinery. Although QM has had experience with developing NMR systems for use with energetic material, we do not now have the experience of developing equipment for the petroleum industry.

2.5 Steel

One possible application of NMR in the steel industry is to measure the hydrogen content of coke used in steel making. This particular application presents a severe challenge and was not pursued. However, interest was expressed in measuring the hydrogen content of quicklime (CaO) used as a fluxing agent in steel making. Ensuing discussions did not go beyond the expression of interest, although NMR testing in the laboratory did indicate feasibility.

3 Feasibility Measurements on Samples

3.1 Experimental Set-up

Measurements were performed with an in-house NMR spectrometer. The static magnetic field was provided by a large (5,000 kg) electromagnet, which is normally operated with a field of approximately 0.14 T. The radio frequency (RF) probe was built by QM and had been modified for various projects. The spectrometer console consisted of an industrial personal computer (PC) chassis with QM's NMR/NQR[2] board set. The data acquisition software is QM's "SpinVision" running on QNX.[3] The 600-watt RF power amplifier was assembled from commercially available modules modified for fast rise time. The low noise amplifier was a Mini-Circuits model ZFL-500HLN.

The coil on the RF probe consists of ten turns of 10 AWG copper wire, 5 cm long and inside diameter of 2.8 cm, intended to hold 27 mm OD sample vials. The coil was stiff enough to not require mechanical support. The winding pitch was adjusted to produce a uniform RF magnetic field inside the coil. The coil was resonated with American Technical Ceramics (ATC) porcelain chip capacitors (100E series). These capacitors both provide a reasonably high voltage rating and are not subject to piezoelectric ringing. Fine tuning and matching were provided by Jennings vacuum variable capacitors. Several carbon composition resistors were used to reduce the coil 'Q' to improve recovery time.

The system was designed to optimize recovery time at the expense of signal to noise ratio (SNR). Typical recovery time was 19 microseconds at 5.9 MHz. The observed "90°" pulse length was 4.7 microseconds, which corresponds to an RF magnetic field strength (B_1) of 25 gauss (2.5 mT). The minimum B_1 field for solid state ^{1}H NMR is 10 gauss (1.0 mT), needed to overcome homonuclear coupling.

The pulse sequence most commonly used was the "Magic Echo"[4]. The pulse sequence refocuses de-phasing due to homonuclear coupling in materials where the respective nuclei are relatively stationary during the pulse sequence (for instance, in a solid material such as cellulose). No refocusing occurs for nuclei in rapidly rotating molecules (for example, in liquid water). The advantage of this pulse sequence is that the center of the echo produced by the sequence can be delayed past the dead time (recovery time) of the NMR detection circuits, allowing detection of tightly bound water.

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[2] Nuclear Quadrupole Resonance is a zero-magnetic-field relative of NMR, used to measure certain crystalline materials.

[3] QNX is the brand name of a commercially available computer operating system.

[4] Rihm W.-K, Pines A., Waugh J.S.; *Phys. Rev.* **B 3**, 684 (1971).

3.2 Wood Samples

3.2.1 Hardwoods

We received samples of green hardwood from several different sources. Species included alder, cypress, poplar and red oak. Samples were usually shipped wrapped in plastic to reduce drying in transit.

Sample preparation consisted of cutting a piece of wood to dimensions 1.2 cm × 1.2 cm × 4.4 cm. A sample vial and cap would be labeled, weighed, and its weight recorded. Then the sample would be placed inside, the cap would be placed on the vial, the vial would be weighed again and that weight would be recorded. The cap on the vial prevented the wood from drying during the measurements.

The measurement sequence consisted of placing the vial in the NMR probe, taking the NMR measurements, recording the raw signal on a disk file and then placing the uncapped sample vial in an oven set for 100°C for a period of time. Once the vial was out of the oven, the cap would be replaced, the vial would be weighed, and another round of NMR measurements would be taken. This process was repeated until the samples were completely dry.

Data from the NMR measurements were processed by a non-linear regression fitting routine to determine the amplitudes of the signals from the solid component and the liquid component. Reference moisture content was determined by subtracting the dry sample weight from the sample weight at the time of a given measurement, and then dividing that result by the dry sample weight. The ratio of the liquid to solid NMR amplitudes was then compared to the moisture content as determined by weight. A good correlation was noted.

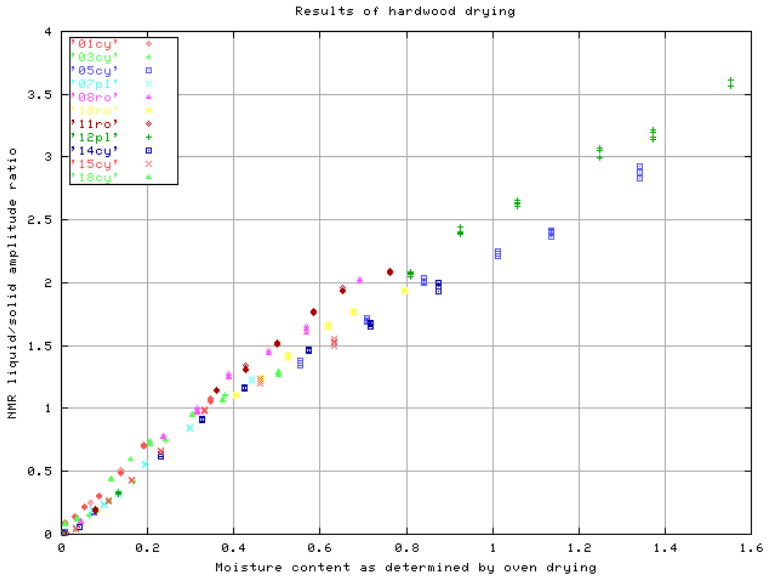

Figure 3. Comparison of liquid to solid amplitude ratio with moisture content (expressed as ratio, not percentage) for cypress (cy), poplar (pl) and red oak (ro). Correlation is generally linear; a decrease in slope for MC > 0.4 is due to a water component with a relaxation time, T_1, very long compared to the delay between acquisitions. Two of the cypress samples appear to contain a non-volatile liquid in addition to the water.

The samples shown in Figure 3 were cut from the boards that were used to generate Figure 2. Figure 3 has more data points due to the intermediate drying points in the process of collecting NMR data. While the correlation is not perfect, the results for MC's above fiber saturation point are much better than obtainable with a resistance gauge.

