New York State Energy Research and Development Authority

# Evaluation of Wood Fuel Moisture Measurement Accuracy for Cordwood-Fired Advanced Hydronic Heaters

Final Report

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# Evaluation of Wood Fuel Moisture Measurement Accuracy for Cordwood-Fired Advanced Hydronic Heaters

***Final Report***

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# Notice



# Abstract

Analysis of emission and energy performance of cordwood-fired advanced hydronic heaters (boilers) require that the wood fuel be consistent and of known moisture content (%MC). In this study, freshly cut split red oak cordwood was dried from green initial moisture of 60 to 90%MC to a 20%MC target in about six days. Detailed moisture analysis of many individual pieces was undertaken using an electrical conductance resistance-type moisture meter with insulated pins, of shell to core and end to center to end regions followed by conventional oven drying for confirmation. Results suggest that accuracy to better than 2%MC is achievable by averaging four meter values, shell and core from the end and middle of each piece, with the ten pieces of split cordwood that would typically make up an approximately 50 pound fuel load.

# Keywords

Red oak, cordwood, moisture content, kiln drying, moisture meter

# Acknowledgments

The insight and assistance provided by Ellen Burkhard, Ph.D. of NYSERDA, and Tom Butcher, Ph.D., Brookhaven National Laboratory in carrying out this work are most appreciated.

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# Acronyms & Abbreviations

| | |
|---|---|
| %MC Dry | Basis moisture content, the amount of water contained in wood, expressed as a percentage of the weight of oven dry (at 218 °F, 103 °C) wood. |
| %RH Relative Humidity | Ratio of the amount of water vapor present in the air to that which the air would hold at saturation at the same temperature. It is usually considered on the basis of the weight of the vapor but, for accuracy, should be considered on the basis of vapor pressures. |
| BNL | Brookhaven National Laboratory |
| Dry-Bulb Temperature | The temperature of air as indicated by a standard thermometer. |
| EMC | Equilibrium Moisture Content, the moisture content at which wood neither gains nor loses moisture when surrounded by air at a given relative humidity and temperature. |
| Fiber Saturation Point | The stage in the drying or wetting of wood at which the cell walls are saturated and the cell cavities free from water. It applies to an individual cell or group of cells, not to whole boards. It is usually taken as approximately 30% moisture content, based on ovendry weight. |
| NYSERDA | New York State Energy Research and Development Authority |
| Psychrometer | An instrument for measuring the amount of water vapor in the atmosphere. It has both a dry-bulb and wet-bulb thermometer. The bulb of the wet-bulb thermometer is kept moistened and is, therefore, cooled by evaporation to a temperature lower than that shown by the dry-bulb thermometer. Because evaporation is greater in dry air, the difference between the two thermometer readings will be greater when the air is dry than when it is moist. |
| Wet-Bulb Temperature | The temperature indicated by the wet-bulb thermometer of a psychrometer. |

# 1 Introduction

Researchers at the State University of New York College of Environmental Science and Forestry (SUNY ESF) initiated this study to evaluate methods to measure the moisture content in split red oak cord wood. A second objective of this project included developing a method to prepare cord wood in a lumber dry kiln to be used as test fuel for wood boilers.

Wood moisture is measured as a percentage of the weight of the wood on a dry basis, with dry basis determined from oven drying the wood to constant weight at 103 °C (ASTM 2007). Fresh cut wood often has a %MC (moisture content) range of more than 80%, whereas kiln-dried hardwood lumber is dried to 6-8%MC. Softwood lumber, used for structural and construction applications, is typically kiln-dried to less than 19%MC (Simpson 1988). For fuel to be used in testing gasification wood boilers, a range of 17 to 25%MC is desired (Butcher 2013) as this presumably is about the moisture achievable over a year or so of air-drying split cordwood.

Wood moisture content is most effectively determined via the oven drying method (ASTM 2007). However, this method is destructive so it is not feasible for determining wood fuel %MC. Alternatively, the electrical conductance wood moisture meters (James 1988) that are widely used in the hardwood and softwood lumber industries can be utilized to indirectly measure and predict wood %MC. These wood moisture meters (such as models made by Delmhorst Instruments) present %MC as related to the electrical resistance of wood at a particular moisture level. An example of this relationship is illustrated in Figure 1, which includes data from previous SUNY ESF Wood Products Engineering Laboratory research work with southern pine lumber, where the electrical resistance of wood measured between two uninsulated electrode pins 0.75 inches apart and 0.5 inches deep increased from less than 1 MegOhm to almost 10,000 MegOhms as wood moisture was reduced from over 70%MC to less than 10%MC. The accuracy of conductance-based resistance-type meters, with appropriate wood species and temperature correction and wood which has an equilibrated and uniform %MC, can be to 0.5%MC when wood is between about 6 and 12% MC, to 1%MC when wood moisture is less than 20%MC, and to 2%MC up to about 30%MC (http://delmhorst.com/FAQs/Flooring-Wood-Products/Industrial-Mil). Values above the fiber saturation point of wood (approximately 30%MC), because of the relatively small change in resistance with MC and uncertain and variable internal moisture gradients, should be considered relatively qualitative (Laurenzi 2012).

When lumber is dried a moisture gradient develops between the outer shell, which has equilibrated at the surface close to the ambient relative humidity (Table 1), and the still moist inner core. Interestingly, the average %MC of lumber with normal moisture gradients has been found to occur at a distance from the surface of about one-quarter to one-fifth of the board thickness (Laurenzi 1996, 2012). This characteristic has enabled accurate prediction of wood %MC in lumber with a moisture gradient, as occurs during normal drying and prior to development of uniform equilibrated moisture. Figure 2 provides an example, where insulated electrode pins driven about 3/8 inch into 1.5-inch-thick southern pine lumber (data from earlier SUNY ESF Wood Products Engineering Laboratory research work) predicted quite accurately wood %MC when below 30%MC. Clearly evident as well from this data are that though values above 30% are somewhat less accurate they do show a qualitative predictability.

Moisture gradients in drying lumber and in split cordwood have important differences. Lumber is a slender material, and it is relatively long to its thickness. And though drying from the end grain (parallel to the fibers) occurs faster than from surface faces (because of the distance from the core to the surface is sufficiently short and due to the way boards are separated and stacked during drying), end drying is generally considered inconsequential (Simpson 1988). These characteristics result in moisture gradients in lumber being two dimensional, from the surface faces to the core. Split cordwood, however, has three-dimensional moisture gradients. Split cordwood has cross sections of 3 to 4 inches and lengths of only about 18 inches. Because development of cracks and splits do not create defects, significant drying from ends occurs, resulting in three-dimensional moisture gradients, from the center of a piece to the ends, as well as the core to the surface.

**Table 1. Equilibrium moisture content (%EMC) of wood at several relative humidity (%RH) conditions at 70 °F**

From Simpson 1988.

| %RH | %EMC |
|---|---|
| 90 | 20.6 |
| 86 | 18.2 |
| 81 | 16.5 |
| 77 | 14.9 |
| 72 | 13.7 |
| 68 | 12.5 |
| 55 | 10.1 |
| 40 | 7.7 |
| 25 | 5.5 |
| 15 | 3.7 |
| 0 | 0.0 |

**Figure 1. Relationship between moisture content and electrical resistance (MegOhms / 0.75 in) in 1.5 by 5.5 inch southern pine lumber**

From SUNY ESF Wood Products Engineering Laboratory research, W.B. Smith, Syracuse, NY.

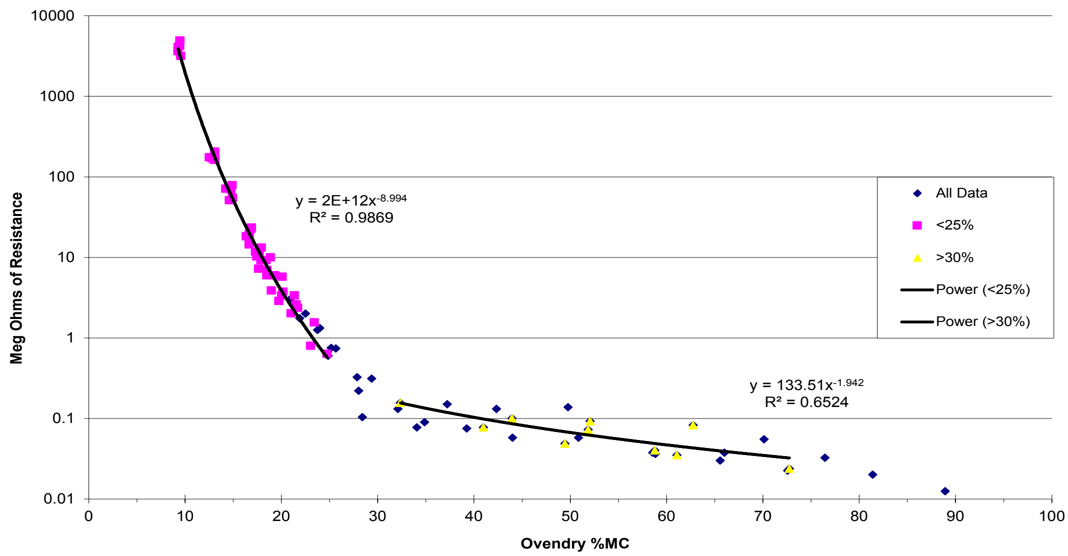
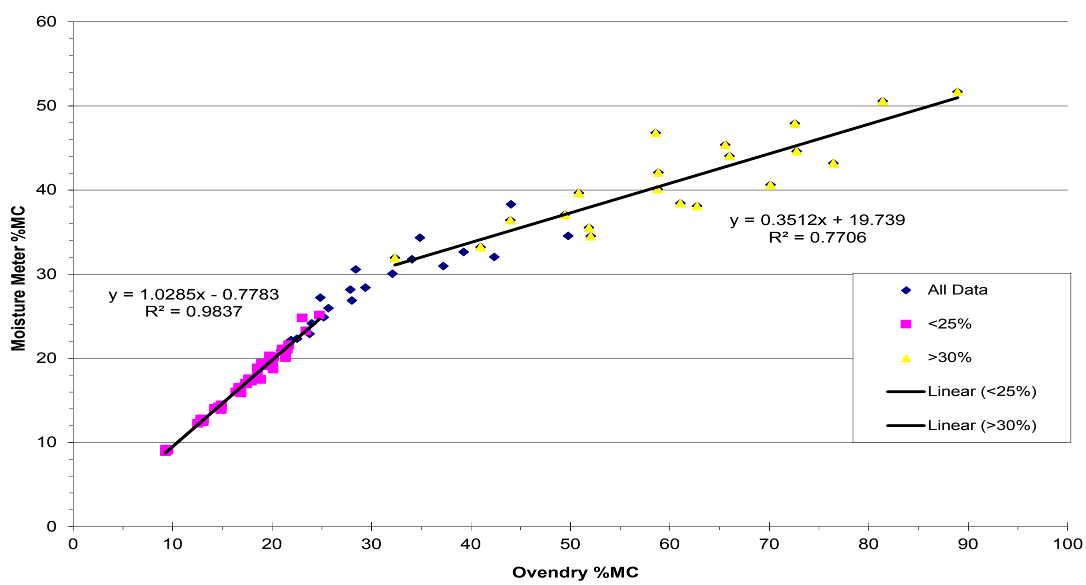



**Figure 2. Relationship between moisture content and Delmhorst electrical resistance moisture meter readings using 3/8 in deep insulated pins in 1.5 by 5.5 inch southern pine lumber.**

From SUNY ESF Wood Products Engineering Laboratory research, W.B. Smith, Syracuse, NY.



# 2 Experimental Methods for Cordwood Drying and %MC Determination

Controlled drying of split red oak cordwood during these studies took place in the SUNY ESF lumber dry kiln (Figure 3) in four separate kiln charge runs. In the first run, several bags of dry but presumably still wet material were shipped from Brookhaven National Laboratory (BNL) in Upton, NY to SUNY ESF. With a target of achieving final dry-basis wood moisture content (%MC) between 17 and 25%MC and as flat moisture gradient between core and shell, and end to center to end as possible, we “dried” the wood for several days at 160 °F dry bulb, 157 °F wet bulb, and then a couple more days at 160 °F dry bulb, 155 °F wet bulb. Relative humidity (%RH) and wood equilibrium moisture content (%EMC), which is the approximate moisture content that wood will equilibrate to at a particular %RH) at these conditions were 93% RH and 18.5% EMC, and 88% RH and 16% EMC, respectively. Under both sets of conditions, 20 sample specimens were utilized to monitor drying gained weight. Then the kiln stopped working.

