DOE F 241.3
(2-01) p. 1 of 4

ANNOUNCEMENT

UNITED STATES DEPARTMENT OF ENERGY (DOE)
Scientific and Technical Information (STI) For Financial Assistance Recipients and Non-M&O/M&I Contractors

OMB Control No. 1910-1400

PART I: STI PRODUCT DESCRIPTION

(To be completed by Recipient/Contractor

A. STI Product Identifiers

1. REPORT/PRODUCT NUMBER(s)
Final report

2. DOE AWARD/CONTRACT NUMBER(s)
DE-FC36-01GO10618

3. OTHER IDENTIFYING NUMBER(s)

B. Recipient/Contractor
University of Tennessee, Knoxville, Tennessee

C. STI Product Title
Final Progress Report

D. Author(s)

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E. STI Product Issue Date/Date of Publication

11/1/2004

F. STI Product Type *(Select only one)*

X 1. TECHNICAL REPORT

x *Final* ☐ *Other (specify)*

☐ 2. CONFERENCE

H. Sponsoring DOE Program Office
Golden Field Office

I. Subject Categories *(list primary one first)*

Microwave moisture sensors
Keywords wireless, microwave, moisture sensor, dry kiln

J. Description/Abstract

Final technical project report

K. Intellectual Property/Distribution Limitations

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G. STI Product Reporting Period (mm/dd/yyyy) ***10/1/2001*** *Thru* ***09/31/2004***	**L. Recipient/Contractor Point of Contact** *Contact* **for additional information (contact or organization name to be included in published citations and who would receive any external questions about the content of the STI Product or the research contained therein)** ***William W. Moschler*** **Name and/or Position** **bmoschle@utk.edu** ***865-946-1122*** **E-mail** **Phone** *University of Tennessee* *Organization*

ANNOUNCEMENT

UNITED STATES DEPARTMENT OF ENERGY (DOE)
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OMB Control No. 1910-1400

PART II: STI PRODUCT MEDIA/FORMAT and LOCATION/TRANSMISSION

(To be completed by Recipient/Contractor)

A. Media/Format Information:

1. MEDIUM OF STI PRODUCT IS:

X Electronic Document **X** Computer medium

☐ Audiovisual material **X** Paper ☐ No full-text

2. SIZE OF STI PRODUCT ____________

3. SPECIFY FILE FORMAT OF ELECTRONIC DOCUMENT BEING TRANSMITTED, INDICATE:

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☐ 2. THIS DELIVERABLE FULFILLS A TECHNICAL REPORTING REQUIREMENT, BUT SHOULD NOT BE DISSEMINATED BEYOND DOE.

B. DOE Releasing Official

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B. Transmission Information:	Released by *(name)* **William W. Moschler**
STI PRODUCT IS BEING TRANSMITTED: **X** 1. Electronic via Elink **X**2. Via mail or shipment to address indicated in award document *(Paper products, CD-ROM, diskettes, videocassettes, et.)* ☐ 2a. Information product file name **Final Technical Report**	Date **01/10/2005** (mm/dd/yyyy) E-mail bmoschle@utk.edu Phone 865-946-1122

Final Report

For: Wireless Microwave Wood Moisture Measurement System for Wood Drying Kilns

Covering Period: January 1, 2001, to September 30, 2004
Date of Report: September 30, 2004

Recipient: University of Tennessee
Award Number: DE-FC36-01GO10618
Subcontractors: Oak Ridge National Laboratory

Other Partners: Kiln Drying Systems, Inc., in-kind support; Averitt Hardwoods, in-kind support; Communications and Power Industries, Inc., in-kind support; International Paper Co.; Navigational Sciences, Inc., in-kind support.

Contact: Principle Investigator: William W. Moschler, 865-974-0201, bmoschle@utk.edu.
ORNL Lead Investigator: Dr. Gregory R. Hanson, 865-574-9681, mailto:hansongr@ornl.gov

Project Team: Department of Energy/Headquarters: Doug Hooker, Jim Alkire

Project Objective: The objective of this project is to develop a prototype microwave-based moisture sensor to be used in hardwood lumber drying kilns. The sensor should be accurate from about 60% dry-weight basis moisture content (MC) down to 7% MC. The moisture sensor will be combined with spread-spectrum wireless telemetry to provide continuous readings during the entire drying cycle.

Background: Existing electronic moisture sensors for use in dry kilns are accurate only over the range of 25 to 6% MC. Weight sensors work over the full MC range but do not read MC directly and cannot be mounted in the lumber stack (they are usually mounted in the kiln plenum) and so are not measuring the MC of boards in the lumber stack. Resistance based MC sensors are only accurate from 25% MC to 8% MC and suffer from long term drift during the drying run. The predominate method of MC monitoring in current use is the daily manual weighting of kiln samples and the estimation of MC from an initial MC-weight determination. This method is slow, labor intensive, and does not provide adequate MC data in terms of accuracy or MC distribution within the load.

The electronic sensors we have developed in this project are sized so that they may be inserted into the lumber pack, illustrated in Figure 1, in various locations in the kiln.

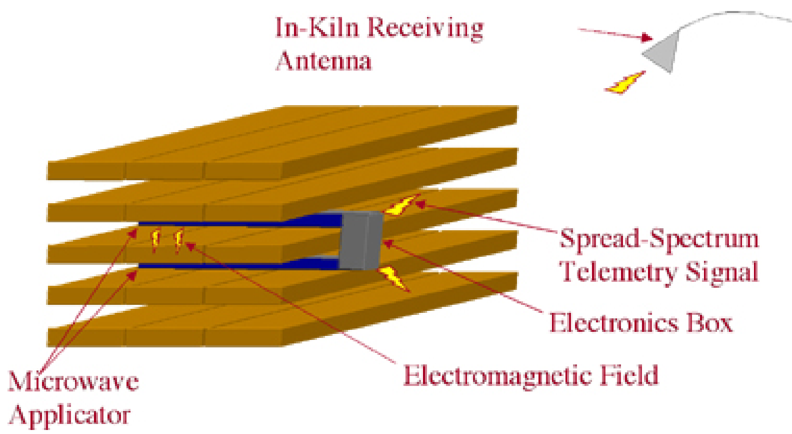

Figure 1. Illustration of a wireless moisture sensor inserted in a stack of lumber.

Figure 2 illustrates the use of a distribution of wireless sensors in a kiln. These sensors can provide better information about the average MC and the distribution of moisture within the kiln load than it is current possible to obtain. This increased knowledge of MC, particularly at the critical region of 35 to 25% MC, allows kiln operators to greatly increase the drying rate without risk of excessive lumber degradation. These sensors can be will interface with existing PLC-based control systems used in the hardwood and softwood drying industry. During this phase 1 project we identified and demonstrated a suitable microwave moisture measurement system and demonstrated wireless telemetry in a dry kiln.