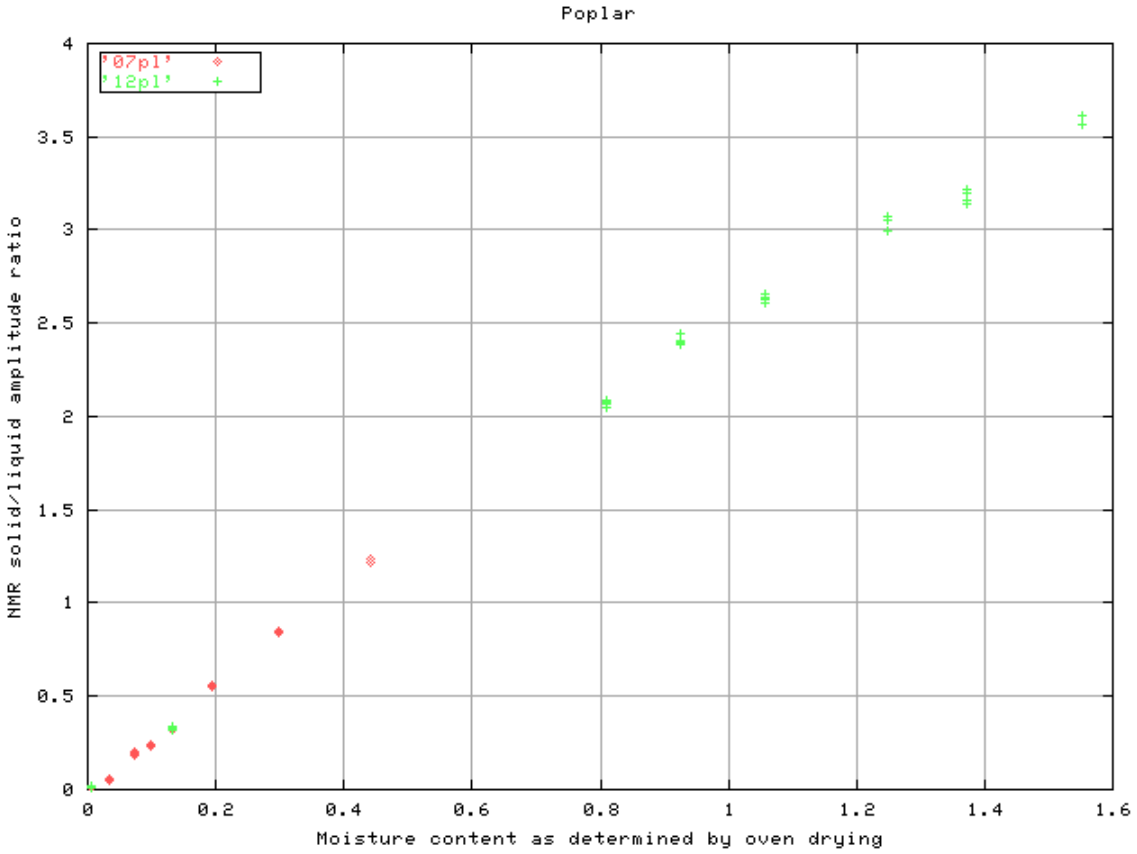

Figure 4. The correlation between NMR results and oven drying becomes much better when restricted to a single species.

3.2.2 Pine samples for particle board

We received samples of pine chips and sawdust from Sierra Pine. The measurement protocol was the same as used for hardwoods: weigh, measure, partially dry, and repeat. No effort was made to segregate results from the pine chips and sawdust. The free moisture in pine is much more viscous than the free moisture in hardwoods, which effectively eliminated the problems with long T_1's affecting measurements at high values of MC.[5]

The results indicate that the accuracy of the NMR measurements is relatively unaffected by packing density. This is an important consideration for other applications such as wood chips for the paper and pulp industry.

[5] The NMR relaxation time called T_1 varies inversely with liquid viscosity.

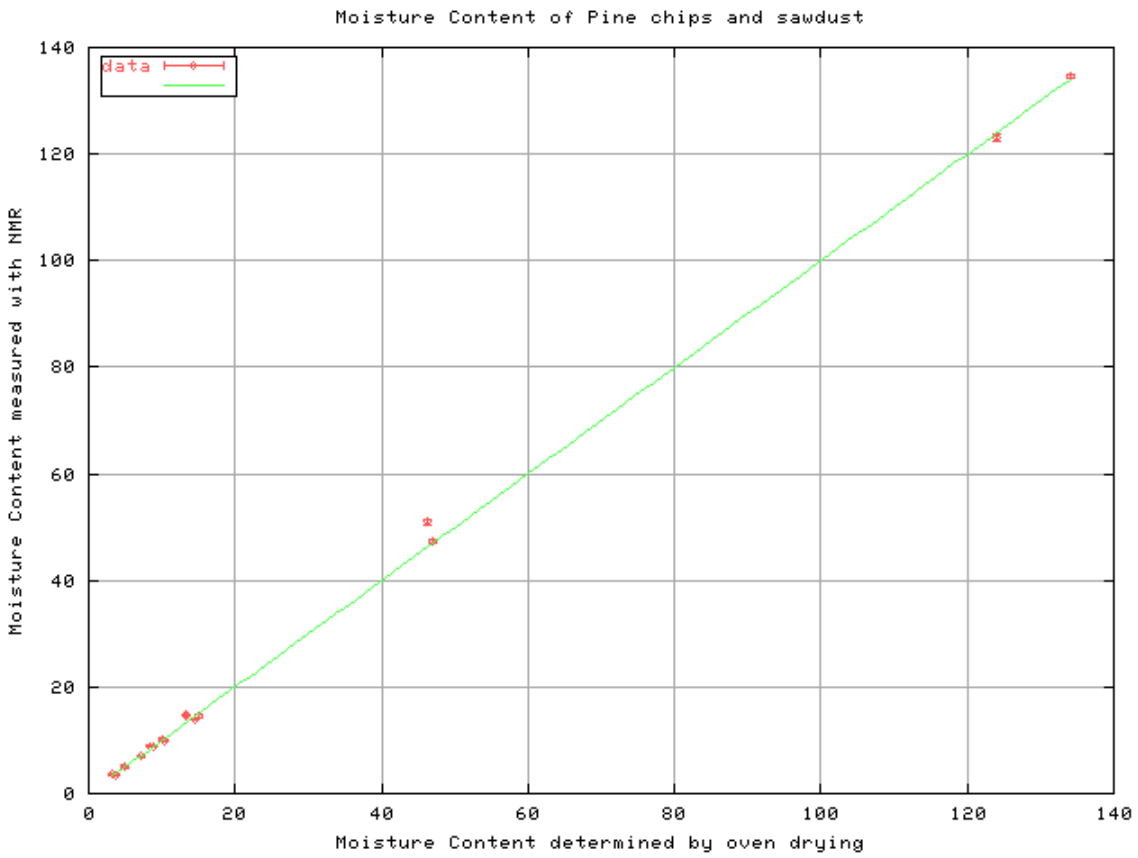

Figure 5. Comparison of NMR measurements of pine chips and sawdust with moisture content determined by oven drying. Note the very linear correlation.