It turned out that one of the three fan motors had an electrical short, which likely developed from having the kiln operate continuously for an extended period at such a high humidity to try to keep the shell %MC from being too dry. The kiln was then run with two fans at 160 °F dry bulb, 150 °F wet bulb (77% RH, 12% EMC), and the sample pieces began drying.

This kiln run was ended when several sample specimens had dried to below 15%MC, too dry to be useful for use in advanced hydronic heater test burn work. Unfortunately, it was also subsequently found that a number of the split red oak cordwood pieces were still in the 35 to 40%MC range. Though somewhat surprising, it was best determined that since most of the pieces had already been partially dried, ability for capillary flow had been lost because the %MC of the outer shell had become sufficiently lower than the fiber saturation point (FSP) compared to the quite moist inner core MC. This phenomena likely significantly reduced moisture movement ability (similar to a freshly cut end of a Christmas tree that is not promptly put in water). It was anticipated that starting with fresh wood, that had the ability to maintain some surface moisture capillarity, would result in better drying rates.

For the next three kiln charges, three face cords of freshly cut and split red oak cordwood were obtained from Treelanders Tree Service, LLC in Syracuse, NY. The pieces were specifically cut to be about 18 inches in length, and approximately 3 to 4 inches across. For the first of the kiln charges, the pieces were stacked on a rack in the SUNY ESF lumber dry kiln such that air flow would expose each piece uniformly to controlled heat and humidity (Figure 3 and Figure 4). A specifically mild drying schedule for firewood was developed using relatively low temperature and high humidity to avoid over drying the ends and shell while the core of each piece remained wet.

During this charge, the initial %MC (dry weight basis; ASTM 2007, Simpson 1988) of 12 pieces used as samples for monitoring while drying were: 76.0, 75.0, 69.5, 77.4, 48.2, 65.0, 81.1, 59.6, 46.8, 84.1, 69.3, and 61.5%MC with an average of 67.8%MC.

Initial %MC of these 12 and other kiln samples measured throughout this research was determined by oven drying wafer samples cut from inside the ends of each piece, as described in Simpson (1988). About 1.5-inch sections were cut from the end of each piece to expose fresh wood, then about three-quarter-inch sections were cut off and oven dried; initial sample %MC was assumed as an average of the two ends. Drying conditions and wood moisture content of sample pieces were regularly monitored and measured by sample weight change at least daily for all kiln operation runs. Of note, the drying rate using mild schedule conditions was quite slow, which from the practical production perspective required raising the temperature and lowering the relative humidity.

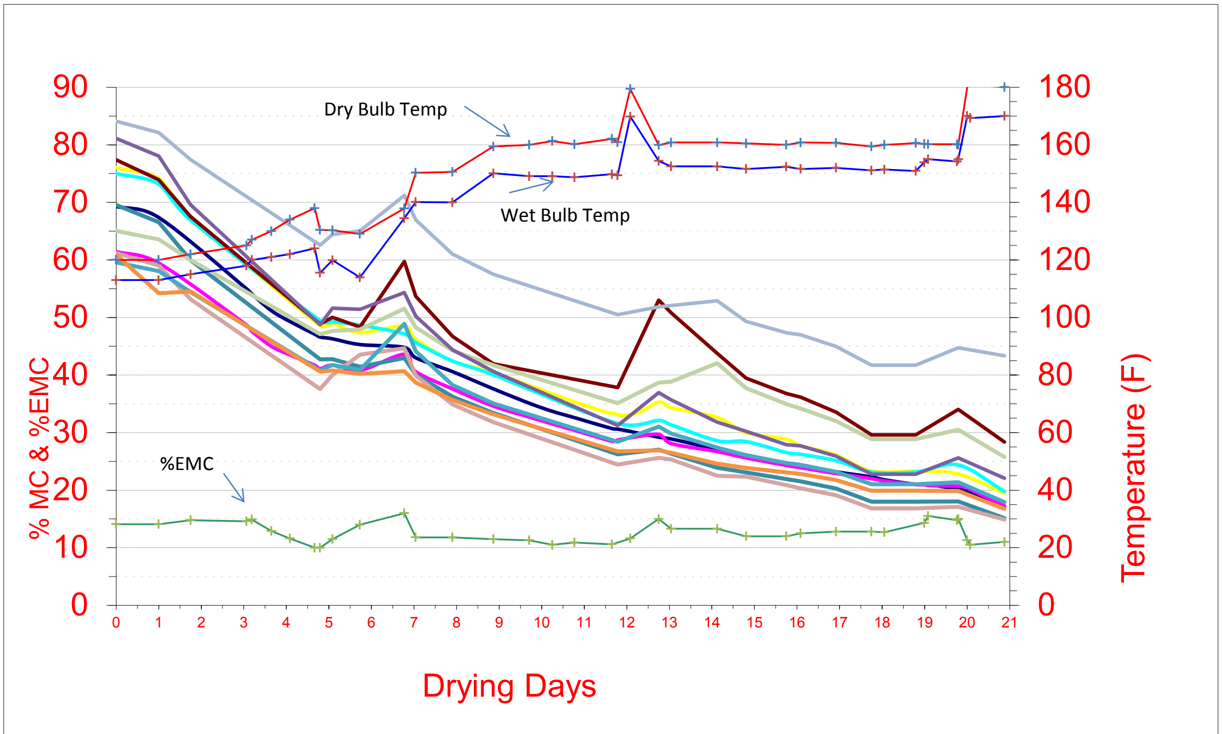
Figure 5 shows a plot of moisture content with time for each of 12 drying samples, with dry bulb, wet bulb, and equilibrium moisture content (EMC) kiln conditions. Noticeable increases in %MC at days 7, 13, and 20 were due to an effort to slow down the drying process, by raising the relative humidity (and with that, wood %EMC) in the kiln, so that the capillaries in the shell did not dry out excessively thereby preventing effective drying of the core. All air-dried cordwood can result in a dry shell and a wet core. Because the cordwood shell and end regions were already likely under 14% MC, raising the EMC above 16% resulted in the samples actually regaining %MC. Also, because raising the relative humidity required spraying moisture into the kiln, some cordwood moisture was regained from dripping and condensation. Drying took place over 21 days, which was considered to be quite long especially as compared to Simpson et al. (1987) where drying was completed in about half that time. However in that research effort was not made to keep surface %MC high and kiln humidity was much lower at 4% EMC conditions. Drying of this kiln charge was ended when the 12 samples that were being used to monitor moisture content loss and manage the drying process reached desired target of about 20%MC. It was subsequently determined that the average moisture content of the 12 samples was 22.6%MC, with a range from 14.9% to 43.3%. The average moisture content of the seven samples (of 12) closest to target was 18.6%, ranging from 17.2% to 22.1%.

**Figure 3 Red oak cordwood being loaded into lumber dry kiln**

**Figure 4. Red oak cordwood on racks in lumber dry kiln**

**Figure 5. Drying time of cordwood samples of second kiln run**

Moisture content at particular dry bulb and wet bulb temperature conditions, and theoretical wood equilibrium %MC (%EMC) (Note that %MC on a dry basis is used).




BNL scientists noted that the advanced hydronic heater devices being tested were able accommodate wood with shell to core and end to center moisture gradients, so long as average individual sample moisture was in the 17% to 25% range. Therefore, another two kiln loads (the third and fourth runs) were dried.

For each of the third and fourth runs, three freshly cut custom prepared 18-inch long split face cords of red oak were delivered. The cordwood was stacked for these two kiln runs crib-style (Figure 6), with sufficient air space around each piece to facilitate uniform exposure to conditioned air in the kiln such that drying would be comparable. The volume of material remaining after kiln loading suggested that somewhat more than approximately 2.5 cords of wood fit in the kiln for drying. With both of these two kiln runs, effort was still made to minimize moisture gradients in each piece by keeping kiln vents closed and without adding additional moisture to the kiln air with spraying of moisture; kiln air humidity came only from moisture evaporated from drying wood.

During drying, six samples (Simpson 1988) were used to monitor moisture content and rate. From the first of these samples, the initial range was from 65.1, 62, 76.9, 77.5, 69.8 and 67.9%MC, indicative of freshly cut material. The split red oak cordwood was dried at initial kiln temperature of 160 °F with the kiln vents closed for the third run (Figure 7). It turned out that there was enough leakage of moisture around gaps in the vents and doors that maximum wet bulb obtained was about 150 °F. As moisture from the wood evaporated after about two days, the wet bulb dropped off to 145°F and then to below 140°F. With this kiln run, humidity was not added with cold water spray; all humidity was from the drying wood.

After four days, the six samples were down to 26.9, 27.1, 27.5, 33, 24 and 21.4 %MC, at which point the heat was turned off and the kiln let to cool slowly with the doors and vent closed; if the doors and vents were open, cooling would occur more quickly but the infusion of fresh dry air to the still hot (160°F) red oak pieces would have likely caused more drying than desired. After one day of cooling, moisture content levels dropped to 24.5, 24.8, 24.2, 29.4, 21.5 and 19.1%MC. Then one day later when the temperature dropped to 90°F, the moisture was only down to 22.9, 22.8, 23.0, 27.9, 20.2 and 17.9%MC.

After a few more days, the same pieces had only dropped to 20.6, 21, 21, 25.6, 18.3 and 16.1%MC, which was quite close to the 17% to 15%MC target. It is important to note that because the six kiln samples were about three inches shorter on each end than the rest of the pieces, their drying would have been somewhat faster than average of the pieces in the kiln load. The two driest sample pieces were also about half the size (weight) of the other four which likely as well contributed to their lower %MC. The fourth kiln charge was run according to a comparable schedule, except in the beginning the dry bulb was initially at 140°F. This procedure was done to see if a higher wet bulb temperature and humidity might be maintainable to reduce moisture gradients, but when this appeared unlikely and drying rate appears to slow, the temperature was raised to 160°F (Figure 8). After five days, the kiln heat was turned off and wood was gradually cooled, again to the desired target %MC. Subsequently, a number of the dried pieces were selected for specific wood moisture determination using a moisture meter and oven drying.

After drying to a target 20%MC, individual split red oak cordwood samples were removed from the kiln. Initially, a large number of pieces were weighed and their %MC estimated using a Delmhorst meter with a two-prong insulated tip electrode driven into shell and core regions at approximate center and end region points. These samples were wrapped with plastic and delivered to the BNL test laboratory for use as fuel. Later, dried pieces were simply stacked tightly on pallets and wrapped in plastic (Figure 9) for shipping to BNL to be used as fuel in stove testing along with the suggestion that storage at BNL should be in an environment that is relatively cool without a particularly low relative humidity.

**Figure 6. Red oak cordwood stacked crib-style for third kiln run**

**Figure 7. Drying time of split red oak cordwood samples of third kiln run**

Moisture content at particular dry bulb and wet bulb temperature conditions, and theoretical wood equilibrium %MC (EMC). Note that %MC on a dry basis is used.