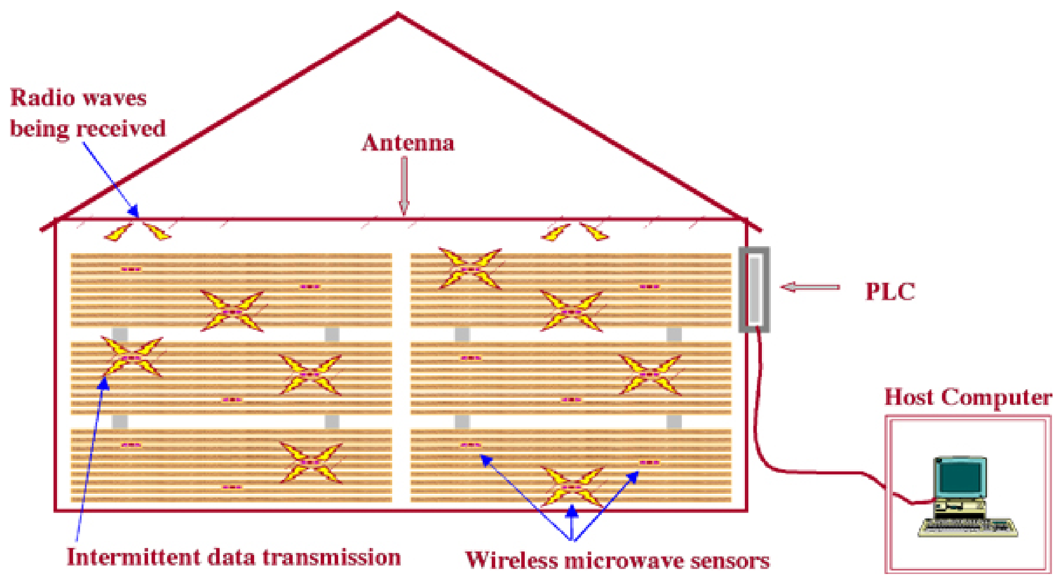

Figure 2. Illustration of the use of multiple wireless moisture sensors distributed throughout a kiln load of lumber, allowing better determination of the average and distribution of the moisture content within the kiln.

The initial sensor development focused on evaluating two different types of microwave measurements. The first method involves measuring the change in the frequency and quality factor, *Q*, of a resonant microwave structure positioned next to a board. The second method is an interferometric measurement in which the phase and amplitude of a microwave signal transmitted through the board are measured. The resonant microwave structure could be, for example, a parallel plate capacitor with the board between the two plates, an open-ended waveguide cavity with the board positioned over the open end of the cavity, or a parallel conductor transmission line positioned on top of the board or bent into a 'U' shape to surround the board. The interferometer method requires a launching antenna on one side of the board and a receiving antenna on the other side of the board. Both methods appeared to meet the criteria of being able to fit within the sticker space of a stack of lumber in the dry kiln. However, the resonant circuit approach suffered from significant influences from lumber stacked above and below the board being tested. This interference made the measurement unreliable for use in a commercial lumber stack.

The interferometer measurement proved to be localized and robust. Microwave launchers were designed to clamp around a board with their apertures in contact with the board. The launchers were designed to minimize the impedance mismatch between the launcher and the board. Impedance matching is accomplished by filling the launchers with a dielectric material having a dielectric constant similar to that of the dry lumber. Specifically, the launchers were formed from waveguide-to-coaxial adapters and filled with Teflon.

We decided to use a swept-frequency approach to the measurement. By sweeping the frequency, we were able to measure the phase and amplitude change of the microwave signal across the frequency band, and therefore the slopes as well. We first tried 7.0 to 9.0 GHz using X-band waveguide. Measurements were performed using a Hewlett Packard Network Analyzer. This proved to work well to make the MC determination. Subsquent evaluation showed the cost of building a custom electronics circuit of the type that we wanted to us at these frequencies was prohibitive. Upon evaluation of the availability and cost of microwave electronics, we determined that 4.5–6.0 GHz was the a cost–effective frequency at which to operate that would still provided sufficient amplitude and phase change for dry lumber. It was then determined that Teflon-filled launchers using WR-137 would operate in this frequency range. This resulted in the prototype sensor design used in the final year of this project.

The data analysis developed for this sensor uses a regression model for estimating the MC. Features generated from this complex frequency-dependent signal are average magnitude, average unwrapped phase, slope of unwrapped phase, and a normalized sum of complex values. These features are combined with other available features such as temperature, board thickness, and density. Statistical learning techniques are applied to these features to develop a regression model for estimating MC. Regression techniques used include least-square modeling, support vector regression, and a least-square model tree. The use of a least-square model tree allows least-square modeling to be used in a step-wise manner so that different models are used for different subsets of the input space.

Microwave Launcher Development: Initial development work focused on comparing two types of measurement techniques. The first was a measurement of the change in the *Q* and frequency of a resonant structure placed against or around a board. The second technique was a transmission interferometer measurement of the amplitude and phase of the microwave signal after propagation through a board. Figure 3 shows the resonant parallel plate capacitor used in these tests; Figure 4 shows the folded parallel transmission line used. In both cases, the board was placed between active areas of the applicator, and the change in the Q and resonant frequency was measured using a network analyzer. This technique proved to be successful, but the measurement also proved to be very sensitive to where the board was positioned in the applicator and to boards placed above or below the applicator. Because of this sensitivity, this technique was dropped.

Figure 3. Parallel plate capacitor microwave applicator. This device has a resonant frequency, when filled with air, of approximately 180 MHz and a *Q* of 127.

The interferometer technique required microwave launchers that would go on each side of the board, would fit in the <1-in. space between each board (the "sticker" space), and would provide a good impedance match to the board. We decided that modified waveguide-to-coax adapters could fit in the sticker space and be easily aligned and held in place with a simple clamping mechanism. But the impedance match of these air-filled launchers proved not to be as good than desired. We therefore tried improving this match by filling the adapter with Teflon and tuning the height to minimize the internal reflections. This proved to be very successful. The first launchers built this way used WR-90 waveguide adapters (see Figure 5).