3.3 Calcium Oxide (Quicklime) Samples

A small quantity of reagent grade calcium oxide (CaO) was obtained to determine feasibility of measuring its hydrogen content. The material as received did have some hydrogen present as determined by NMR measurements. Since quicklime changes its chemical state upon heating in air, drying the material would have been difficult, requiring re-calcination (that is, heating the sample to 1,000°C in an atmosphere with no water vapor or carbon dioxide). Instead of comparing to a zero-moisture sample, more samples were prepared, weighed and NMR measurements taken. These were then exposed to water vapor, weighed again and additional NMR measurements taken.

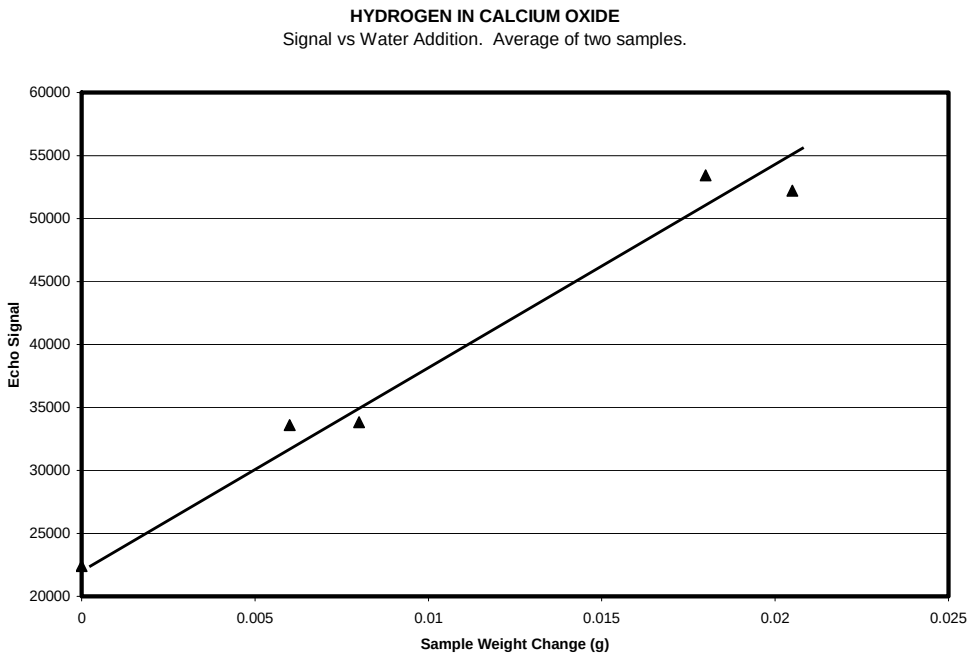

Figure 6. Correlation between quicklime weight change from water absorption and NMR signal amplitude. Experimental limitations preclude high precision, but the results indicate good correlation between absorbed water and signal, thus demonstrating that the hydrogen in quicklime may be measured by magnetic resonance. The observed amplitude corresponds to 80% of the signal expected from pure water.

4 Design and Model Magnet and RF Coil

4.1 Magnet Design

The magnet is the heart of an NMR system. Magnet design determines what NMR measurements are possible, the size of sample that can be accommodated, and much of the overall system cost. The magnet can also vary in being either a permanent magnet or an electromagnet with either resistive (normal) or superconducting windings. Still another variation is whether the magnet is enclosing or single sided.

One of the first design decisions is the static field strength. The signal obtainable from a sample increases with the square of the static field.[6] Higher fields come at a cost of higher magnet costs (and higher operating cost for a resistive electromagnet). Further problems occur due to higher voltages present during pulse transmission. Cost considerations drive to the lowest fields consistent with obtaining the requisite signals.

[6] The voltage induced in the RF coil is proportional to the product of the magnetization of the spins and the resonant frequency (Larmor frequency). For normally obtainable static fields and for a given temperature (above the milli-Kelvin range), the magnetization is proportional to the applied magnetic field. Since the resonant frequency is also proportional to the applied field, the induced voltage is proportional to the square of the applied field.

QM's experience with the Magic Echo pulse sequence supported a minimum operating frequency of 5 to 6 MHz in order to maintain a reasonable recovery time (receive circuit dead-time following the transmitted pulse). One of the reasons is that the recovery time for common RF amplifiers is inversely proportional to the low frequency cut-off. That is, an amplifier with a low frequency cut-off of 1 MHz will usually have twice the dead-time of an amplifier with a low frequency cut-off of 2 MHz. While the prime advantage of using the Magic Echo is allowing for longer dead-times, there are limits on how much the dead time can increase (typically 25 microseconds) without unacceptable loss of signal.

The other aspect of magnetic field strength is required homogeneity. High-resolution NMR magnets need to have fields with better than 1 ppm homogeneity and may reach 1 part per billion (ppb) homogeneity over the intended sample volume. The system built under this award was not intended for high resolution NMR, and acceptable homogeneity was on the order of 200 ppm.

Yet another design decision is the source of the magnetization. Since the system was intended for use in an industrial environment, superconducting windings were not considered practical. What are left are resistive electromagnets and permanent magnets. Generally speaking, electromagnets are the most economical for very large magnets and permanent magnets are the most economical solution for small magnets. Safety considerations often dictate the use of electromagnets, which have the benefit of being able to be turned off in an emergency.

The final design decision is configuration. Choices vary from single sided design to a fully enclosed design.

4.1.1 Single sided magnet

QM has built several single sided NMR magnets for non-destructive evaluation. The magnet sizes ranged from 10 cm square by 5 cm tall to 1 meter square by 60 cm tall, the latter weighing over 2,000 kg. The chief advantage of the single sided approach is that the magnet can be much smaller than the object being inspected. The disadvantages are that it is much more difficult to get a uniform field from a single sided design and that it requires a much larger permanent magnet assembly or electromagnet coil assembly to get the same static field as an enclosing design.

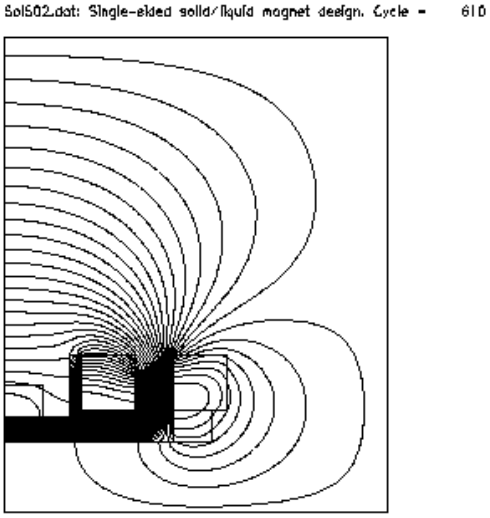

Figure 7. Two-dimensional modeling of a 0.09 T single sided magnet. The symmetry axis of the magnet lies along the left edge of the figure, which only shows the right half of the magnet. Lines on the plot represent magnetic field lines, not contours of constant flux density.

The magnet shown in figure 7 had a small volume where the homogeneity was good enough to do the liquid/solid measurement. Further design work would have been needed in order to make the homogeneous volume large enough to be useful in a wide range of applications. Cost of the magnet would have been prohibitive for its originally intended use in coal flow analysis.