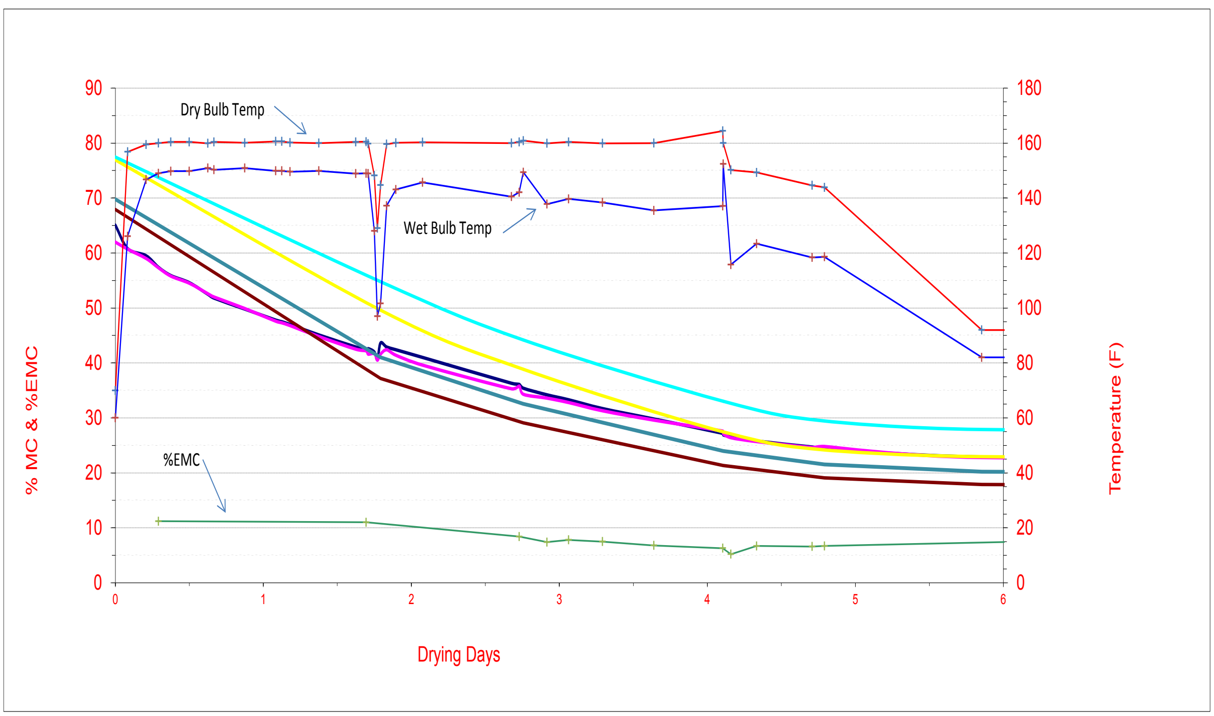


**Figure 8. Drying time of split red oak cordwood samples of fourth kiln run**

Moisture content at particular dry bulb and wet bulb temperature conditions, and theoretical wood equilibrium %MC (EMC). Note that %MC on a dry basis is used.

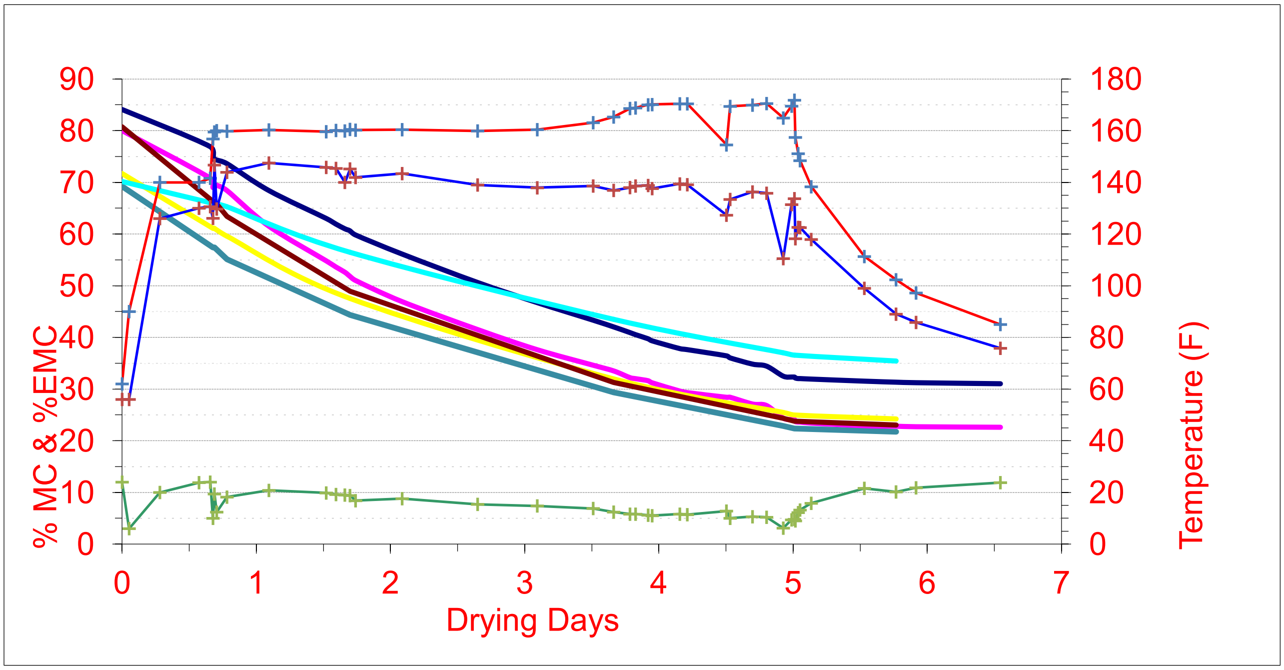



**Figure 9. Dried and heat treated split red oak cordwood**

The wood was stacked on pallet and wrapped in plastic to protect wood from over drying during shipment from SUNY ESF Syracuse Wood Products Engineering Drying Laboratory to BNL.

# 3 Moisture Meter Accuracy Determination

Particular effort was undertaken during this research to determine the accuracy with which an electronic resistance moisture meter could be used to usefully predict oven-dry based %MC of the red oak fuel cordwood. Despite an initial goal of drying these pieces under controlled temperature and elevated humidity conditions that would achieve minimal moisture gradients, a moisture gradient was determined necessary for the development and continuation of the drying rate.

Using the Delmhorst moisture meter with 2-inch-long insulated pins and set to the red oak species and correct ambient temperature settings, readings for shell (approximately one-quarter inch depth; Figure 10) and core (approximately 1.125-inch depth; Figure 11) were collected from radial and tangential faces at five places for some of the sample sets and eight places for other sample sets along the length of each piece. Subsequently, shell and core moisture content specimens were cut from each piece of cordwood from each location using shop band saws and then oven dried to determine actual %MC gravimetrically (ASTM 2007). As expected, the moisture meter indicated the outer shell and the ends of the wood were drier than the inner core pieces of each piece of red oak cordwood (ASTM 2013). Oven drying pieces showed comparable results. Statistical analysis of the data using the Minitab 16 software package Paired T-Test methodology has been used to determine, to a 95% confidence interval, how best the moisture meter values accurately predict actual %MC. Experimental results for three sets of tests to develop the gradient are explained in the following sections.

## 3.1 Set 1

Eighteen individual specimens were tested in Set 1. The final actual %MC (oven-dry basis) ranged from 8.5 to 22.6, averaging 16.6%MC.

Using average shell and core moisture meter results, from zones located between3 inches and 2 inches from the ends, and zones located between 2 inches from the center, predicted values were within about 2.5%MC of actual with a range of 9.3 to 24.8%MC and an average of 19.1%MC. Summary results are shown in Table 2. (Zones I, II, III are averages of Zones 1 & 2, 4 & 5, 7 & 8 along the length of each piece). A plot of the data using the actual %MC (x-axis) and moisture meter averages of Zones I, II, and III (y-axis) are shown in Figure 12 along with a 1:1 line. The averaged moisture meter results generally lay above the 1:1 line suggesting a systematic bias in accuracy.

**Figure 10. Shell moisture determined with moisture meter (ex. 20.2% MC)**

This moisture value was determined about 1 inch from the end and 0.25 inch into the shell of a piece of split red oak cordwood using a Delmhorst TotalCheck resistance moisture meter with insulated pins.


**Figure 11. Core moisture determined with moisture meter (ex. 24.3% MC)**

This moisture value was determined about 1.125 inches deep from the center of a piece of split red oak cordwood using a Delmhorst TotalCheck resistance moisture meter with insulated pins.

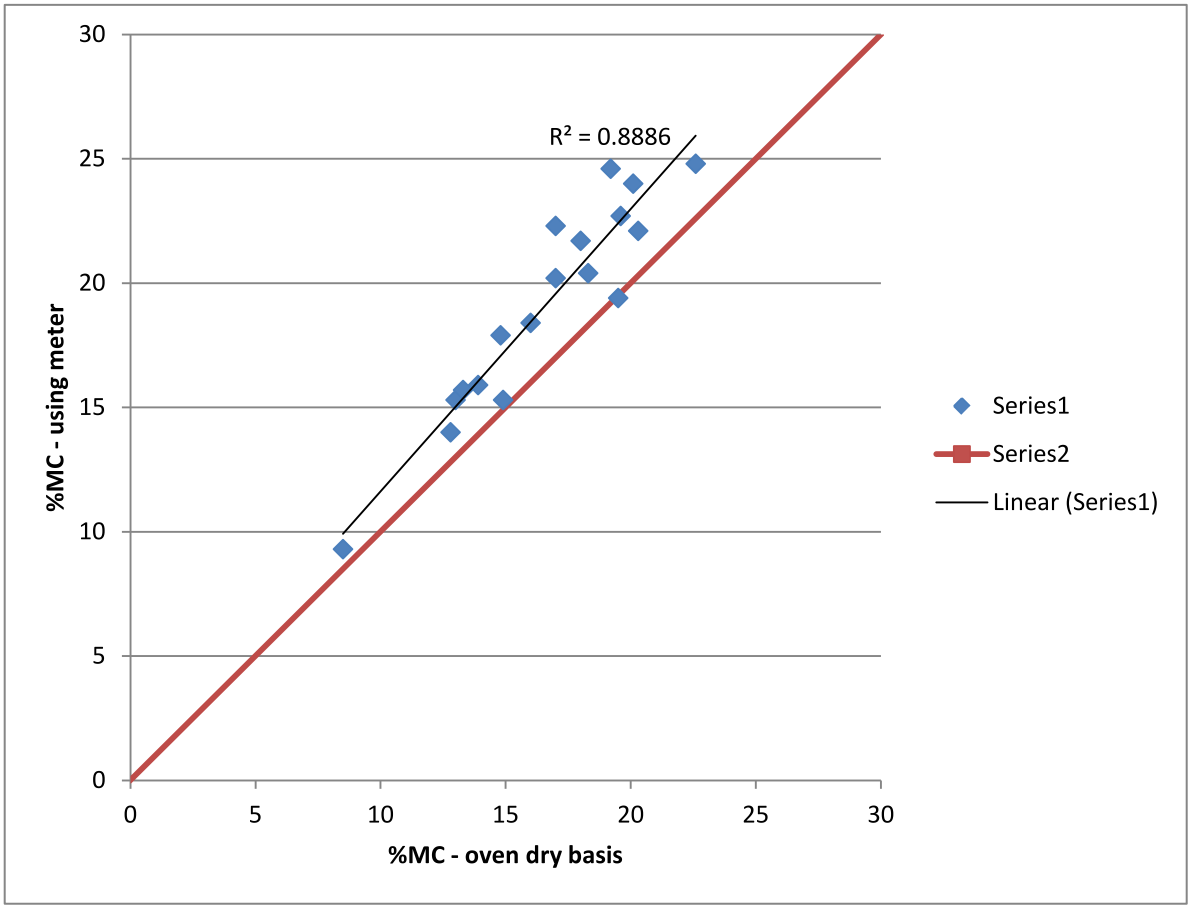
**Table 2. Predicted %MC for Set 1**

Average moisture meter values were obtained from three zones along the length (Zones I, II, II are averages of Zones 1 & 2, 4 & 5, 7 & 8 along the length of each piece) compared to actual obtained via oven drying.

| %MC | meter avg. | %MC |
|---|---|---|
| **Sample** | **I, II, III** | **Actual** |
| P | 15.3 | 13.0 |
| Q | 20.4 | 18.3 |
| R | 20.2 | 17.0 |
| S | 18.4 | 16.0 |
| U | 17.9 | 14.8 |
| 151 | 19.4 | 19.5 |
| 41 | 24.8 | 22.6 |
| 24 | 21.7 | 18.0 |
| 249 | 15.7 | 13.3 |
| 235 | 22.1 | 20.3 |
| 296 | 24.0 | 20.1 |
| 234 | 15.9 | 13.9 |
| 204 | 22.3 | 17.0 |
| 332 | 15.3 | 14.9 |
| 30 | 22.7 | 19.6 |
| 112 | 9.3 | 8.5 |
| 231 | 14.0 | 12.8 |
| 339 | 24.6 | 19.2 |
| **average** | **19.1** | **16.6** |
| **minimum** | **9.3** | **8.5** |
| **maximum** | **24.8** | **22.6** |

**Figure 12. Averages for Set 1**

A plot of the data using the actual %MC (x-axis) and moisture meter averages of Zones I (near end), II (approximately ¼ in from end), and III (center) (y-axis) are shown with a 1:1 line.