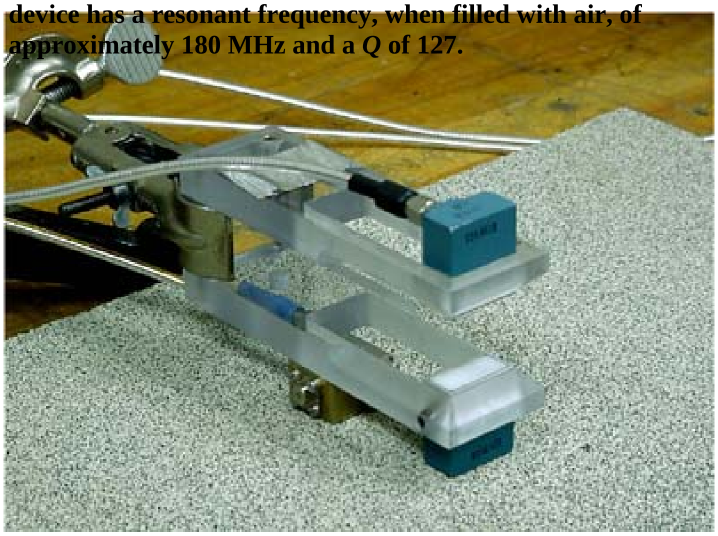

Figure 5. WR-90 teflon-filled waveguide launchers.

After demonstrating the efficacy of the Teflon-filled waveguide launchers, we decided to use a lower frequency range so that cheaper solid-state microwave electronics could be used in the detection circuit. We determined that operating over the frequency range of 4.5 to 6.0 GHz would allow utilization of commercial off-the-shelf microwave electronics components. Using WR-137 waveguide-to-coax adapters, we fabricated new launchers optimized for this frequency range. These are shown in Figure 6. One drawback to these launchers is their height. Each launcher is 1.1 in. tall and so will not fit in a sticker space. We therefore developed a second design for the waveguide launchers using WR-159 waveguide-to-coax adapters and a waveguide taper. In these launchers, the microwaves are launched into the air-filled waveguide-to-coax adapter. The waveguide then tapers down to the dimensions of a WR-137 waveguide. In this taper is a Teflon cone tapering up to fill the WR-137 section of the waveguide. The Teflon-filled waveguide then undergoes a 90° H-plane bend, and then a 90° E-plane bend, to launch the microwaves into the board. These launchers are shown in Figure 7. These launchers fit in the standard 3/4-in. sticker space.. We demonstrated that both launcher designs can be used to make accurate MC measurements, although we prefer the simple design of the launchers shown in Figure 6.

Interferometer Electronics Development: Once we had settled on a frequency range for the measurement and proved the validity of the measurement by recording data with a microwave vector network analyzer, we designed and implemented a custom electronics circuit to provide the 4.5 to 6.0 GHz microwave signal and then detect the phase and amplitude of the transmitted microwave signal. Two concerns with making measurements in the kiln are the effects of temperature variations on the electronics and the long-term stability of the electronics. To allow both these effects to be calibrated out, we implemented a bypass loop as part of the electronics circuit, illustrated in Figure 8. Two solid-state switches were used to switch between the measurement loop and the bypass loop. When MC measurements are made, the microprocessor obtains a wood measurement and a bypass loop measurement, and then subtracts the two to get the contribution from just the board (launcher contribution is also included but does not affect MC determination regression analysis).

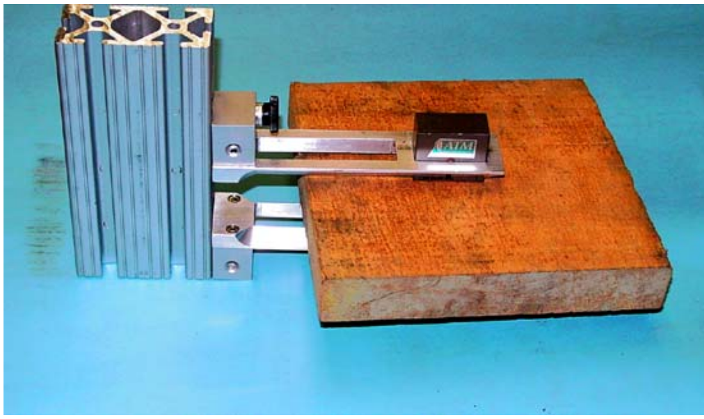

Figure 6. WR-137 teflon-filled waveguide launchers.

As shown in Figure 9, the moisture sensor consists of two antennas, two synthesized signal generators, a downconvert mixer, a synchronous I&Q signal detector, two solid-state switches, a bypass loop, an embedded computer for controlling the system, and a power supply system (not shown). A reference oscillator provides the time base signal for the two signal generators and the synchronous detector so that the generators and detector will have the same phase. The difference in the two generator frequencies is equal to the frequency of the reference oscillator for purposes of operating the synchronous detector. One of the generators is fed to the transmitting antenna, and the receiving antenna receives this signal after it has propagated through the wood sample. The other generator and the received signal are fed to the downconvert mixer to produce the signal for the detector. The detector senses the amplitude and phase of the received signal with respect to the

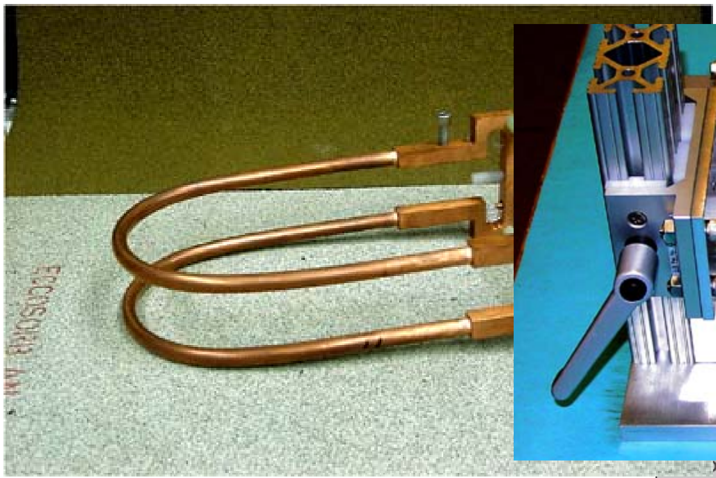

Figure 4. Folded resonant parallel transmission line applicator. This device has a resonant frequency, when filled with air, of approximately 250 MHz and a *Q* of 50.

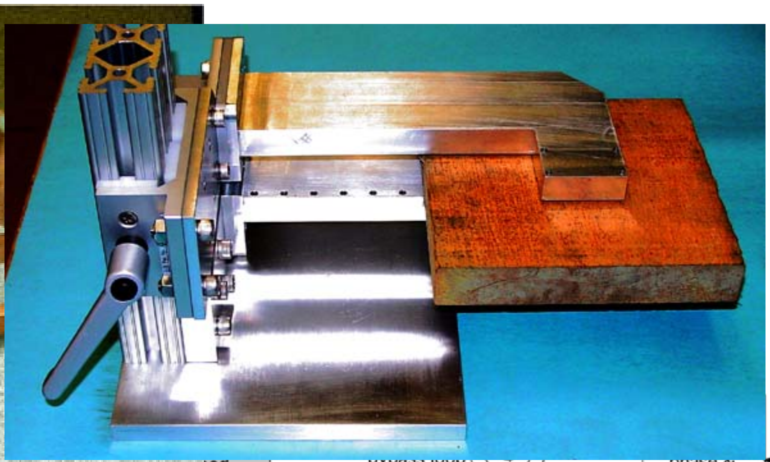

Figure 7. WR-137 Teflon-filled waveguide launchers using air-filled WR-159 waveguide-to-coax adapters tapering to Teflon-filled WR-137.