4.1.2 C-magnet design

By the time the magnet design phase of the work started, what appeared to be the most likely first use of the system was measuring moisture content of lumber. In the interest of cost, it was important to determine the maximum board size that would be handled. During discussions with mill operators, little interest was expressed for measuring boards more than 3 inches thick, but there was a significant interest in measuring the moisture content in the center of boards up to 12 inches wide.

The requirement for measuring boards strongly suggested that the magnet be built in the shape of a ‘C’ as opposed to the more traditional ‘O’ frame. The advantage of the ‘C’ design is an unimpeded path from the open side of the magnet. The most significant disadvantage of the ‘C’ design over the ‘O’ design is the problem of insuring that the frame be sufficiently rigid. Other than that, there is very little that can be done with an ‘O’ frame that can’t be done with a ‘C’ frame magnet.

The design criteria were: (a) a gap between the magnet poles of 4 inches (actually 10 cm) to accommodate the 3 inch thick boards with clearance, and (b) 8 inches between the center of the magnet poles and the end of the ‘C’ to accommodate the center of a 12 inch wide board with

clearance. The diameter of the magnet poles is chosen to enable a reasonably large volume with adequate field homogeneity.

One design decision was whether to go for an electromagnet or permanent magnet. The following trade-offs were considered in the decision.

Permanent magnets:

- Advantages: Are good for small, high field magnets as it is difficult to get sufficient current density to make a small high field electromagnet. Do not require an external energy source to generate the magnetizing force.

- Disadvantages: Cannot be turned off (safety hazard). The generated magnetic field declines with increasing temperature, most pronounced with ferrite (ceramic) and NdFeB, least pronounced with Alnico and samarium cobalt. Large magnets become a challenge to build – especially the assemblies of permanent magnet material.

Electromagnets:

- Advantages: Can be turned off. Field can be adjusted. Large magnets are easier to design – ancillary costs (power supply, cooling) increase at a lower rate than material costs for a permanent magnet.

- Disadvantages: An external energy source is required and typically requires a very well regulated power supply. Some form of cooling is sometimes needed for the coil windings.

The final decision was to go with a permanent magnet design. To compensate for the temperature drift inherent in permanent magnets, the design included a set of trim windings. The power supply for the trim windings could be much smaller than for a straight electromagnet, and the low power consumption of the trim windings eliminated the need for a magnet cooling system. An additional advantage was that the stability requirements for the trim supply were not as stringent as for a straight electromagnet supply.

The initial magnet design started with a pole diameter of 15 cm. The tradeoff with pole diameter is cost and magnet weight for larger diameters and increased difficulty in obtaining adequate homogeneity for smaller diameters[7]. The magnetization would be provided by six cubes of NdFeB material arranged in a hexagonal pattern. Several pole face designs were modeled to produce a design with sufficiently large homogeneous volume. None of the designs had an adequately large homogeneous volume.

[7] This is due to edge effects, which become more severe as the ratio of gap to diameter increases. These effects can be partly overcome by narrowing the gap along the edges and shaping the interior portion of the face to increase homogeneity. The amount of shaping required decreases when the pole radius becomes much larger than the gap.

The next design involved increasing the pole diameters from 15 cm to 21 cm. This allowed for an array of seven NdFeB cubes and made it possible to have a much larger homogeneous volume. Previous experience in designing, building and adjusting (shimming) magnets to produce a homogenous field showed that the dimensions of the physical magnet that produced the desired field, would vary from the dimensions predicted by the model. The pole face design consisted of three concentric pieces to allow for minor adjustments without needing to remove the entire pole face (a task much easier to do with an electromagnet than a permanent magnet).

The magnet frame was designed to have a large enough cross section so that the flux density in the steel would be significantly less than 2 T. This also yielded a frame with more than adequate mechanical rigidity.

4.2 RF Coil Design

The RF coil is the means by which RF magnetic fields are coupled into and out of the sample being measured. Ideally, the RF magnetic field is orthogonal to the static magnetic field.

Two types of coil designs were considered. One was a form of solenoid suitable for liquid, powder or particulate samples (e.g. wood chips). The other was a coil suitable for measuring the moisture content of wide boards.

One of the most important considerations in coil design is that the sample being measured fill as much of the volume of the coil as possible; this parameter is termed “filling factor”. Stated more generally, the desire is to make the fraction of the total RF magnetic field energy in the sample volume as high as possible. This gives the best sensitivity and lowest RF power requirements.

Another design consideration is generating a homogeneous RF magnetic field in the sample volume. This is important for the performance of the NMR pulse sequences and for insuring a uniform sensitivity over the sample volume. Only some of the more exotic pulse sequences will require homogeneity better than 1%.

4.2.1 Solenoid coil

Solenoid coils offer good filling factors and can be designed to produce a homogeneous field. The design chosen was a single turn coil (sometimes referred to as a loop gap resonator) formed from a copper sheet with an array of resonating capacitors positioned along the gap. The values and placement of the capacitors are adjusted to produce a uniform field along the axis of the coil, in a manner similar to decreasing the winding pitch on a multi-turn solenoid.

The primary advantage of a single turn coil (loop gap resonator) over a more conventional multi-turn solenoid is the absence of an axial electric field gradient. The axial electric field gradient can excite piezoelectric ringing in some samples and can cause the coil tuning to change when the dielectric constant of the samples changes.

4.2.2 E-Quad coils

The design goal for this coil design was to produce a uniform RF magnetic field in a cylindrical volume between the pole faces. A further design constraint was that no part of the coil should extend more than 10mm above the outer ring of the pole face.

The starting point for the design was the back to back 'D'-shaped coils often used to generate gradients in MRI systems. One pair of coils would be placed adjacent to each pole face. This was modeled using Vector Fields, a 3-dimensional electromagnetic modeling package. The modeling results showed that the design had considerable room for improvement.

Two methods were used to improve the RF homogeneity. One was to re-shape the 'D' coils, with the coil outlines resembling thick crescents. The other method was to use two sets of coils in each pole face oriented 90° with respect to each other and fed 90° out of phase with each other. The latter method produces a rotating magnetic field (also referred to as circular polarization), which provides for an improvement in SNR[8] as well. The resulting field has acceptable homogeneity within a cylindrical volume with radius of 7 cm and a thickness of 5 cm.

5 Prepare Engineering Drawings and Quotes

5.1 Magnet

The dimensional information for the magnet model was turned over to an electromechanical engineer for preparation of the fabrication drawings. Parts to be fabricated included the magnet frame, components of the pole pieces, field spreader plates, aluminum disk for holding the NdFeB cubes, and an assembly fixture.

Quotes were based on purchasing components for two magnets, as the incremental cost of the second magnet was small in comparison with the design costs.