## 3.2 Set 2

In a total of 10 specimens in Set 2, %MC was measured using the Delmhorst resistance meter with insulated pins along five sections of the length of each sample piece (labeled I, II, III, IV and V) . Results suggest (Table 3) that accuracy within around 3% of actual oven-dry basis are obtainable from averaging shell and core results from end and center regions together. Figure 13 plots the average of shell and core moisture meter values from Zones I, II and III along the $y$ axis versus the actual piece dry basis %MC along the $x$ axis. With the exception of samples 56, 57 and 59 (Table 3) the data points above the red line show that averaging the meter measurements from these three zones tends to over predict actual %MC. The data spread also suggests further analysis should be performed to better qualify best zones where actual average piece %MC can be measured. It is clear that the ends (Zones I and V) are much drier (lower) than the measurements from the center (Zone III), and while it seems an average of end and inner %MC meter values might accurately predict actual %MC it is difficult to determine just yet what zones should best be used. Figures 14 to 23 show average of shell and core %MC, of Zones I, II, III, IV, and V in these 10 individual pieces, and clearly illustrate that the end to center to end % MC gradient. The actual (oven dry) value is plotted across the zones for reference.

**Table 3. Shell and core %MC for Set 2**

Measured along specimens with moisture meter and actual oven-dry based %MC.

| | SHELL | CORE | SHELL | CORE | ACTUAL | Shell | ACTUAL | Core | ACTUAL | 50:50 S:C | AVG | AVG |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 51 | M MC RAD | M MC RAD | M MC TAN | M MC TAN | MC | M MC | MC | M MC | MC | | I, II, II | I, II |
| I | 6.9 | 9.1 | 6.7 | 8.6 | 15.8 | 6.8 | 15.8 | 8.9 | 15.8 | 7.8 | | |
| II | 14.8 | 34.4 | 17.4 | 27.3 | 15.8 | 16.1 | 15.8 | 30.9 | 15.8 | 23.5 | | |
| III | 15.6 | 42.8 | 15.0 | 40.2 | 15.8 | 15.3 | 15.8 | 41.5 | 15.8 | 28.4 | | |
| IV | 14.6 | 37.2 | 16.2 | 35.4 | 15.8 | 15.4 | 15.8 | 36.3 | 15.8 | 25.9 | | |
| V | 7.5 | 11.1 | 9.2 | 11.0 | 15.8 | 8.4 | 15.8 | 11.1 | 15.8 | 9.7 | 19.9 | 15.7 |
| | | | | | | | | | | | | |
| | SHELL | CORE | SHELL | CORE | ACTUAL | Shell | ACTUAL | Core | ACTUAL | 50:50 S:C | AVG | AVG |
| 52 | M MC RAD | M MC RAD | M MC TAN | M MC TAN | MC | M MC | MC | M MC | MC | | I, II, II | I, II |
| I | 6.1 | 8.5 | 6.9 | 8.8 | 11.6 | 6.5 | 11.6 | 8.7 | 11.6 | 7.6 | | |
| II | 13.3 | 17.4 | 13.3 | 19.3 | 11.6 | 13.3 | 11.6 | 18.4 | 11.6 | 15.8 | | |
| III | 14.2 | 21.0 | 16.0 | 23.8 | 11.6 | 15.1 | 11.6 | 22.4 | 11.6 | 18.8 | | |
| IV | 12.5 | 18.7 | 13.3 | 18.8 | 11.6 | 12.9 | 11.6 | 18.8 | 11.6 | 15.8 | | |
| V | 6.8 | 8.7 | 7.6 | 9.0 | 11.6 | 7.2 | 11.6 | 8.9 | 11.6 | 8.0 | 14.1 | 11.7 |
| | | | | | | | | | | | | |
| | SHELL | CORE | SHELL | CORE | ACTUAL | Shell | ACTUAL | Core | ACTUAL | 50:50 S:C | AVG | AVG |
| 53 | M MC RAD | M MC RAD | M MC TAN | M MC TAN | MC | M MC | MC | M MC | MC | | I, II, II | I, II |
| I | 8.0 | 7.9 | 10.1 | 12.5 | 15.6 | 9.1 | 15.6 | 10.2 | 15.6 | 9.6 | | |
| II | 22.4 | 30.2 | 17.5 | 26.6 | 15.6 | 20.0 | 15.6 | 28.4 | 15.6 | 24.2 | | |
| III | 29.5 | 35.6 | 20.7 | 26.0 | 15.6 | 25.1 | 15.6 | 30.8 | 15.6 | 28.0 | | |
| IV | 32.5 | 38.0 | 14.0 | 18.3 | 15.6 | 23.3 | 15.6 | 28.2 | 15.6 | 25.7 | | |
| V | 11.8 | 11.7 | 7.4 | 8.7 | 15.6 | 9.6 | 15.6 | 10.2 | 15.6 | 9.9 | 20.6 | 16.9 |
| | | | | | | | | | | | | |
| | SHELL | CORE | SHELL | CORE | ACTUAL | Shell | ACTUAL | Core | ACTUAL | 50:50 S:C | AVG | AVG |
| 54 | M MC RAD | M MC RAD | M MC TAN | M MC TAN | MC | M MC | MC | M MC | MC | | I, II, II | I, II |
| I | 6.6 | 8.4 | 7.9 | 8.3 | 16.6 | 7.3 | 16.6 | 8.4 | 16.6 | 7.8 | | |
| II | 18.8 | 30.9 | 19.5 | 25.6 | 16.6 | 19.2 | 16.6 | 28.3 | 16.6 | 23.7 | | |
| III | 17.8 | 39.8 | 14.3 | 29.0 | 16.6 | 16.1 | 16.6 | 34.4 | 16.6 | 25.2 | | |
| IV | 16.4 | 33.4 | 19.8 | 29.6 | 16.6 | 18.1 | 16.6 | 31.5 | 16.6 | 24.8 | | |
| V | 7.1 | 8.8 | 7.1 | 8.3 | 16.6 | 7.1 | 16.6 | 8.6 | 16.6 | 7.8 | 18.9 | 15.8 |
| | | | | | | | | | | | | |
| | SHELL | CORE | SHELL | CORE | ACTUAL | Shell | ACTUAL | Core | ACTUAL | 50:50 S:C | AVG | AVG |
| 55 | M MC RAD | M MC RAD | M MC TAN | M MC TAN | MC | M MC | MC | M MC | MC | | I, II, II | I, II |
| I | 6.1 | 8.4 | 7.2 | 7.3 | 13.9 | 6.7 | 13.9 | 7.9 | 13.9 | 7.3 | | |
| II | 11.7 | 19.5 | 15.5 | 18.7 | 13.9 | 13.6 | 13.9 | 19.1 | 13.9 | 16.4 | | |
| III | 14.1 | 28.6 | 18.5 | 26.9 | 13.9 | 16.3 | 13.9 | 27.8 | 13.9 | 22.0 | | |
| IV | 10.9 | 23.4 | 20.4 | 24.7 | 13.9 | 15.7 | 13.9 | 24.1 | 13.9 | 19.9 | | |
| V | 7.1 | 9.7 | 7.9 | 8.2 | 13.9 | 7.5 | 13.9 | 9.0 | 13.9 | 8.2 | 15.2 | 11.8 |
| | | | | | | | | | | | | |
| | SHELL | CORE | SHELL | CORE | ACTUAL | Shell | ACTUAL | Core | ACTUAL | 50:50 S:C | AVG | AVG |
| 56 | M MC RAD | M MC RAD | M MC TAN | M MC TAN | MC | M MC | MC | M MC | MC | | I, II, II | I, II |
| I | 6.9 | 8.6 | 8.6 | 8.6 | 26.4 | 7.8 | 26.4 | 8.6 | 26.4 | 8.2 | | |
| II | 13.9 | 29.9 | 19.9 | 31.2 | 26.4 | 16.9 | 26.4 | 30.6 | 26.4 | 23.7 | | |
| III | 16.5 | 40.3 | 35.8 | 36.8 | 26.4 | 26.2 | 26.4 | 38.6 | 26.4 | 32.4 | | |
| IV | 18.1 | 36.0 | 34.9 | 33.2 | 26.4 | 26.5 | 26.4 | 34.6 | 26.4 | 30.6 | | |
| V | 8.8 | 11.5 | 8.7 | 9.1 | 26.4 | 8.8 | 26.4 | 10.3 | 26.4 | 9.5 | 21.4 | 16.0 |
| | | | | | | | | | | | | |
| | SHELL | CORE | SHELL | CORE | ACTUAL | Shell | ACTUAL | Core | ACTUAL | 50:50 S:C | AVG | AVG |
| 57 | M MC RAD | M MC RAD | M MC TAN | M MC TAN | MC | M MC | MC | M MC | MC | | I, II, II | I, II |
| I | 8.5 | 11.1 | 8.1 | 10.6 | 25.4 | 8.3 | 25.4 | 10.9 | 25.4 | 9.6 | | |
| II | 15.8 | 52.4 | 12.2 | 28.8 | 25.4 | 14.0 | 25.4 | 40.6 | 25.4 | 27.3 | | |
| III | 16.4 | 55.3 | 12.0 | 34.8 | 25.4 | 14.2 | 25.4 | 45.1 | 25.4 | 29.6 | | |
| IV | 13.3 | 48.4 | 11.5 | 35.1 | 25.4 | 12.4 | 25.4 | 41.8 | 25.4 | 27.1 | | |
| V | 9.2 | 14.4 | 8.1 | 10.8 | 25.4 | 8.7 | 25.4 | 12.6 | 25.4 | 10.6 | 22.2 | 18.4 |
| | | | | | | | | | | | | |
| | SHELL | CORE | SHELL | CORE | ACTUAL | Shell | ACTUAL | Core | ACTUAL | 50:50 S:C | AVG | AVG |
| 58 | M MC RAD | M MC RAD | M MC TAN | M MC TAN | MC | M MC | MC | M MC | MC | | I, II, II | I, II |
| I | 8.2 | 26.8 | 6.4 | 11.2 | 23.7 | 7.3 | 23.7 | 19.0 | 23.7 | 13.2 | | |
| II | 15.6 | 47.3 | 11.4 | 34.9 | 23.7 | 13.5 | 23.7 | 41.1 | 23.7 | 27.3 | | |
| III | 17.0 | 52.2 | 16.1 | 46.6 | 23.7 | 16.6 | 23.7 | 49.4 | 23.7 | 33.0 | | |
| IV | 12.9 | 44.3 | 14.7 | 41.4 | 23.7 | 13.8 | 23.7 | 42.9 | 23.7 | 28.3 | | |
| V | 8.8 | 16.0 | 7.7 | 13.0 | 23.7 | 8.3 | 23.7 | 14.5 | 23.7 | 11.4 | 24.5 | 20.2 |
| | | | | | | | | | | | | |
| | SHELL | CORE | SHELL | CORE | ACTUAL | Shell | ACTUAL | Core | ACTUAL | 50:50 S:C | AVG | AVG |
| 59 | M MC RAD | M MC RAD | M MC TAN | M MC TAN | MC | M MC | MC | M MC | MC | | I, II, II | I, II |
| I | 8.5 | 12.2 | 8.9 | 11.1 | 24.8 | 8.7 | 24.8 | 11.7 | 24.8 | 10.2 | | |
| II | 15.4 | 43.0 | 18.4 | 39.2 | 24.8 | 16.9 | 24.8 | 41.1 | 24.8 | 29.0 | | |
| III | 16.1 | 46.3 | 15.2 | 41.0 | 24.8 | 15.7 | 24.8 | 43.7 | 24.8 | 29.7 | | |
| IV | 16.4 | 42.9 | 13.8 | 38.5 | 24.8 | 15.1 | 24.8 | 40.7 | 24.8 | 27.9 | | |
| V | 8.0 | 10.4 | 7.5 | 9.5 | 24.8 | 7.8 | 24.8 | 10.0 | 24.8 | 8.9 | 22.9 | 19.6 |
| | | | | | | | | | | | | |
| | SHELL | CORE | SHELL | CORE | ACTUAL | Shell | ACTUAL | Core | ACTUAL | 50:50 S:C | AVG | AVG |
| 60 | M MC RAD | M MC RAD | M MC TAN | M MC TAN | MC | M MC | MC | M MC | MC | | I, II, II | I, II |
| I | 8.4 | 12.3 | 8.7 | 11.2 | 21.3 | 8.6 | 21.3 | 11.8 | 21.3 | 10.2 | | |
| II | 15.8 | 45.3 | 17.2 | 40.0 | 21.3 | 16.5 | 21.3 | 42.7 | 21.3 | 29.6 | | |
| III | 16.7 | 53.2 | 19.8 | 46.2 | 21.3 | 18.3 | 21.3 | 49.7 | 21.3 | 34.0 | | |
| IV | 16.0 | 42.0 | 17.6 | 39.7 | 21.3 | 16.8 | 21.3 | 40.9 | 21.3 | 28.8 | | |
| V | 8.3 | 10.2 | 8.7 | 11.3 | 21.3 | 8.5 | 21.3 | 10.8 | 21.3 | 9.6 | 24.6 | 19.9 |

.