Figure 8. Illustration of the moisture sensor showing the use of a bypass loop.

reference oscillator. Depending on the characteristics of the wood sample, the received signal will be attenuated and shifted in phase; thus the characteristics of the wood can be determined from the amplitude and phase signal.

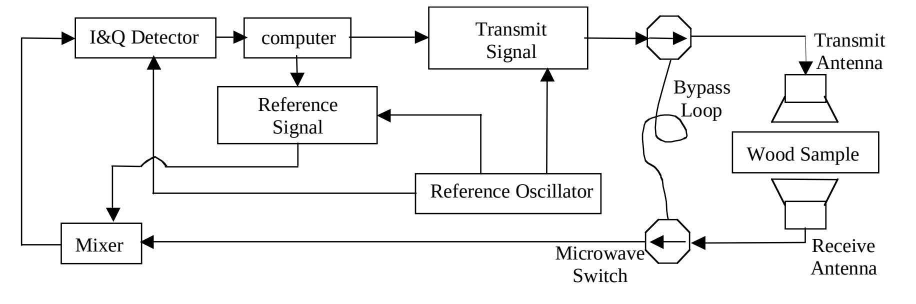

Figure 9. Simplified block diagram of the moisture sensor system.

This system used a transmitting signal generator stepped in 10-MHz increments operating at frequencies of 4.5 to 6.0 GHz. The reference signal generator operated at 10 MHz below the transmit signal generator, or 4.490 to 5.990 MHz. The mixer converted the received signal to 10 MHz for the I&Q detector. The reference oscillator frequency was 10 MHz. The computer controlled the transmit and reference signal generators, the switches, and the analog-to-digital converters. Once the I&Q data were converted to digital signals, they were passed to a laptop computer for analysis. The onboard computer could eventually do this data analysis, but this was not implemented in the prototype system. Figure 10 shows the prototype electronics board.

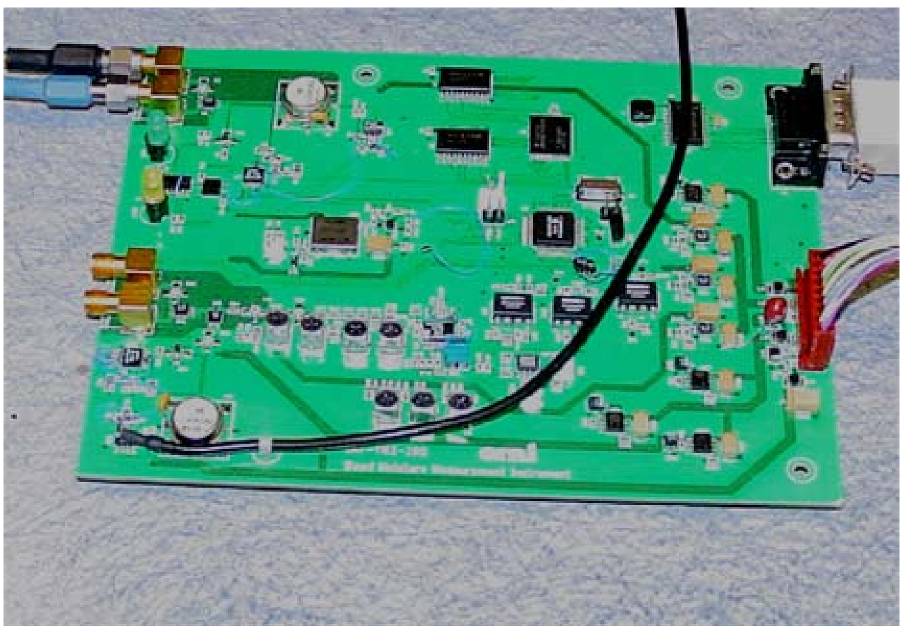

Figure 10. Photograph of the prototype moisture sensor electronics.

Algorithm Development: A number of previous works consider the problem of estimating MC using microwave aquametry [i][ii][iii]. Most previous work consider a single frequency point, although [iii] uses two frequency points. These previous works attempt to fit magnitude and phase microwave measurements to wood MC using simple equations. In this work, we use a magnitude and phase microwave measurement for a range of frequencies. Average parameters were extracted from this data and used to fit to a model, for which three approaches were explored. The best results were obtained with the use of a model tree that chooses a different least-squares model depending on the input data. This enables the piece-wise linear nature of the data to be best exploited.

To enable data-fitting, the magnitude and phase response vectors are reduced to scalar features. The features considered were average magnitude, average unwrapped phase, slope of unwrapped phase, and a normalized sum of complex values. Average magnitude was simply calculated as

$$\mu_a = \frac{1}{N}\sum_{n=0}^{N-1} a(n) \quad ,$$

where $a(n)$ is the amplitude at frequency point n, and N is the number of frequency sampling points. The average unwrapped phase was calculated as

$$\mu_u = \frac{1}{N}\sum_{n=0}^{N-1} u(n) \quad ,$$

where $u(n)$ is the phase obtained by unwrapping the measured phase. The unwrapping occurs by indexing through the phase sample points starting at point $n = 0$, and at each point adding an offset of $r360°$, where r is chosen to reduce the difference between the current and previous phase values. Another phase feature is σ, the slope of the unwrapped phase, which is obtained by performing a least-squares fit on the slope of $u(n)$. It was generally found that phase slope helped more than average phase, and it was used to replace average phase. Finally, the normalized sum of complex values was calculated as

$$\delta = \frac{\left|\sum_{n=0}^{N-1} a(n)e^{j\theta(n)}\right|}{\sqrt{\sum_{n=0}^{N-1} a^2(n)}} \quad ,$$

where $\theta(n)$ is the phase.

MATLAB programs were created to view, process, and analyze the data. For example, a MATLAB graphical user-interface (GUI) tool for plotting microwave responses is shown in Figure 11.