5.1.1 Magnet frame

The magnet frame serves two purposes. One is to provide a low-reluctance return path for the magnetic flux in the gap. The other is to provide a rigid mounting for the magnet assembly; the field quality can be adversely affected by small changes in the gap spacing. A fair amount of discussion centered on how best to join the sides of the C with the back in order to assure that the magnet would hold its dimensions. A local machine shop with considerable experience working with large steel pieces suggested flame cutting the frame as one piece from an 8-inch thick steel plate.

5.1.2 Pole faces

The pole faces were composed of three major parts: the main outer ring and base, the intermediate ring and the central disk. The intention was to allow for small adjustments in the position of the intermediate ring and central disk as part of the procedure to adjust the magnetic field for best homogeneity.

[8] Recall that the protons are precessing around the static magnetic field and thus produce a rotating magnetic field, with the axis of rotation parallel to the static magnetic field. A 3 dB improvement in SNR is possible when using circular polarization (rotating field) versus linear polarization.

5.1.3 Assembly fixture

The magnet pole faces need to be accurately positioned on the permanent magnet assemblies despite the several hundred pounds of force resulting between the pole faces and permanent magnet assemblies. A fixture was designed that would guide the pole face for both the assembly and disassembly process.

5.1.4 Magnet enclosure

Two magnet enclosure designs were completed. One was for use with the solenoid RF coil and the other was for use with measuring lumber.

5.2 Electronics

At the time the major work was being done on this award, QM's standard spectrometer hardware consisted of a rack mounted industrial PC, with rack mounted RF power amplifier and auxiliary electronics[9]. The system developed under this award used the standard spectrometer. It is lower in cost than the industry standard for similar capability. Since that time, work funded by DOD has dramatically reduced the spectrometer cost, and future iterations of the DOE system can leverage the benefits of the DOD work.

6 Procure and Fabricate Components of the System

6.1 Magnet

Jiffy Machine, located in Santee, CA, fabricated the magnet frame, pole face assembly, magnet holders and assembly fixture. They were chosen on the basis of past experience, having previously machined parts of a 5,000 kg electromagnet for QM.

Several requests for quotes were sent out for the magnet material and installation of the material in the magnet holder. The lowest price by far was from Magnetic Technologies Corporation of Group Arnold. The magnet frame and holders were shipped to Magnetic Technologies and the frames were shipped backed after installation of the magnetic material (which were comprised of 2 inch cubes of NdFeB permanent magnet material).

The next step in fabrication was installing the pole faces on the magnet. The assembly fixture worked as planned, making the process much easier and *safer*. The fixture was of immense help later on when it became necessary to remove the pole faces for adjusting the applied field.

[9] Rack mounting refers to 19-inch telephone relay racks widely used in the electronics industry.

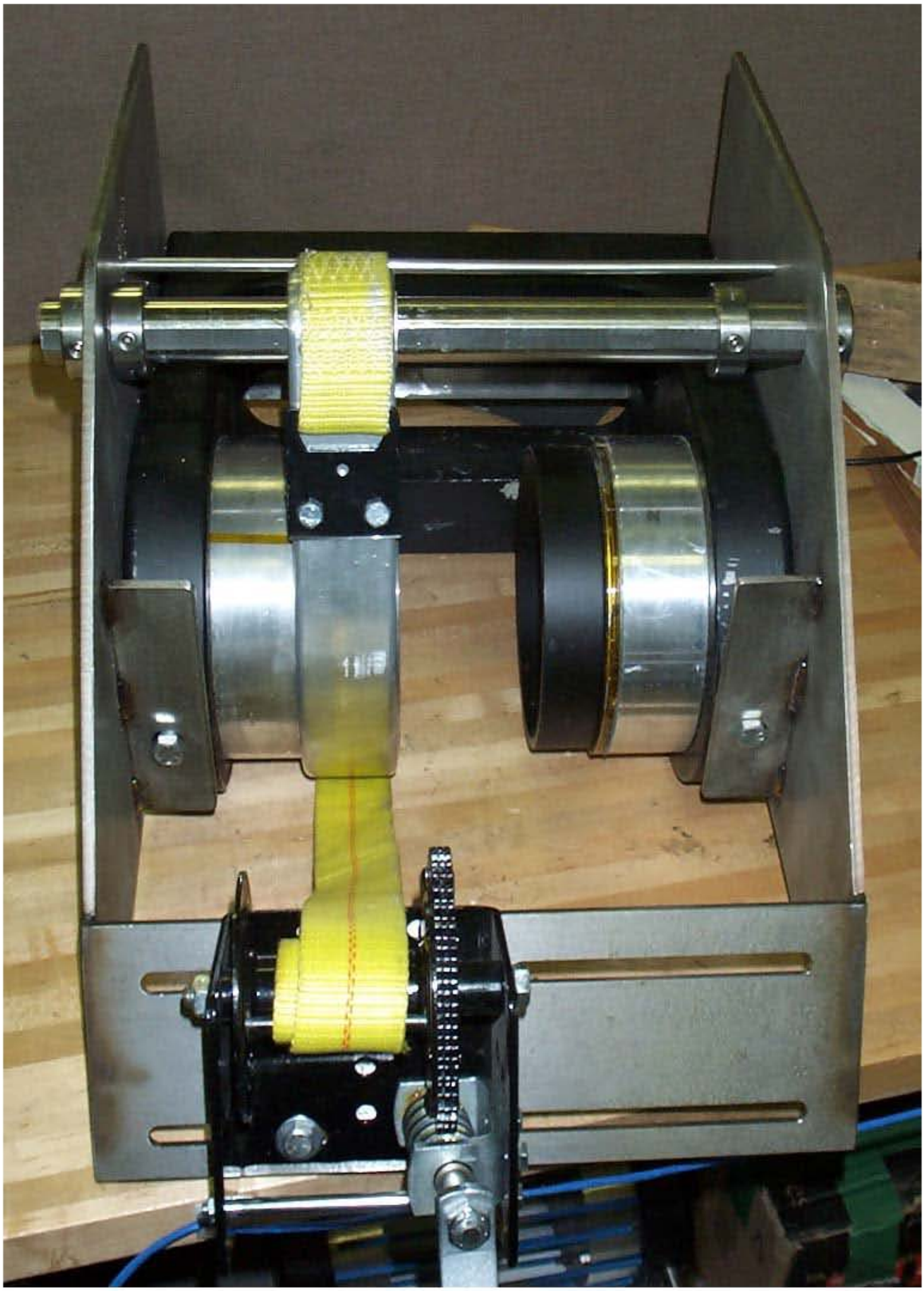

Figure 8. Magnet in assembly fixture.

Figure 9. Assembled magnet. The frame is the large "U" shape painted steel (paint marred in the process of assembly). The magnet holders are the large aluminum disks attached to the inside top of the frame. The pole faces are the black steel pieces mounted on the magnet holders.

6.2 Electronics

The electronics consists of: an industrial PC with QM's DRF-3 digital RF transceiver board and MR-0 pulse programmer and digitizer board; an RF power amplifier; a low noise preamplifier; and a magnet trim power supply.