**Figure 13. Averages for Set 2**

Averages of the shell and core moisture meter measurements were plotted for Zones I (end), II (about 1/3 in) and III (middle) along the *y* axis versus the actual piece dry basis %MC along the *x* axis.

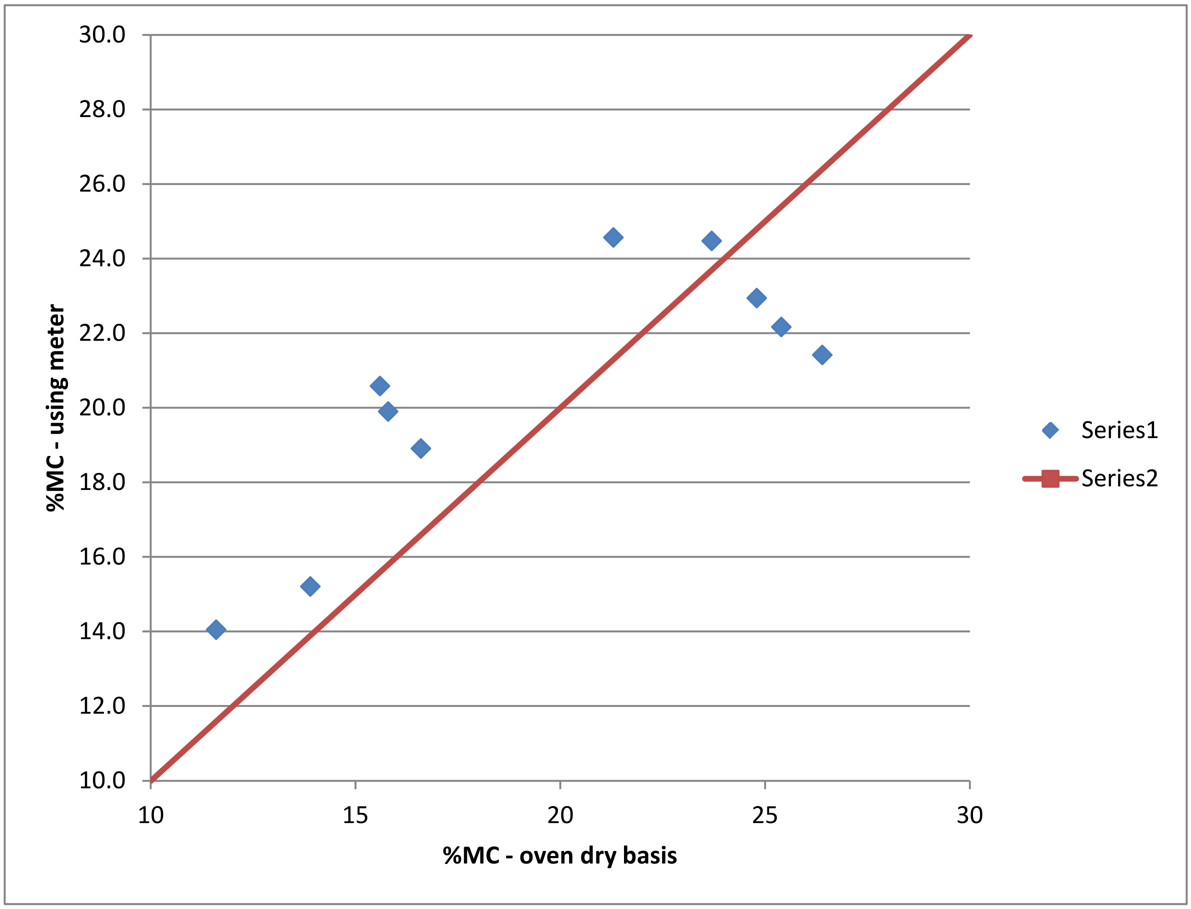


**Figure 14. Sample 51**

Moisture content bars representing average of meter shell and core %MC at end, center and intermediate regions of sample #51, with red bar showing actual %MC.

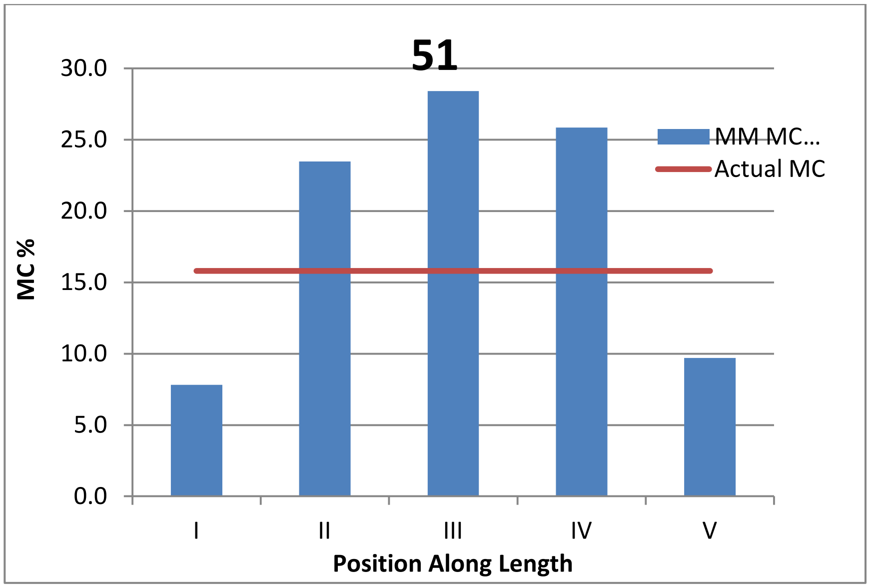



**Figure 15. Sample 52**

Moisture content bars representing average of meter shell and core %MC at end, center and intermediate regions of sample #52, with red bar showing actual %MC.

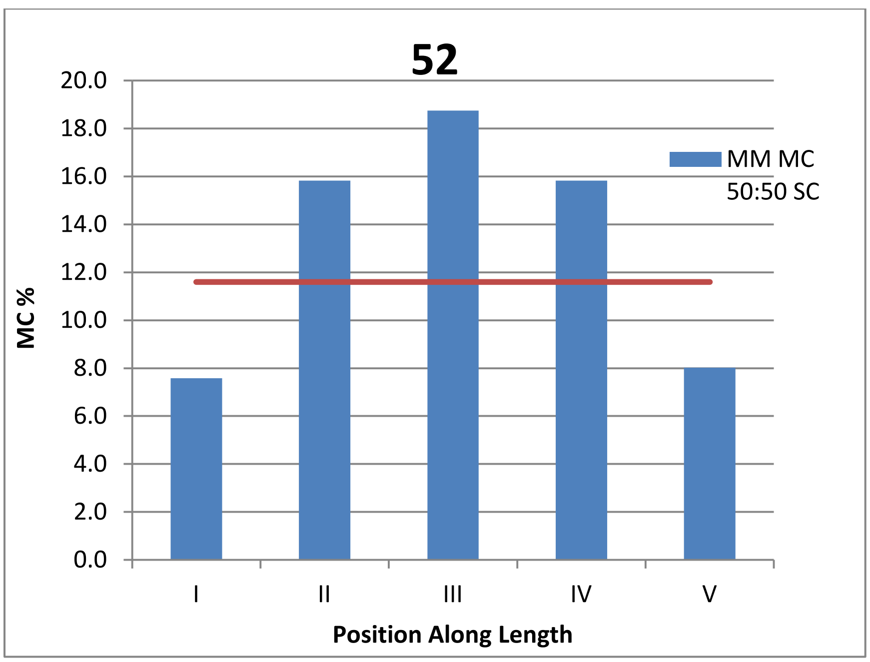


**Figure 16. Sample 53**

Moisture content bars representing average of meter shell and core %MC at end, center and intermediate regions of sample #53, with red bar showing actual %MC.

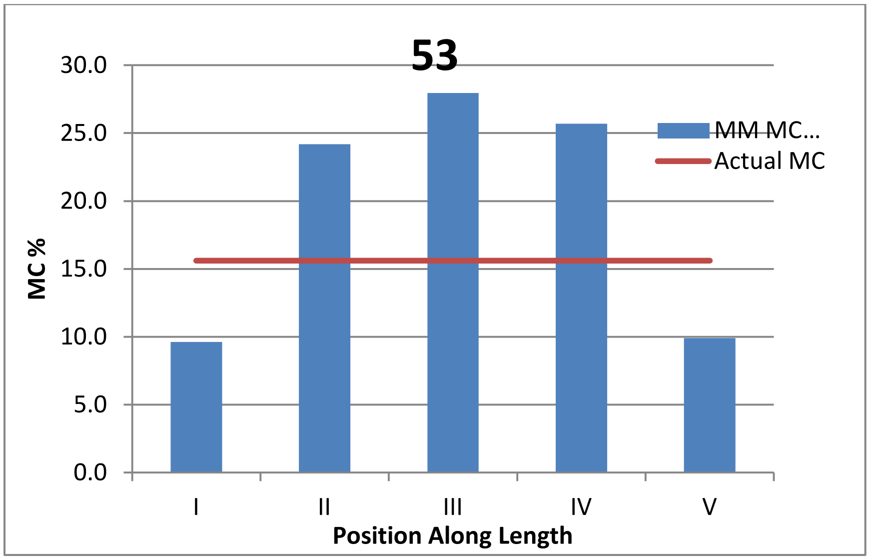



**Figure 17. Sample 54**

Moisture content bars representing average of meter shell and core %MC at end, center and intermediate regions of sample #54, with red bar showing actual %MC.

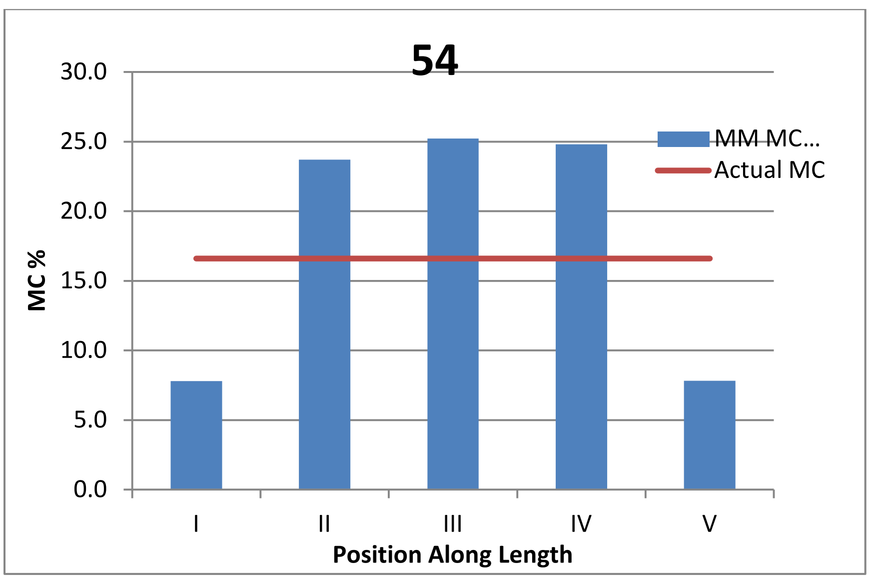


**Figure 18. Sample 55**

Moisture content bars representing average of meter shell and core %MC at end, center and intermediate regions of sample #55, with red bar showing actual %MC.