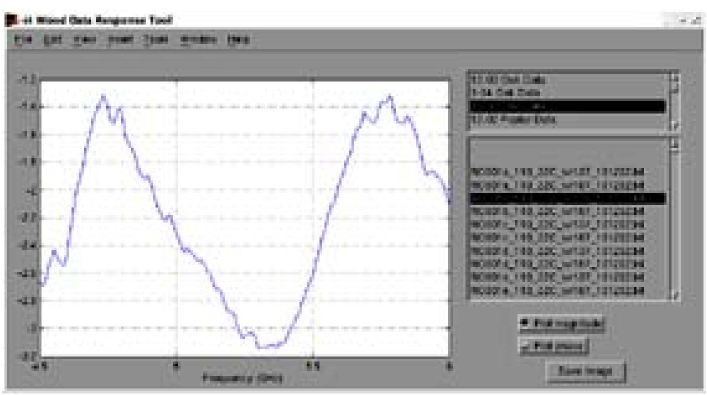

Figure 11. Image of microwave response GUI.

Additionally, a program was created for fitting different models to the data for the prediction of MC. This program uses least-squares fitting, support vector regression, and a model tree. The least-squares is a pseudo-inverse solution of the equation $Ax = b$, where A is a matrix in which each column is a feature for many training samples, x is a column vector containing the over-constrained coefficients, and b is a column vector containing the MC for the samples corresponding to the features in A. The last-used feature row-vector was

$$\begin{bmatrix} \mu_a & \mu_a^2 & \mu_a^3 & \sigma & \sigma^2 & \sigma^3 & \delta & \delta^2 & \delta^3 & t & t^2 & 1 \end{bmatrix},$$

where t is the measured board thickness, and the 1 is used as a constant offset in the least-squares fit. The least-squares approach was very robust, but generally not accurate enough.

Support vector regression (SVR) was explored briefly for modeling the MC. The freely available **libsvm** library was used to make this approach quickly accessible. SVR was somewhat difficult to use in that it requires choosing the type of kernel function, as well as parameter tweaking. Also, given the technique's flexibility, there was a fear of over-fitting the data.

The last and best-performing approach was a model tree. In the model tree approach, the data are sequentially partitioned. The tree consists of a number of nodes, of which there are two types: splitting and terminal nodes. The splitting nodes are points at which the data will be divided into two groups. In this application, and as is the case for most decision trees, the splitting nodes are binary in that they divide the data into two groups. Principal component analysis (PCA) is used to determine the best splitting direction in the data when each splitting node is inserted. A terminal node represents a final partition for the data. Generally, in this application, only four terminal nodes are generated. In the terminal nodes, a least-squares fit is applied to the data using the following feature row-vector:

$$\begin{bmatrix} \mu_a & \mu_a^2 & \sigma & \sigma^2 & \delta & \delta^2 & t & t^2 & 1 \end{bmatrix}.$$

The MATLAB program that fits the data plots the results in an interactive window that allows a researcher to parse through the results. This is shown in Figure 12.

Results: Sensor development has focused on southern hardwoods, although the sensor system will function on any hardwood or softwood. For development and testing, we used red oak and poplar. The algorithm development proceeded simultaneously with the microwave applicator and electronics development. As new sensor designs were developed, vector network analyzers were used to record the amplitude and phase data of the microwave signal. These data were then processed to determine the measured MC for comparison with the "true" dry-weight basis MC.

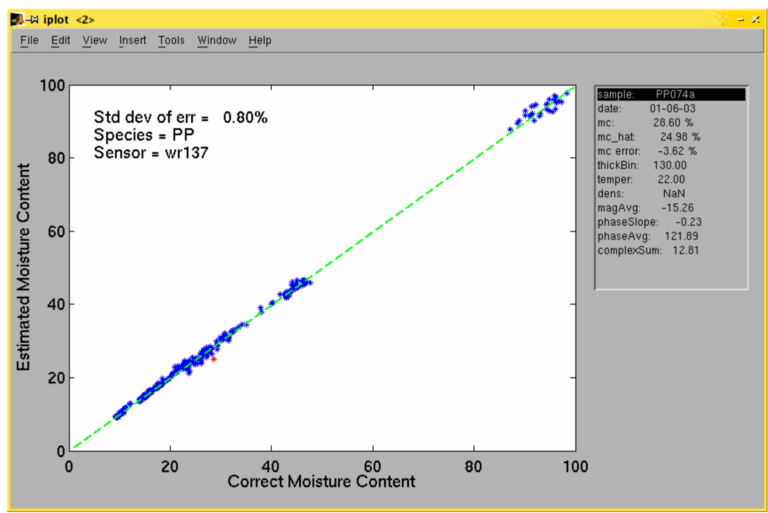

Figure 12. Interactive plotting of results. Information for highlighted data points (red data point) are displayed in the text box at the right.

The true MC was determined by cutting out the sample area from the board and then weighing, drying, and re-weighing. The true MC was then calculated as

$$MC_{true} = \frac{m_{wet} - m_{dry}}{m_{dry}} \quad ,$$

where m_{wet} is the weight of the wet wood sample, and m_{dry} is the weight of the sample after drying. The first MC measurements were made using the WR-90 applicators (shown in Figure 5) operating from 7 to 9 GHz. The analysis algorithm used the average values of the phase and amplitude and their average slopes, plus a complex average value. During the initial tests, we found that the electric field orientation with respect to the grain direction had a significant impact on the measured values. An orientation having the electric field parallel to the grain resulted in amplitude and phase changes of about twice those of measurements with the electric field perpendicular to the grain. This showed that we must design the launchers to ensure that we always have the desired electric field orientation.

Figure 13 shows an example of early data taken for red oak and poplar lumber. Note that the vertical axis is given as a measured microwave parameter, which can be converted to MC by appropriate calibration. The line overlaid on the data is a two-part linear fit with a break at 26% MC (the approximate moisture saturation point). Additionally, little difference is seen between the poplar and red oak data. Later measurements at lower frequencies showed more significant dependence on species and a much smaller change in the fit at the moisture saturation point. The scatter in the data appeared to be due to variations in the wood samples, such as thickness, density, and grain size.

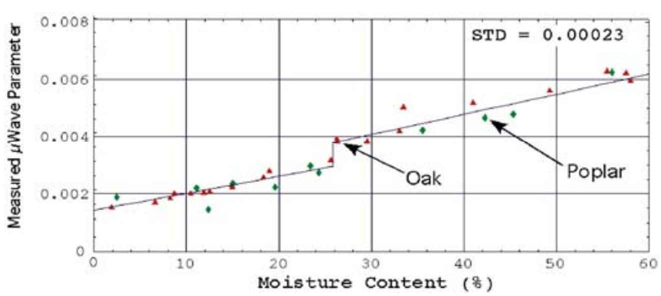

Figure 13. Microwave measured MC versus the true MC for 1.1-in. nominal poplar and red oak lumber. Microwave data was recorded using a vector network analyzer.