Since this system was assembled, many parts used on the DRF-3 have become obsolete; it can no longer be manufactured. Both the DRF-3 and MR-0 used ISA slots; computers featuring these slots are becoming harder to find. To replace the functionality of the DRF-3 and MR-0, QM has been developing a self-contained spectrometer known internally as the "MAAC and FRIES", which will yield substantial costs savings over the DRF-3 and MR-0 in an industrial PC.

We had looked into using a Class-D power amplifier developed for a DOD-funded landmine detection award, but the difficulty of coupling to the DRF-3 and to the RF coil suggested using a conventional Class-AB power amplifier.

The original intent for a low noise preamplifier was to use a commercially available amplifier. Since work on the award began, QM had started work on a novel low noise amplifier for the landmine detection program that greatly reduced recovery time without affecting noise performance. We decided that this amplifier would offer significant advantage to this program. It is discussed in more detail in Section 7.6.

6.3 RF Coil

The solenoid coil consists of a copper sheet wrapped around a piece of PTFE (Teflon) busing stock and resonated with American Technical Ceramics (ATC) type 100C capacitors. The PTFE bushing stock provides mechanical support for the coil and satisfies the constraints of being non-conductive, non-magnetic and non-hydrogenous. The ATC capacitors are non-magnetic and have no piezoelectric ringing.

7 Assemble the System

7.1 Magnet Shimming

Currently available 3-dimensional magnet modeling packages will predict the fields with accuracies on the order of 1% or better. The models assume that the materials used are uniform and that there is no remnant magnetization from machining. An additional assumption is that the magnet was fabricated exactly as the model specified. With permanent magnets, the field prediction is dependent on how accurately the coercive field H_c and remnant magnetization B_r are characterized. It has been our experience from modeling and building several magnets that some shimming will be required for most magnets intended for NMR use.

Shimming is the process of mapping the magnetic field and then adjusting the magnet to produce the desired field. In an iron-dominated magnet, adjusting the magnet involves adding iron where a local increase in field is needed and subtracting iron where a local decrease in filed is needed. The iron is often added in the form of shim stock, hence the name “shimming”.

Initial mapping was done with a Hall-effect gauss meter, which allows for a rapid and coarse mapping of the field. The resolution of the gauss meter is 1 gauss at the fields generated by the magnet. Finer resolution is achieved by building a small NMR probe and measuring the Larmor frequency. This has an additional advantage that the absolute accuracy is on the order of a few parts per million.

The results of the NMR mapping suggested that new center disks be made, and a set was made. This was a much simpler job than having to machine a whole new pole face. After some work, the magnet was considered to be acceptably shimmed and was mounted in the magnet enclosure.

7.2 Magnet Enclosure and RF Probe

As mentioned before, the RF probe was fabricated from copper sheet, PTFE bushing stock (ID 2.0 inches, OD 2.5 inches). The probe is anchored to the enclosure by a pair of brass collars

fabricated from plate stock. The coil was then resonated at 5.9 MHz, which is slightly below the hydrogen Larmor frequency for the magnet. A slightly lower frequency was chosen, because tuning could then be adjusted by means of a shorted turn brought near one end of the coil, the resonant frequency increasing as the shorted turn is brought closer.

7.3 Computer with DRF-3 and MR-0

The computer operated normally as received. One of the first tasks was installing QNX 6.22, since QM's SpinVision spectrometer software was written for the QNX operating system. This was followed by physical installation of the DRF-3 and MR-0 boards. The computer and board set were tested and found to be operating normally.

7.4 RF Power Amplifier

The power amplifier is built in two stages. The first is a QM-designed driver amplifier using Elantec EL-2009[10], which works well at 6 MHz and has excellent transient response. The second stage is intended to be a pair of EB-104 modules from Communications Concepts Inc, with the outputs connected to a power combiner. The system was found to operate well with only one module; so only one module is installed.

The amplifier is fitted with thermal cutout switches to prevent overheating of the components. Panel mounted LED's show the status of the amplifier power supplies. Most amplifier faults would result in a large drop in power supply voltage.

7.5 Magnet Trim Supply

The magnet trim supply feeds the trim coils placed on the magnet. One drawback of using permanent magnets is that the field changes with temperature, with the field from NdFeB magnets decreasing 0.1% per degree Celsius. The trim coils are set to buck the field when the temperature drops below 20°C and to boost the field above that temperature.

The supply consists of a Weeder Technologies WTDAC-M four channel digital to analog converter board with an RS-232 interface. The output of the WTDAC-M is fed into a pair of Apex Microtechnology PA-01 power op-amp modules normally run in bridged mode. It is possible to use two outputs of the WTDAC-M to independently control the trim coils in case a gradient is desired. The gradient would be useful for depth profiling the moisture content of a piece of lumber.

[10] These were high speed (>50 MHz) buffer amplifiers. Unfortunately, these parts are no longer in production and no equivalent part is being made.

7.6 Low Noise Amplifier (LNA) – QM VILNAD

7.6.1 VILNAD background

The Variable-Impedance Low-Noise Amplifier Design (VILNAD) was developed for a vehicle-mounted landmine detection system. Modern landmines are typically made out of plastic, which is cheaper and lighter than a metallic equivalent. Unfortunately, the plastic landmines are much more difficult to detect than metal landmines. The QM system relies on the nuclear quadrupole response of the explosive to signal the presence of the mine.

Sensitivity is important for the landmine detection system, as it can literally make the difference between life and death. The detection sensitivity for TNT is highly dependent on the receiver recovery time, with sensitivity increasing with decreasing recovery time.[11] This assumes that methods used to decrease recovery time do not result in an increase in noise.

Recovery time can be broken down into three factors. The first is how fast the RF coil rings down from the transmit pulse. The second is how fast the low-noise amplifier (LNA) recovers from the severe overdrive. The third factor is how fast the signal rings up.

The first factor can be minimized by a combination of transmitter over-coupling and Q-switching. One consequence of Q-switching is that switching transients often excite more ringing in the RF coil, although at a much lower level than the transmit pulse. The ringing increases the dead time.

The effects of Q-switching transients and ring-up delays can be minimized by reducing the Q of the coil during receive. The simplest method is to add resistance to the coil, but that comes with a penalty of increased noise[12]. A better method for reducing Q is by over-coupling the LNA to the coil. This comes at a price of reduced signal to noise ratio, due in part to the coil impedance being substantially different from the optimal noise impedance of the amplifier.

The VILNAD overcomes this by using a low noise amplifier with high input impedance, a large gain with an inverted output, and a large-value resistor in a feedback loop. The feedback loop cancels the voltage noise of the resistor and yields an amplifier with an input impedance much lower than the source impedance for optimal noise performance. The feedback loop does not cancel the current noise of the resistor, but this is much lower than the current noise of a resistor equivalent to the input impedance of the amplifier. The overall result is that the VILNAD gives a much faster ring-down and ring-up time than a conventional LNA with no increase in noise.