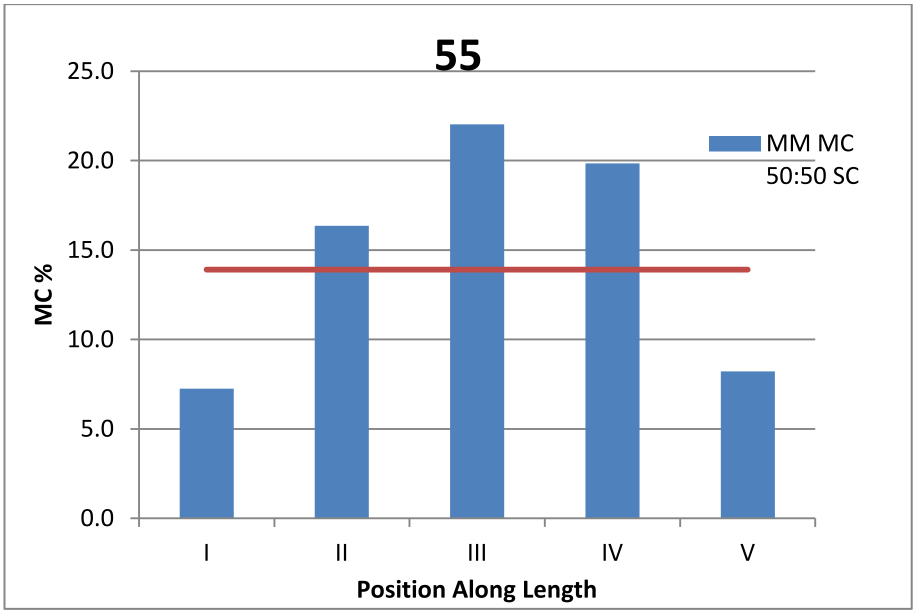



**Figure 19. Sample 56**

Moisture content bars representing average of meter shell and core %MC at end, center and intermediate regions of sample #56, with red bar showing actual %MC.

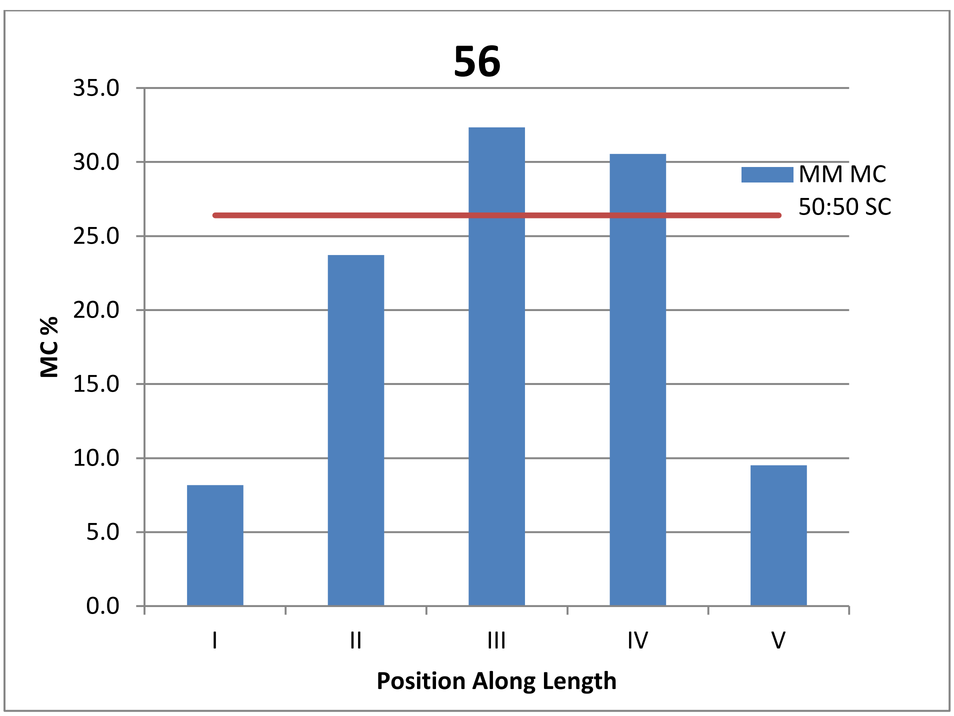


**Figure 20. Sample 57**

Moisture content bars representing average of meter shell and core %MC at end, center and intermediate regions of sample #57, with red bar showing actual %MC.

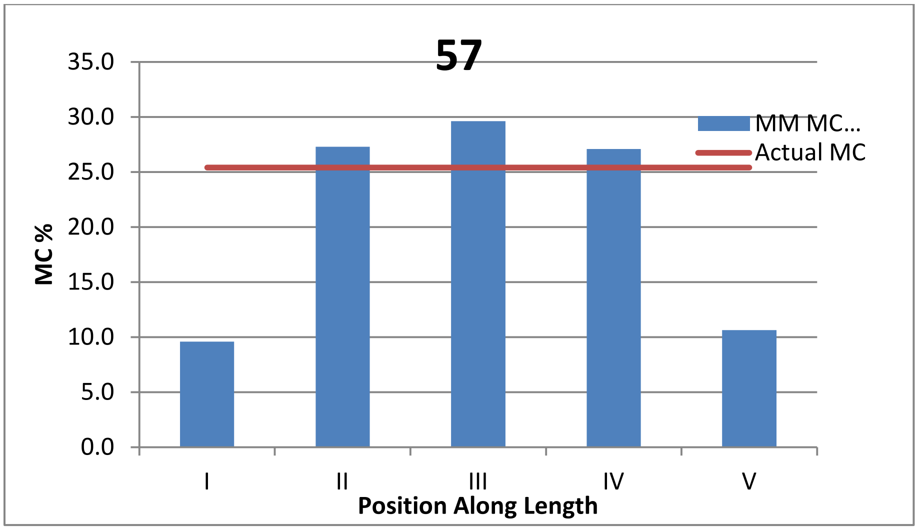



**Figure 21. Sample 58**

Moisture content bars representing average of meter shell and core %MC at end, center and intermediate regions of sample #58, with red bar showing actual %MC.

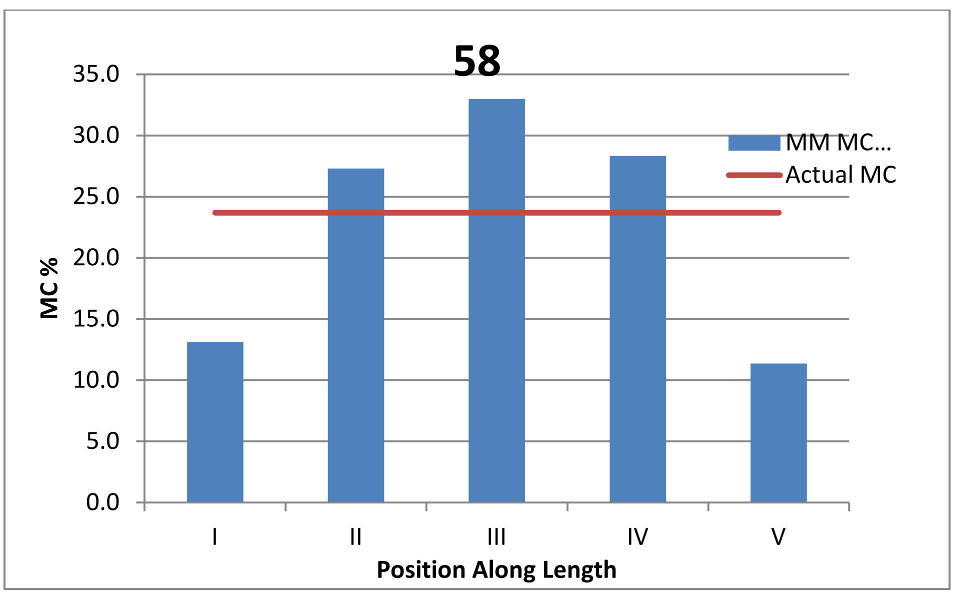


**Figure 22. Sample 59**

Moisture content bars representing average of meter shell and core %MC at end, center and intermediate regions of sample #59, with red bar showing actual %MC.

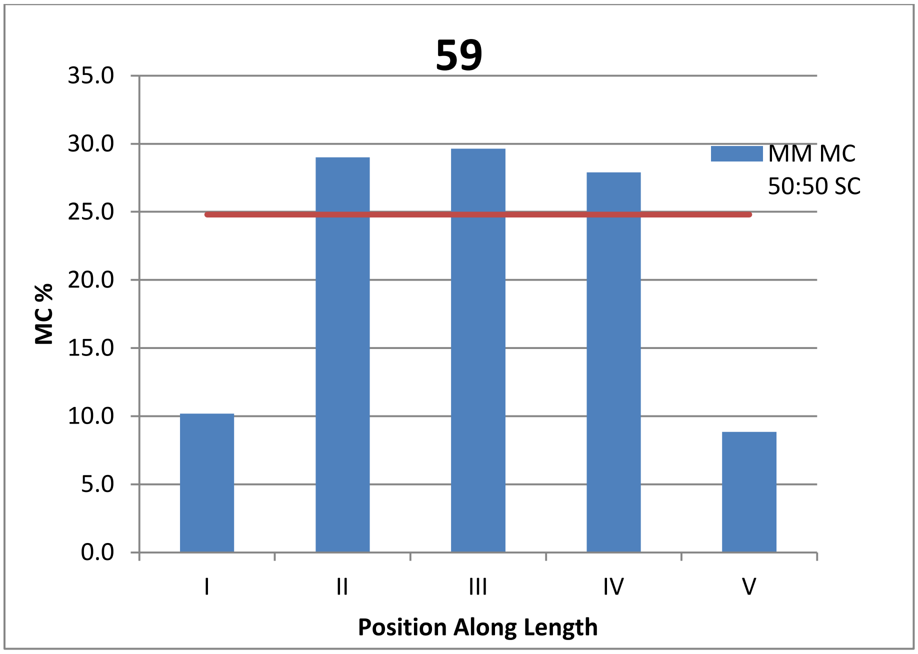
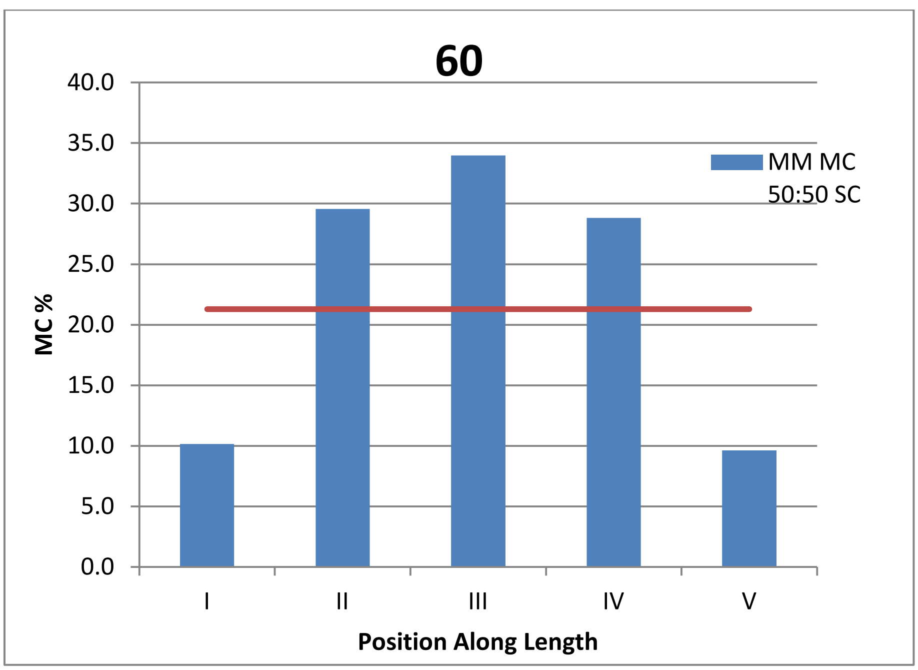



**Figure 23. Sample 60**

Moisture content bars representing average of meter shell and core %MC at end, center and intermediate regions of sample #60, with red bar showing actual %MC.



## 3.3 Set 3

In Set 3 containing 35 specimens, %MC was measured with the meter along five sections of the length (labeled zones I, II, III, IV, and V). Actual moisture content of each entire piece of cordwood was determined from oven drying shell and core wood from each zone, and the remaining four pieces between each zone. Because results have suggested that an average of the shell (Figure 10), core values from the end (zone I), and the shell and core (Figure 11) values from the middle (zone III) comes closest to predicting actual moisture content (oven dry basis) of the entire piece, these results are specifically presented in Table 4.