These results indicated that the microwave transmission measurement approach could provide a satisfactory method of measuring the board MC. We therefore proceeded with designing a custom sensor system. Solid state electronics at 7–9 GHz were not available at the time, or at least were very expensive. We therefore chose to go to lower frequencies. Based on laboratory tests, we determined that we could operate at 4.5–6 GHz and obtain sufficient amplitude and phase changes for accurate MC measurements. A key point here is that the lower the measurement frequency, the smaller the amplitude and phase changes and so the more difficult the detection problem. By using an electric field orientation parallel to the grain, we maximized the amplitude and phase changes so that, even for very dry boards, we had measured amplitude and phase values well above the noise level of the instrument

Once this new frequency range was determined, new microwave applicators were developed. Figures 14 and 15 show MC data obtained for poplar and red oak using the new frequency range and the new microwave applicators (shown in Figure 6). These data were recorded using the vector

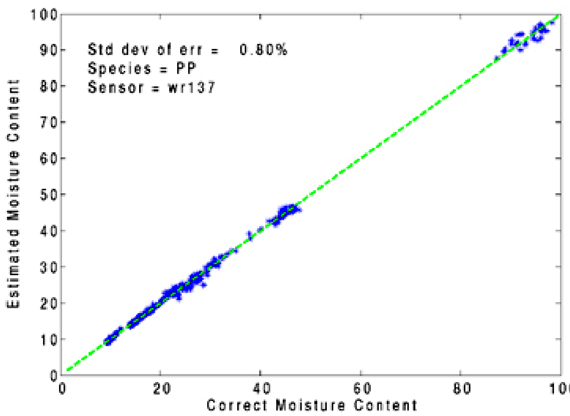

Figure 14. MC data for poplar measured with the WR-137 microwave launchers using the least-squares model tree. Note that the standard deviation of this data set is 0.8% MC. This data set contains approximately 500 measurements.

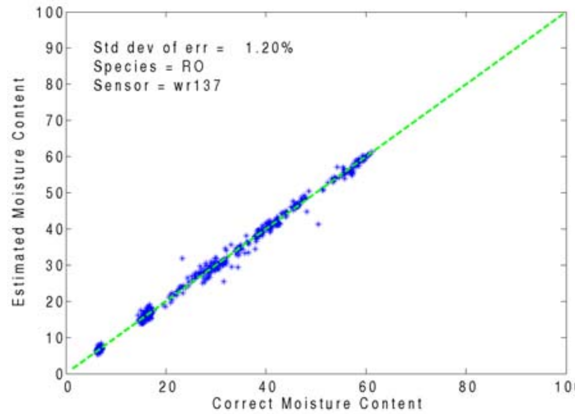

Figure 15. MC data for red oak measured with the WR-137 microwave launchers and the custom electronics and analyzed using the least-squares model tree. Note, the standard deviation of this data set is 1.2% MC. This data set contains over 500 measurements.

network analyzer, and then the measurements were repeated using the new custom electronics. All board samples were between 1.0 and 1.2 in. in thickness. Thickness data were included in the least-square model tree fit to the data.

The results with the custom electronics are shown in Figure 16. The data in Figures 15 and 16 were recorded at the same measurement locations on the same set of boards; i.e., measurements were first made with the network analyzer and then repeated with the custom electronics. Note that the standard deviation with the custom electronics was only slightly higher than that recorded with the network analyzer.

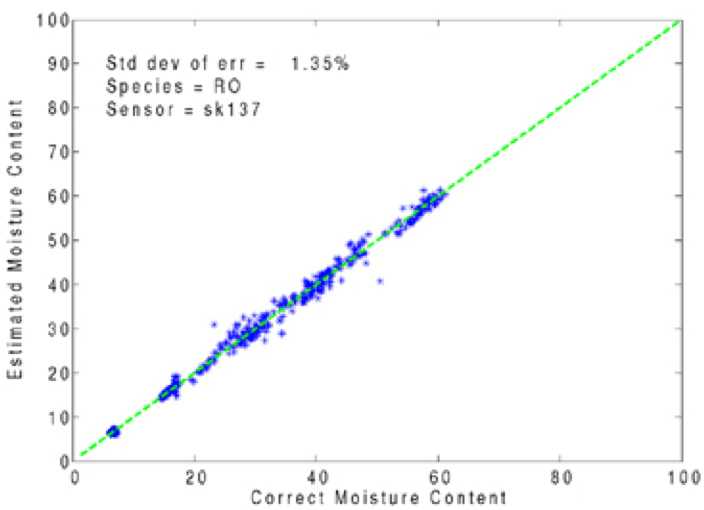

Figure 16. MC data measured using the custom electronics. Note that the standard deviation of this data set is 1.35% MC. Data were recorded at the same board locations as shown in Figure 13, but Figure 13 data were recorded with the vector network analyzer.

The least-square model tree fit includes board thickness and board temperature, in addition to the measured microwave parameters, in determining the MC. We performed several sensitivity studies to determine how important thickness and temperature were in determining the moisture content. In the thickness test, we recorded data (poplar data are shown below) at board thicknesses of 0.8, 1.0, 1.2, 1.4, 1.6, 1.8 and 2.0 in. Shown in Figure 17 are MC values determined for boards 1.0 and 1.8 in. thick but analyzed using data at 1.4 in. to train the least-squares fit algorithm. Note the thinner boards appear to be dryer, while the thicker boards appear to be wetter. Shown in Figure 18 are the same measured data for boards 1.0 and 1.8 in. thick but analyzed using all of the data from 0.8 to 2.0 in. to train the least-squares fit algorithm. These values clearly show the improved accuracy when board thickness is included as one of the parameters in the algorithm. Note that these data in Figures 17 and 18 were processed using a straight least-squares fit model, not the least-square model tree developed later in this project.

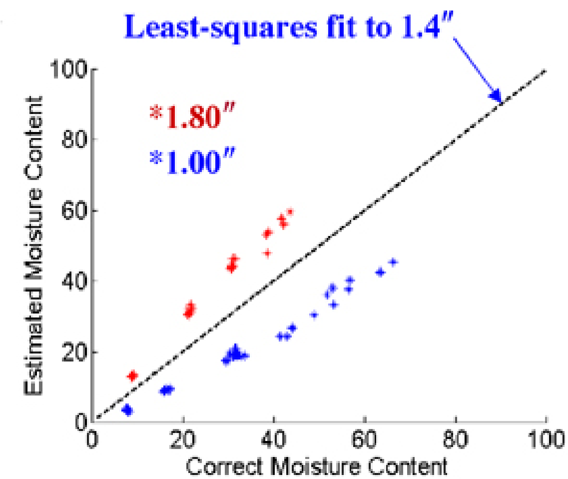

Figure 17. Poplar data recorded using the WR-137 launchers for board thickness of 1.0 and 1.8 in. but analyzed using a least-squares fit to 1.4 in. thickness data.