The technique described in the previous paragraph is not new. What is new is a combination of switching and protection circuitries that will protect the amplifier from overload during transmit and allow for rapid recovery to normal operation.

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[11] Reducing time between transmit pulses improves “spin locking”, which allows for more signal averaging.

[12] Some researchers have resorted to immersing the resistors in liquid nitrogen or liquid helium to reduce noise.

7.6.2 Incorporating the VILNAD into this system

The VILNAD was originally designed to operate between 700 kHz and 3.5 MHz. The present system requires operation at 6 MHz, which requires increasing the gain bandwidth product. The increased gain bandwidth product resulted in some stability problems.

The RF coil used in this system has a primary resonance of 5.94 MHz. Due to the construction of the coil, there are other resonant modes at much higher frequencies, starting at 24 MHz. This coincides with the input impedance of the VILNAD going negative (i.e., it is not unconditionally stable) at higher frequencies and multiple oscillation modes were noted. Several methods were tried to kill the oscillations, most of which had an adverse effect on the noise performance.

The stability problems were cured after several months of work. The next step was applying RF pulses to the coil and checking for recovery time. A low level Q-switching system was implemented in order to get the recovery time down to the desired 20 to 25 microseconds.

7.7 System Assembly

System assembly mainly involved connecting the components together. A sample was inserted into the RF probe and an NMR signal was detected in the first attempt.

Initial testing demonstrated that using the VILNAD resulted in a 13 dB improvement in SNR over the laboratory system. This is taking into account differences in coil size and is a spectacular improvement. We are getting better SNR in two seconds than we used to obtain in one minute.

Figure 10. The completed system. The magnet, RF coil and VILNAD are in the enclosure sitting on the table to the right. The components in the rack enclosure from top to bottom are: LCD monitor and keyboard; Industrial PC chassis; Trim coil power supply cabinet; RF power amplifier cabinet. The interconnecting cable assembly is 6 meters long.

8 Application Engineering

A graphical user interface (GUI) was written to permit operation by personnel not familiar with NMR instrumentation. The GUI included a means for determining liquid to solid ratios (e.g. moisture content in wood). The interface to the outside world is initially via Ethernet, with the beta test site preferring a LabView interface. It is a simple matter to use a 4-20 mA current loop, RS-232 interface or another Ethernet based protocol.

9 Beta Testing

Mr. Thanh Trung of PAPRICAN contacted QM expressing interest in evaluating the moisture content measurement system. This appeared as an ideal test situation, since we did not have to worry about interfering with a production process. PAPRICAN operates a pilot plant-scale testbed facility near Vancouver, B.C. It is funded by an international consortium of paper and wood pulp businesses, so that successful beta testing results can be disseminated rapidly to an important segment of the wood products industry. In addition, since QM is not in the process control business,[13] PAPRICAN offers an ideal low-cost method to obtain industry feedback on the prototype system.

We are very grateful for Paprican's patience in waiting for the system delivery.

9.1 Results of Beta Testing

The prototype system was shipped to PAPRICAN on May 27th, 2005 and arrived a week later. Uncrating took place the afternoon of June 7th and the system was set up on the 8th. The system was brought up and appeared to be functioning normally. PAPRICAN had samples of Jack Pine with known moisture content and a few of those were measured with the prototype system with some large and disconcerting discrepancies between PAPRICAN's previous measurements and the results of the NMR measurements. The discrepancies turned out to be due to the system reporting moisture content on a dry basis, that is weight of moisture as a percentage of the weight of the dry wood, and PAPRICAN's measurements having been reported on a wet basis, weight of moisture as a percentage of the weight of wet wood. A 100% MC dry basis is the same as 50% MC wet basis, 200% MC dry basis is the same as 66.6% MC wet basis.

The system software did not work as well as expected. Though data acquisition worked well, the automated data analysis was not as robust as expected, nor was the software to lock the magnetic field at the right value. A shell script replaced the original magnet field-lock software. The data analysis problem was traced to the curve-fitting routine. It sometimes found that a negative value of the baseline offset constant yielded the best fit, with an error being reported consequently. A more uniform magnetic field would reduce the likelihood of this error by increasing the time span over which the signal displays a true exponential decay.

Denys LeClerc, Shannon Huntley and Kathy Woo of PAPRICAN were trained to operate the system independently of QM support. Except for the fitting routine, it has operated reliably.

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[13] Although GE does have other business units involved in process control.

PAPRICAN's initial testing has shown that the system is capable of measuring moisture content to better than 1% accuracy, which is a major milestone in the demonstration of NMR moisture measurement capability.

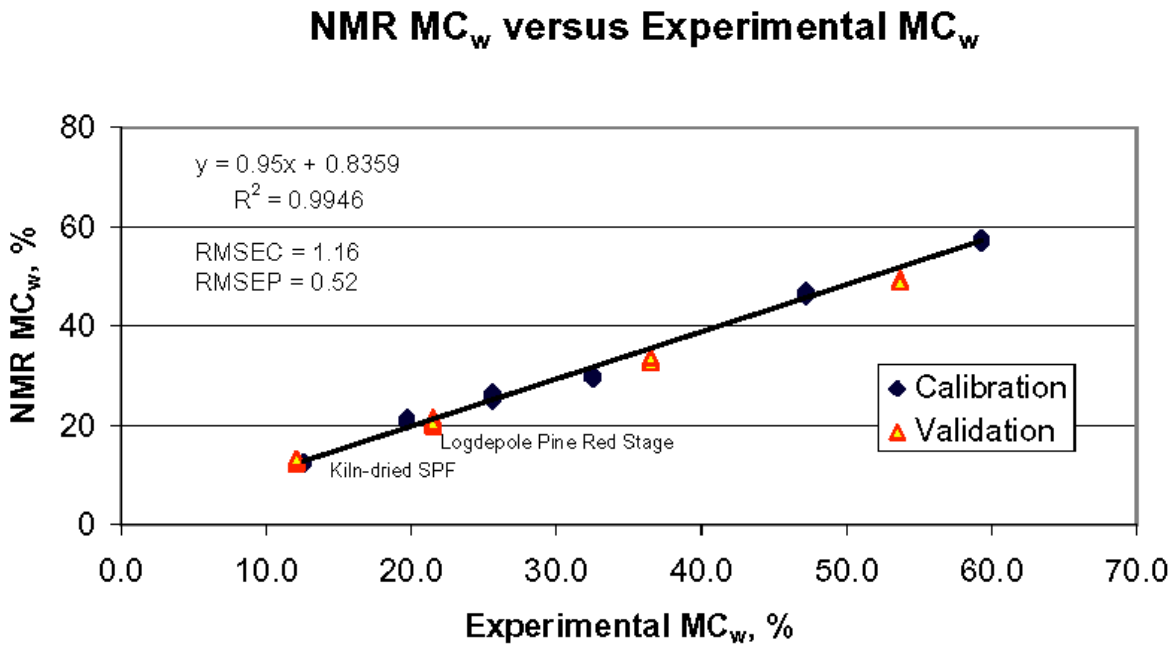

Figure 11a. Curves showing moisture content (wet basis) of Lodgepole pine samples. From D. Leclerc, "Measurement of Moisture Content in Wood Chips by Low-resolution Pulsed NMR Relaxometry", PAPRICAN, Vancouver, BC, Canada, October, 2005.