The average difference between predicted %MC using the moisture meter and the actual %MC determined of the entire piece was less than 2% (Table 4). However, sometimes the meter was off by as much as 5%. Interestingly, when comparing whether predicted %MC was determined from measuring one end and center (zones I and III, respectively), versus the other end and center (zones III and V, respectively), the average differences were virtually identical (1.7975% versus 1.7990%). This similarity suggests that end to center moisture gradient from either direction is quite comparable and that it does not especially matter which end is utilized for meter measurement.

The up to 5% error difference, as contrasted to the less than 2% average, between predicted and actual %MC is likely due to unexpected and unknowable moisture gradients that might be from unique anatomical structure or cellular tissue to that specific piece of cordwood. Because it is likely that a test burn or other such use would involve at least about 10 individual pieces of wood, then from a random selection statistical perspective, an accuracy of within about 2 to 3%MC is reasonable to expect for a full fuel charge.

Figure 24 is a plot of data from Table 4, and shows a good relationship, with a few outlier data points, between predicted %MC using the moisture meter and actual cordwood piece oven dry %MC.

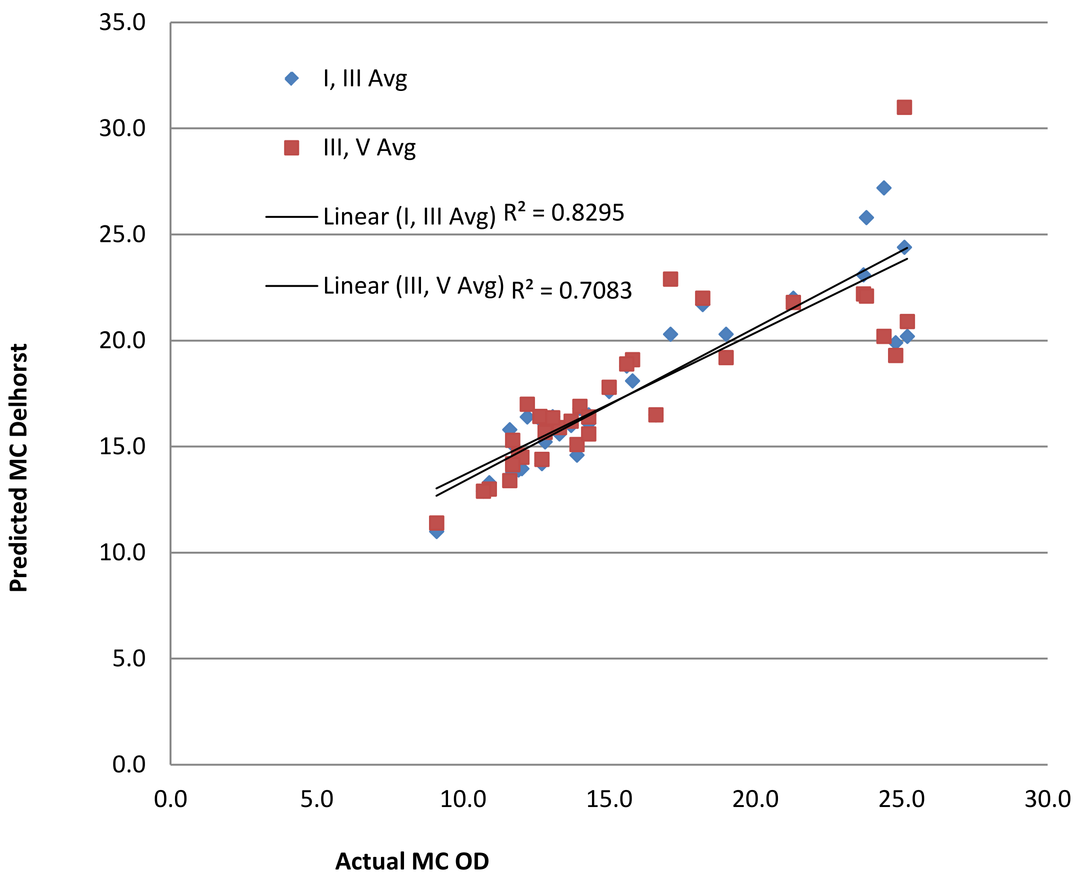
**Table 4. Averages for Set 3**

Averaged shell and core %MC from ends and middle with meter and actual oven-dry based %MC, with differences. Roman numerals refer to zones on the sample.

| | | | | | Difference | |
|---|---|---|---|---|---|---|
| Sample | I, III Average | III, V Average | Actual MC | | I,III to actual | III, V to actual |
| 15 | 21.7 | 22.0 | 18.2 | | 3.5 | 3.8 |
| 39 | 15.6 | 15.9 | 13.3 | | 2.3 | 2.6 |
| 51 | 18.1 | 19.1 | 15.8 | | 2.3 | 3.3 |
| 52 | 15.8 | 13.4 | 11.6 | | 4.2 | 1.8 |
| 53 | 18.8 | 18.9 | 15.6 | | 3.2 | 3.3 |
| 54 | 16.5 | 16.5 | 16.6 | | -0.1 | -0.1 |
| 55 | 14.6 | 15.1 | 13.9 | | 0.7 | 1.2 |
| 56 | 20.2 | 20.9 | 25.2 | | -5.0 | -4.3 |
| 57 | 27.2 | 20.2 | 24.4 | | 2.8 | -4.2 |
| 58 | 23.1 | 22.2 | 23.7 | | -0.6 | -1.5 |
| 59 | 19.9 | 19.3 | 24.8 | | -4.9 | -5.5 |
| 60 | 22.0 | 21.8 | 21.3 | | 0.7 | 0.5 |
| 179 | 16.4 | 17.0 | 12.2 | | 4.2 | 4.8 |
| 220 | 16.8 | 16.9 | 14.0 | | 2.8 | 2.9 |
| 239 | 14.0 | 14.2 | 11.7 | | 2.3 | 2.5 |
| 294 | 16.0 | 16.2 | 13.7 | | 2.3 | 2.5 |
| 465 | 16.5 | 16.4 | 14.3 | | 2.2 | 2.1 |
| 473 | 14.2 | 14.4 | 12.7 | | 1.5 | 1.7 |
| 502 | 20.3 | 22.9 | 17.1 | | 3.2 | 5.8 |
| 506 | 25.8 | 22.1 | 23.8 | | 2.0 | -1.7 |
| 510 | 24.4 | 31.0 | 25.1 | | -0.7 | 5.9 |
| 520 | 20.3 | 19.2 | 19.0 | | 1.3 | 0.2 |
| 535 | 17.6 | 17.8 | 15.0 | | 2.6 | 2.8 |
| 31 | 11.0 | 11.4 | 9.1 | | 1.9 | 2.3 |
| 304 | 13.9 | 14.6 | 11.9 | | 2.0 | 2.7 |
| 457 | 13.3 | 13.0 | 10.9 | | 2.4 | 2.1 |
| 464 | 16.1 | 15.6 | 14.3 | | 1.8 | 1.3 |
| 158 | 15.1 | 15.3 | 11.7 | | 3.4 | 3.6 |
| 26 | 12.9 | 12.9 | 10.7 | | 2.2 | 2.2 |
| 4 | 14.0 | 14.5 | 12.0 | | 1.9 | 2.5 |
| 578 | 15.8 | 16.3 | 12.9 | | 3.0 | 3.5 |
| 581 | 16.3 | 16.4 | 12.6 | | 3.7 | 3.8 |
| 459 | 15.2 | 15.7 | 12.8 | | 2.4 | 2.9 |
| 622 | 16.4 | 16.4 | 13.1 | | 3.3 | 3.3 |
| 537 | 13.8 | 14.2 | 11.7 | | 2.1 | 2.4 |
| | | | | | | |
| | | | | avg | 1.7975 | 1.7990 |
| | | | | | | |
| | | | | min | -5.0 | -5.5 |
| | | | | max | 4.2 | 5.9 |

**Figure 24. Comparing predicted and actual %MC values**

Moisture meter predicted from shell and core from center and end (zones I, III and zones III, V) to actual % MC, with linear regression and r2 coefficient.



# 4 Statistical Analysis of Set 3: Paired T-Test

Paired T-Test statistical analyses were performed on sample data Set 3 using Minitab 16 (statistical software program). This set was chosen because the procedures used with the 35 specimens in Set 3 appear to balance accuracy and practicality, a large set of data was developed for each specimen, and the number of specimens seems reasonably large. Also, because the suggested procedure requires averaging meter measurement of shell and core %MC from the center and an end of a piece of red oak fuel wood (split cord fire wood), there are actually 70 separate specimen results due to measurements from both ends of each experimental specimen. From these data, statistical analysis was carried out to compare the predicted %MC through using the Delmhorst resistance moisture meter with insulated pin probes to the actual moisture content of a specimen determined via oven drying on:

- Group 1: 70 “effective” specimens (35 specimens with measurement of each end, independently).
- Group 2: 24 specimens for which the predicted %MC was less than 25% and greater than 17%.
- Group 3: Half of the specimens for which the predicted %MC was less than 25% and greater than 17% (12 specimens, taken as every other from the set of 24; comparable to about the 10 which would be used in a typical wood-fueled boiler test run).
- Group 4: The other half of the specimens for which the predicted %MC was less than 25% and greater than 17% (12 specimens, taken as every other from the set of 24; comparable to about the 10 which would be used in a typical wood-fueled boiler test run).

Results from these groups are provided in the following sections, and importantly show, to a 95% confidence interval, the range with which the Moisture Meter accurately predicts true moisture.

## 4.1 Group 1

This group includes all 70 specimens.

### 4.1.1 Paired T-Test and CI: core, end Average, Actual MC

```
all data
Paired T for core, end Average - Actual MC
                    N    Mean  StDev  SE Mean
core, end Average  70  17.418  3.786    0.452
Actual MC          70  15.620  4.744    0.567
Difference         70   1.798  2.317    0.277
```

95% CI for mean difference: (1.246, 2.351)

T-Test of mean difference = 0 (vs not = 0): T-Value = 6.49 P-Value = 0.000

## 4.2 Group 2

Results are for specific specimens with predicted Moisture Content less than 25%, and greater than 17%.

### 4.2.1 Paired T-Test and CI: core, end Average_1, Actual MC_1

```
less than 25%, greater than 17%
Paired T for core, end Average_1 - Actual MC_1
                      N    Mean  StDev  SE Mean
core, end Average_1  24  20.408  1.930    0.394
Actual MC_1          24  19.871  4.173    0.852
Difference           24   0.537  3.378    0.690

95% CI for mean difference: (-0.889, 1.964)
T-Test of mean difference = 0 (vs not = 0): T-Value = 0.78 P-Value = 0.444
```

## 4.3 Group 3

Results are for 12 specimens with predicted Moisture Content less than 25%, and greater than 17%..

### 4.3.1 Paired T-Test and CI: core, end Average_1_1, Actual MC_1_1

```
Paired T for core, end Average_1_1 - Actual MC_1_1
                       N   Mean  StDev  SE Mean
core, end Average_1_1  12  20.61   2.04     0.59
Actual MC_1_1          12  19.73   3.91     1.13
Difference             12  0.875  3.414    0.986

95% CI for mean difference: (-1.294, 3.044)
T-Test of mean difference = 0 (vs not = 0): T-Value = 0.89 P-Value = 0.394
```

## 4.4 Group 4

Results are for 12 specimens with predicted Moisture Content less than 25%, and greater than 17%.

### 4.4.1 Paired T-Test and CI: core, end Average_1_2, Actual MC_1_2

```
Paired T for core, end Average_1_2 - Actual MC_1_2
                       N   Mean  StDev  SE Mean
core, end Average_1_2  12  20.21   1.88     0.54
Actual MC_1_2          12  20.01   4.59     1.32
Difference             12  0.200  3.458    0.998

95% CI for mean difference: (-1.997, 2.397)
T-Test of mean difference = 0 (vs not = 0): T-Value = 0.20 P-Value = 0.845
```

# 5 Statistical Analysis: Verification

An additional set of 50 split red oak, kiln-dried cordwood specimens were analyzed to further verify the proposed method of averaging shell and core moisture meter readings from an end and the center of each piece to predict accurately true dry-basis weight %MC. In addition to taking moisture readings, wafers were cut at the one-quarter, one half, and three-quarter zones and oven dried because that method has also been suggested to predict actual overall piece %MC (Butcher 2013). Data for these pieces are presented in Table 5. Of the specimens, 21 are within the actual range of 17 to 25%MC. Average error is shown in the five columns on the right: first column is the three wafer method and the other four columns show the moisture meter averaging the shell (approximately one-quarter inch) and core (approximately 1.125 inch) readings about one inch from the end and in the center of each piece (four replicates for each piece of cordwood). Though there were some individual outliers in both directions that were likely due to pieces with especially high or low core %MC, the overall average prediction seems to average accuracy to within about 1% of true value.