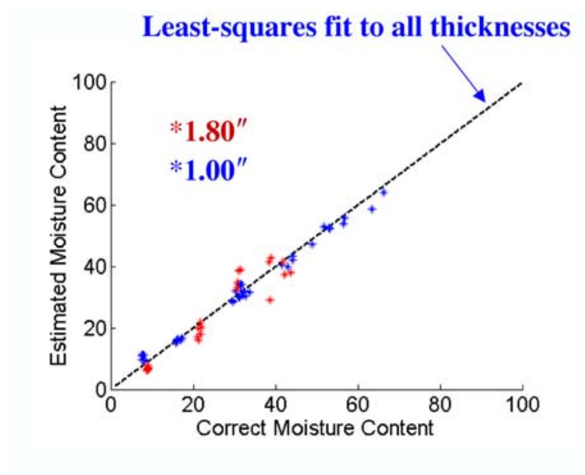

Figure 18. Poplar data recorded using the WR-137 launchers for board thickness of 1.0 and 1.8 in. but analyzed using a least-squares fit to data for board thicknesses of 0.8 to 2.0 in.

In addition to the thickness sensitivity test, a temperature sensitivity test was performed. Temperature sensitivity is critical to determine since we expect this system to operate in a dry kiln. We measured boards (1.0-in-thick red oak shown here) at temperatures of 40°, 50°, 60° and 70° C. This test was conducted by heating boards to 75° C in the kiln with a thermocouple inserted into the end of each board. Once a board was at temperature, it was removed from the kiln and allowed to cool. At each measurement temperature, the board was placed in the microwave applicator and a measurement made. The board was removed from the microwave applicator after each measurement to prevent the applicators from being heated. It is expected that this calibration would eventually be done with both the board and the sensor in the kiln, so temperature affects on the sensor would be calibrated out.

As shown in Figure 19, we first compared high-temperature data with room-temperature data; that is, we used a least-squares fit to room-temperature data to analyze higher-temperature data (40° and 60° data shown in Figure 19). Then we retrained the least-squares fit using both high-temperature and room-temperature data, and then reanalyzed the same 40° and 60° data (shown in Figure 20). As with thickness, temperature shows a clear effect on the measurement of MC.

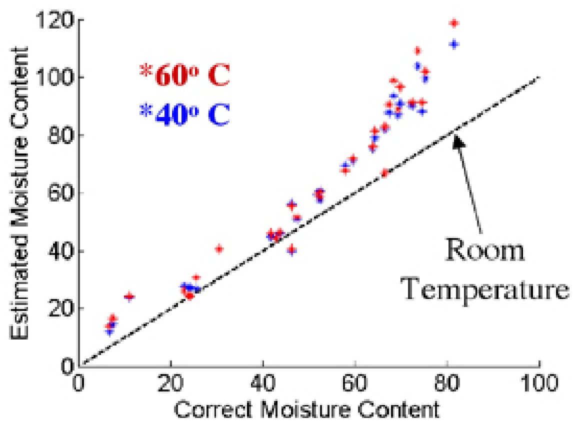

Figure 19. Red oak data recorded using the WR-137 launchers for board temperatures of 40° and 60°, analyzed using a least-squares fit to room-temperature data.

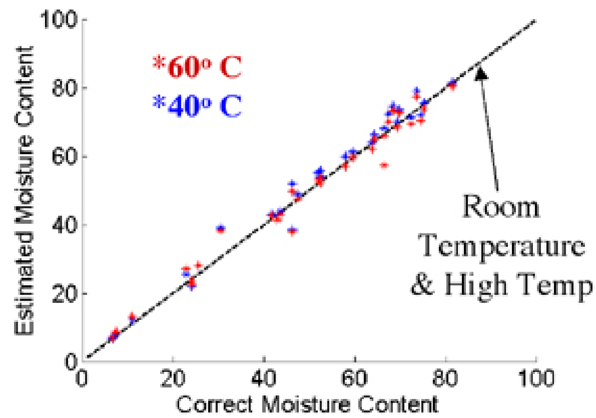

Figure 20. Red oak data recorded using the WR-137 launchers for board temperatures of 40° and 60°, analyzed using a least-squares fit to high-temperature and room-temperature data.

Wireless Telemetry: Wireless telemetry was planned for this instrument to alleviate the need for running signal cables in a kiln. Commercial use of other types of sensors has shown that cables are continually damaged or broken in dry kiln use and so are a weak point for in-kiln sensors. Our plan was to use a communication system that ORNL is developing on a separate project. This project was delayed because of funding constraints, and we therefore first attempted to use a commercial system.

For in-kiln communication, we decided that a spread-spectrum waveform is required to overcome the problems of multipath (signal bouncing off walls, etc.) and high attenuation (wet lumber will significantly absorb the signal). Our initial plans were to use a hybrid spread-spectrum (HSS) system we were building for Navigational Sciences, Inc. (a partner on this project). Unfortunately, the schedule for that system was delayed by 18 months. So we attempted to use direct sequence spread-spectrum (DSSS) hardware purchased from a commercial vendor. This hardware proved to be difficult to use and unreliable as a data telemetry system. Therefore, we dropped the commercial DSSS system and waited on the HSS system we were developing for Navigational Sciences. In April of 2004, we were able to test two HSS communication nodes. Each node was a transceiver and included a temperature sensor. These nodes did not have the capability to accept an external data stream (such as the stream from the moisture sensor). These two nodes were tested in the University of Tennessee kiln. One node was placed inside the kiln, and the other was placed outside the kiln but with an antenna inside the kiln door. High-reliability communication was achieved with both line-of-sight and non-line-of-sight between the antennae.

Final Status of Project: We have successfully demonstrated a microwave-based moisture sensor capable of performing MC measurements from 6 to 100% MC with a standard deviation of 1.5% MC or less. The next step in the sensor development would be to implement a proposed new design for the microwave electronics that will reduce the per-unit cost of the sensor to less than $400. This new design uses a novel method of phase and amplitude detection, but achieved with the fewest possible components allowing for the lowest possible cost. This novel technique has been proved in a benchtop experiment and would be capable of operating in a kiln while the kiln is operating.

Wireless communication in the dry kiln has been tested. This test successfully demonstrated that the ORNL-developed HSS (provided by Navigational Sciences, Inc.) can reliably transmit data between two nodes in a kiln. The next step would be to obtain next-generation systems from Navigational Sciences and demonstrate full telemetry operation in a kiln during kiln operation.