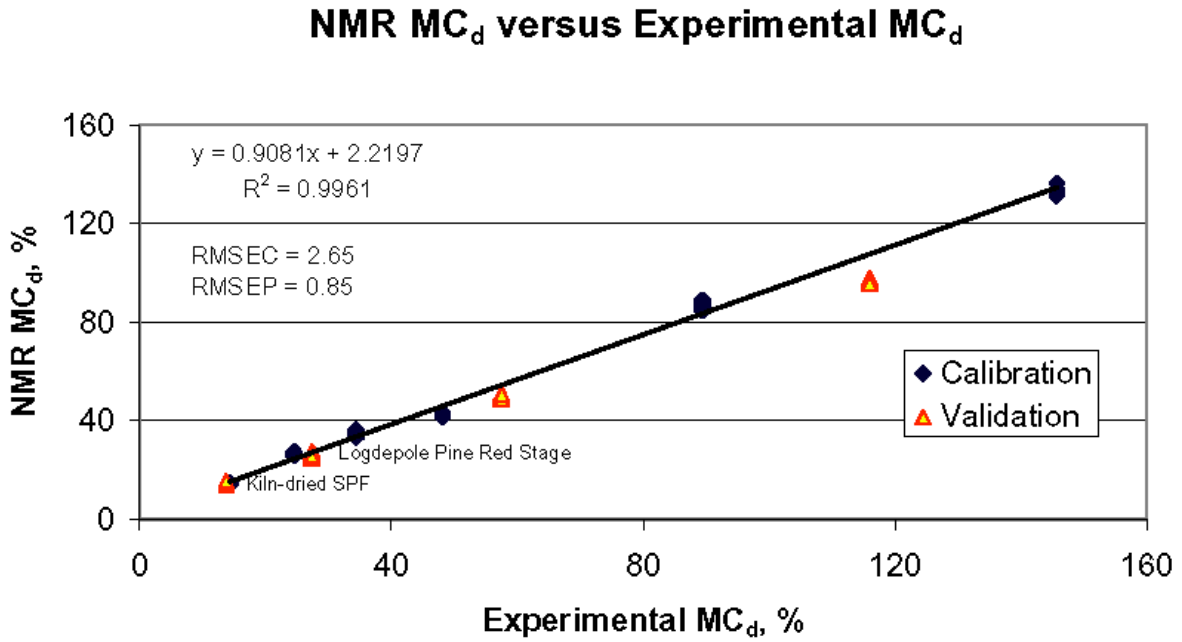

Figure 11b. Same data as above expressed in terms of dry-basis moisture content.

The prototype system has demonstrated that it is capable of delivering the required accuracy of measurement. What has yet to be developed is a sampling protocol and integration with a process control system.

10 Future work

10.1 Applications

Interest has been expressed in the softwood lumber industry for pre-sorting green lumber before kiln drying. Current practice is to over-dry the lumber to insure that the wettest boards do not have excessive moisture content after drying. Pre-sorting should allow for a more uniform drying and reduced energy consumption during drying.

10.2 System Design

10.2.1 Cost reduction

The performance of the VILNAD suggests that a future system can operate well at a lower frequency – equivalently, at lower magnetic field strength. This would result in several avenues of cost savings. One is that it would be possible to use ferrite magnets instead of the NdFeB magnets used in the existing magnet. The raw material is much cheaper and much easier to work with. The magnet frame could be lighter, since the amount of steel needed to avoid saturation is proportional to the field strength in the gap.

Further cost reductions can come from using QM's "MAAC and FRIES" spectrometer board set instead of the industrial PC with DRF-3 and MR-0. The lower frequency will make Class-D RF power amplifiers more practical, which will also allow for larger sample volumes with a minor increase in cost.

An example of potential cost reduction is seen in a prototype NMR system, intended to detect freeze damage in citrus fruit, delivered to U.C. Davis. The overall system weight is 20 kg; the system is battery operated. It uses an early version of the "MAAC and FRIES" board set. We are confident that a production unit could be sold for less than $30,000 and possibly less than $20,000. A system capable of measuring moisture content of wood would likely be somewhat more expensive due to the two requirements of higher RF power and much shorter receiver recovery time.

10.2.2 Performance improvements – magnet design

Measurement error is presently dominated by the error in analyzing the amplitude of the liquid component. This in turn is dominated by the inhomogeneity of the magnet, which causes noticeable de-phasing of the NMR signal within 150 microseconds after the end of the transmit pulse. The fitting algorithm used in determining the liquid and solid amplitudes performs best when the start of de-phasing is postponed to at least 400 microseconds after the end of the transmit pulse.

The fitting algorithm treats the NMR signal as the sum of a Gaussian (the solid component), a Lorentzian (decaying exponential, decay constant varying from 100 microseconds to 4 milliseconds) and a constant.[14] Increasing the time before de-phasing allows for a more robust fit of the Lorentzian time constant (which isn't critical) and Lorentzian amplitude (which is critical). It would be possible to deconvolve the effects of the magnetic field gradients ***if*** the samples were of uniform size and density, but real world samples are neither.

Lowering the magnetic field would help in two ways. The first is that the magnetic field gradients, for a given magnet design, scale with the field.[15] The second is that for a given magnet weight, cost and spacing between the pole faces, a lower field would allow for larger-diameter pole faces, leading to further reduction in the field gradients. A larger magnet will be easier to shim than a smaller magnet and it may end up that the magnet with lowest production cost is considerably larger than the magnet with lowest cost of raw materials.

10.2.3 Performance improvements – electronics

The system recovery time was not as short as desired. The issue with the prototype system was dissipating (quenching) the stored energy in the detection coil when the coil voltage was between ~1 V and ~1 mV.[16] A switched quenching network was added to improve recovery time, but was limited by the voltage and current ratings of the switching diodes (1N4150's). Recent advances in SiC Schottky diodes offer the possibility of much more effective switched quenching networks. Schottky diodes have the advantage of no reverse recovery charge, but silicon based Schottky diodes had insufficient reverse voltage ratings to be useful.

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[14] Which for wet woods (i.e. above fiber saturation point) is really composed of two or three exponentials, which can be approximated by a constant for time scales small compared to the decay constants.

[15] This is a first order approximation as it ignores the effects of saturation (or lack thereof) in the iron used in the frame and pole faces. Reduction/elimination of saturation can be either beneficial or detrimental, depending on system particulars.

[16] The transmitter was effective in quenching above 1 V and the VILNAD was effective below 1 mV.