Finally, the decision to use 4.5–6.0 GHz signals for this prototype measurement was based on the availability of microwave components for designing and building the custom microwave electronics. This frequency range cannot be used for commercial sensors, as the Federal Communications Commission (FCC) has designated two forbidden frequency bands (4.5–5.15 GHz and 5.35–5.46 GHz) in this frequency range. The moisture sensor microwave emissions would have to be almost zero (fully contained) to operate in these forbidden frequency bands. However, the FCC does allow operation in the 5.46–7.25 GHz band with restrictions on the maximum radiated power. The moisture sensor can readily be designed to operate within this frequency band as a result of the new simplified microwave circuit design. Designing new launchers for this frequency range is straightforward. The amount of microwave power emitted during moisture measurements is well within the permissible levels for this band. Consequently, the FCC restrictions affecting the potential commercialization of this prototype moisture sensor are readily overcome by a straightforward redesign of the electronics and launchers.

We are now exploring potential partners for entering into a Phase II project, or companies that can fund a technology transfer project directly. We have received several serious inquiries but have not received any commitments for future funding.

Milestone Status Table:

ID Number	Task / Milestone Description	Planned Completion	Actual Completion	Comments
	First quarter, 1st year (project started Jan., 2001)			
Task	Develop guidelines and begin sensor testing	March, 01	March, 01	
Task	Develop sensor testing technique	Mach, 01	March, 01	
	Second quarter, 1st year			
Task	Detailed testing of sensor design	June, 01	July, 01	
	Third quarter, 1st year			
Milestone #1	Demonstration of capability to determine average moisture content of the lumber at various stages of the drying process using microwaves.	September 31, 2001	September 31, 2001	We have successfully demonstrated the measurement of MC over a range of 6% mc to 80% mc on lumber samples.
	Fourth quarter, 1st year			
Task	Develop lower-frequency sensor prototypes, which will have a lower cost and will measure the average MC over a larger volume.	December, 01	December, 01	We have successfully tested 2 different launcher designs both working at a lower frequency band than that of the first measurements.
	First quarter, 2nd year (Jan.-Mar., 2002)			

ID Number	Task / Milestone Description	Planned Completion	Actual Completion	Comments
Milestone #2	Test the lower-frequency sensor designs for sensitivity to temperature, species (density), and MC distribution.	March 31, 2002	March 29, 2002	
Task	Design and build prototype microwave electronics system for MC measurement.	March, 02		microwave electronics system designed and parts ordered.
	Second quarter, 2nd year			
Task	Select best sensor design from the two candidate designs tested in previous quarter.	May, 02	May, 02	
Task	Integrate microwave electronics with sensor. Test assembly in the laboratory.	June, 02	September, 02	
Task	Begin evaluation of kiln environment for wireless telemetry system.	June, 02	June, 02	The UT kilns were examined to determine the basic path lengths for the multipath signals.
Task	Develop and evaluate a surface MC sensor which can be integrated with the microwave MC sensor (volume averaged measurement) to allow determination of the MC profile. Determine whether to incorporate surface MC sensor into the sensor system.	June, 02	June, 02	Surface moisture evaluated and promising results obtained. Sensor development suspended due to insufficient funds
	Third quarter, 2nd year			
Milestone #3	Demonstrate operation of the prototype microwave MC sensor in a Kiln during a drying charge.	September 30, 2002	October 14, 2002	Short delay in meeting milestone due to problems with the microwave electronics.
Task	Perform design study for the spread-spectrum wireless telemetry system.	September, 02	September, 02	
	Fourth quarter, 2nd year			
Task	Order hardware for wireless telemetry system and start fabrication of telemetry system.	December, 02	December, 02	
	First quarter, 3rd year (Jan.-Mar., 2003)			
Milestone #4	Perform laboratory testing of wireless telemetry system.	June 30, 2003	June 15, 2003	Delay Milestone date by 1 quarter due to delay in funding.
Task	Complete evaluation of first generation microwave electronics circuit and design of second generation microwave electronics circuit	June, 03	June, 03	
	Second quarter, 3rd year			
Task	Perform testing of prototype wireless telemetry system in the UT kiln.	September, 03	postponed	This test planned on using commercially available prototyping modules for the telemetry system. These modules have proven unreliable and so kiln test postponed until new telemetry system available in June, 2004.
Task	Fabricate and test the second generation microwave electronics circuit.	September, 03	September, 03	System works. Will need to do 3rd iteration to attain a design that can be used for commercial applications.
Task	Identify industry requirements for a commercial MC sensor and investigate methods to integrate MC sensor into existing kiln control systems.	September, 03	Initiated	Industry requirements defined. Integration methods explored. Will need to do further programming when actual output of sensors is available.
	Second quarter, 4th year (Ari.-Jun., 2004)			
Milestone #5	Field test wireless telemetry system in UT Kiln at room temperature.	June 30, 2004	June 30, 2004	Telemetry system sends and receives signals. Telemetry system will not yet interface to data steam from wireless sensors
Task	Test custom moisture sensor electronics in UT kiln at kiln high temperature.	June 30, 2004	June 30, 2004	Tested sensors for shot periods of time to 180 degrees F.
	Third quarter, 4th year (Sep.-Dec., 2003)			
Milestone #6	Prepare report detailing future work required to commercialize prototype MC sensor.	September 30, 2004	September 30, 2004	

Budget Data This data represents the University of Tennessee portion of the budget. ORNL is budgeted separately for this project:

			Approved Spending Plan			Actual Spent to Date		
Phase / Budget Period			DOE Amount	Cost Share	Total	DOE Amount	Cost Share	Total
	From	To						
Year 1	1/01	9/01	28,000	48,000	76,000	28,000	48,000	76,000
Year 2	10/01	9/02	40,000	70,000	110,000	40,000	70,000	110,000
Year 3	10/02	9/03	55,000	75,000	130,000	55,000	100,000	155,000
Year 4	10/03	9/04	7,000					

Oak Ridge National Laboratory budget (all cost share shown in the UT budget).

			Approved Spending Plan			Actual Spent to Date		
Phase / Budget Period			DOE Amount	Cost Share	Total	DOE Amount	Cost Share	Total
	From	To						
Year 1	1/01	9/01	130,000		130,000	130,000		130,000
Year 2	10/01	9/02	235,000		235,000	235,000		235,000
Year 3	10/02	9/03	235,000		235,000	204,000		204,000
Year 4	10/03	9/04	60,000					

[i] R. J. King, D. R. Dunn, and B. W. Maxfield. Measurement of moisture content and density of wood products using microwaves. Technical report, U.S. Department of Agriculture, Jan. 1989.
[ii] Andrzej W. Kraszewski. Microwave aquametry: Introduction to the workshop. *Microwave Aquametry: Electromagnetic Wave Interaction with Water-Containing Materials*, pp. 3–34, 1996.
[iii] Yangjun Zhang and Seichi Okamura. New density-independent moisture measurement using microwave phase shifts at two frequencies. *IEEE Transactions on Instrumentation and Measurement*, **48**(6), Dec. 1999.