## Table 5. Comparing three-wafer and moisture meter methods

Averaged shell and core %MC from ends and middle with meter, 3-wafer method and actual oven-dry based %MC, with differences; the 17 to 25% actual % MC range is highlighted.

| SUNY ESF Red Oak Firewood Moisture Content Prediction - 3 wafer method v. Moisture Meter | | | | | | | | | | Error | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Specimen # | weight | weight | **Actual %MC** | **3 wafer avg** | **Meter Prediction** | | | | | 3 wafer avg | Meter Prediction | | | |
| | g | pounds | | | 1 | 2 | 3 | 4 | | | 1 | 2 | 3 | 4 |
| 1 | 2347.1 | 5.2 | 9.2 | 10.6 | 9.9 | 9.9 | 9.6 | 9.1 | | 1.4 | *0.7* | *0.7* | *0.4* | *-0.1* |
| 6 | 961.0 | 2.1 | 9.8 | 10.3 | 11.4 | 12.4 | 10.1 | 10.4 | | 0.5 | *1.6* | *2.6* | *0.3* | *0.6* |
| 4 | 2935.8 | 6.5 | 9.8 | 11.0 | 10.3 | 9.8 | 12.5 | 12.3 | | 1.2 | *0.5* | *0.0* | *2.7* | *2.5* |
| K | 1592.5 | 3.5 | 10.7 | 11.1 | 11.6 | 11.4 | 11.7 | 11.4 | | 0.4 | *0.9* | *0.7* | *1.0* | *0.7* |
| 12 | 2091.5 | 4.6 | 10.9 | 12.6 | 11.8 | 11.2 | 11.7 | 11.0 | | 1.7 | *0.9* | *0.3* | *0.8* | *0.0* |
| 5 | 896.7 | 2.0 | 11.1 | 11.7 | 11.4 | 11.7 | 15.2 | 14.7 | | 0.6 | *0.3* | *0.6* | *4.1* | *3.6* |
| S7 | 1432.3 | 3.2 | 11.2 | 11.6 | 13.1 | 13.0 | 13.4 | 13.7 | | 0.4 | *1.9* | *1.8* | *2.2* | *2.5* |
| 3 | 1715.0 | 3.8 | 11.4 | 12.0 | 12.6 | 12.1 | 11.7 | 11.8 | | 0.6 | *1.2* | *0.7* | *0.3* | *0.4* |
| 13 | 2430.4 | 5.4 | 12.6 | 13.1 | 10.1 | 10.2 | 13.6 | 14.4 | | 0.5 | *-2.5* | *-2.4* | *1.0* | *1.8* |
| 10 | 2403.4 | 5.3 | 12.8 | 15.7 | 13.4 | 13.3 | 11.6 | 11.2 | | 2.9 | *0.6* | *0.4* | *-1.2* | *-1.6* |
| 7 | 1422.1 | 3.1 | 13.4 | 12.4 | 16.6 | 16.1 | 12.3 | 13.4 | | -1.0 | *3.2* | *2.7* | *-1.2* | *0.0* |
| J | 2879.4 | 6.3 | 14.7 | 15.7 | 15.9 | 16.4 | 15.4 | 15.8 | | 1.0 | *1.2* | *1.7* | *0.7* | *1.1* |
| B | 1238.5 | 2.7 | 14.9 | 16.3 | 24.2 | 23.7 | 23.6 | 23.2 | | 1.4 | *9.3* | *8.8* | *8.7* | *8.3* |
| 4 | 2364.1 | 5.2 | 15.1 | 16.4 | 15.2 | 15.8 | 12.8 | 13.4 | | 1.3 | *0.1* | *0.7* | *-2.3* | *-1.8* |
| 9 | 3047.5 | 6.7 | 15.7 | 18.6 | 14.0 | 13.1 | 15.1 | 15.9 | | 2.9 | *-1.8* | *-2.6* | *-0.6* | *0.2* |
| 9 | 1503.2 | 3.3 | 15.9 | 17.2 | 19.5 | 18.4 | 17.8 | 17.1 | | 1.3 | *3.6* | *2.5* | *1.9* | *1.2* |
| 4 | 1774.9 | 3.9 | 17.7 | 19.7 | 18.1 | 18.4 | 20.3 | 17.1 | | 2.0 | *0.4* | *0.7* | *2.6* | *-0.6* |
| H | 2875.0 | 6.3 | 17.9 | 19.4 | 19.9 | 20.6 | 16.4 | 16.0 | | 1.5 | *2.0* | *2.7* | *-1.5* | *-1.9* |
| B | 1333.8 | 2.9 | 18.5 | 22.7 | 20.8 | 20.5 | 16.2 | 15.6 | | 4.2 | *2.3* | *2.0* | *-2.4* | *-2.9* |
| 6 | 1799.7 | 4.0 | 18.8 | 22.6 | 21.3 | 20.2 | 21.1 | 20.8 | | 3.8 | *2.5* | *1.4* | *2.3* | *2.0* |
| J4 | 2017.6 | 4.4 | 18.8 | 27.3 | 23.2 | 23.8 | 21.7 | 22.4 | | 8.5 | *4.4* | *5.0* | *2.9* | *3.6* |
| 5 | 1581.2 | 3.5 | 18.9 | 21.7 | 18.3 | 19.5 | 18.5 | 19.0 | | 2.8 | *-0.6* | *0.6* | *-0.4* | *0.1* |
| 6 | 1970.2 | 4.3 | 19.1 | 21.6 | 23.2 | 24.0 | 21.9 | 17.9 | | 2.5 | *4.1* | *4.9* | *2.8* | *-1.2* |
| 3 | 1860.8 | 4.1 | 19.6 | 21.8 | 23.6 | 23.8 | 24.7 | 23.0 | | 2.2 | *4.0* | *4.2* | *5.1* | *3.4* |
| A | 2282.2 | 5.0 | 19.8 | 22.2 | 18.1 | 17.5 | 17.4 | 18.8 | | 2.4 | *-1.8* | *-2.4* | *-2.4* | *-1.0* |
| 3 | 1799.7 | 4.0 | 20.0 | 24.5 | 21.8 | 20.8 | 14.9 | 15.9 | | 4.5 | *1.8* | *0.8* | *-5.1* | *-4.1* |
| 5 | 1697.1 | 3.7 | 20.1 | 22.8 | 26.1 | 27.4 | 22.4 | 24.4 | | 2.7 | *6.0* | *7.3* | *2.3* | *4.3* |
| 1 | 1549.2 | 3.4 | 20.2 | 22.4 | 24.7 | 26.3 | | | | 2.2 | *4.5* | *6.1* | | |
| A | 2663.8 | 5.9 | 20.4 | 24.9 | 20.9 | 20.2 | 19.5 | 19.2 | | 4.5 | *0.5* | *-0.2* | *-0.9* | *-1.2* |
| I | 3135.8 | 6.9 | 21.5 | 24.6 | 20.9 | 22.2 | 17.9 | 18.3 | | 3.1 | *-0.6* | *0.7* | *-3.7* | *-3.3* |
| J5 | 2663.5 | 5.9 | 21.5 | 23.7 | 20.9 | 19.8 | 17.9 | 19.2 | | 2.2 | *-0.6* | *-1.7* | *-3.6* | *-2.3* |
| 2 | 2832.8 | 6.2 | 22.7 | 25.4 | 17.3 | 18.6 | 27.7 | 25.0 | | 2.7 | *-5.4* | *-4.1* | *5.0* | *2.3* |
| J3 | 2260.5 | 5.0 | 22.8 | 29.5 | 22.6 | 21.4 | 22.2 | 21.7 | | 6.7 | *-0.3* | *-1.5* | *-0.6* | *-1.1* |
| J9 | 2844.8 | 6.3 | 23.3 | 27.3 | 20.8 | 27.1 | 16.2 | 19.6 | | 4.0 | *-2.5* | *3.8* | *-7.2* | *-3.7* |
| 8 | 2464.9 | 5.4 | 23.3 | 26.7 | 27.7 | 27.4 | 23.3 | 18.8 | | 3.4 | *4.3* | *4.1* | *0.0* | *-4.5* |
| J13 | 2823.4 | 6.2 | 23.4 | 27.7 | 20.5 | 22.4 | 24.6 | 25.7 | | 4.3 | *-3.0* | *-1.1* | *1.2* | *2.3* |
| J17 | 3621.2 | 8.0 | 24.7 | 28.6 | 22.2 | 26.5 | 25.7 | 27.6 | | 3.9 | *-2.5* | *1.8* | *1.0* | *2.9* |
| J12 | 2603.0 | 5.7 | 25.4 | 29.7 | 17.4 | 20.4 | 23.9 | 25.9 | | 4.3 | *-8.0* | *-5.0* | *-1.5* | *0.5* |
| J6 | 3916.1 | 8.6 | 25.9 | 32.4 | 25.4 | 26.8 | 17.5 | 20.0 | | 6.5 | *-0.5* | *0.9* | *-8.5* | *-5.9* |
| J14 | 2798.1 | 6.2 | 26.1 | 29.8 | 22.1 | 24.0 | 18.2 | 22.2 | | 3.7 | *-4.0* | *-2.1* | *-7.9* | *-3.9* |
| J11 | 3333.6 | 7.3 | 26.5 | 30.0 | 18.3 | 19.9 | 27.5 | 31.5 | | 3.5 | *-8.2* | *-6.6* | *0.9* | *5.0* |
| J16 | 2510.3 | 5.5 | 26.6 | 30.9 | 21.4 | 29.0 | 26.4 | 29.7 | | | *-5.3* | *2.4* | *-0.3* | *3.1* |
| J1 | 3106.7 | 6.8 | 26.8 | 35.4 | 24.4 | 22.2 | 18.9 | 15.4 | | | *-2.4* | *-4.6* | *-7.9* | *-11.5* |
| J18 | 4493.2 | 9.9 | 27.3 | 34.0 | 24.5 | 27.5 | 33.6 | 33.5 | | 6.7 | *-2.9* | *0.2* | *6.3* | *6.2* |
| J2 | 4536.6 | 10.0 | 27.4 | 41.7 | 27.5 | 29.8 | 32.8 | 31.7 | | 14.3 | *0.1* | *2.4* | *5.4* | *4.3* |
| J15 | 2760.7 | 6.1 | 28.1 | 33.5 | 25.0 | 26.7 | 24.0 | 33.0 | | 5.4 | *-3.1* | *-1.4* | *-4.1* | *4.9* |
| 4 | 2912.2 | 6.4 | 28.2 | 39.3 | 33.2 | 33.2 | 18.5 | 20.1 | | 11.1 | *5.0* | *5.0* | *-9.7* | *-8.1* |
| J8 | 2504.0 | 5.5 | 28.3 | 33.6 | 19.7 | 21.9 | 31.3 | 31.8 | | 5.3 | *-8.6* | *-6.4* | *3.0* | *3.5* |
| J7 | 3222.4 | 7.1 | 29.7 | 34.7 | 27.1 | 34.1 | 30.0 | 34.7 | | 5.0 | *-2.6* | *4.4* | *0.3* | *5.0* |
| J10 | 4153.3 | 9.2 | 34.8 | 40.8 | 29.6 | 33.8 | 30.3 | 32.2 | | 6.0 | *-5.2* | *-1.0* | *-4.6* | *-2.6* |
| | | | | | | | | | | | | | | |
| All | | ***5.4*** | ***19.9*** | ***23.4*** | ***19.8*** | ***20.7*** | ***19.6*** | ***20.1*** | ***Average -*** | 3.5 | *-0.1* | *0.8* | *-0.3* | *0.3* |
| | | | | | | | | | | | | | | |
| %MC - 17 to 25% | | ***5.0*** | ***20.6*** | ***24.1*** | ***21.6*** | ***22.3*** | ***20.5*** | ***20.3*** | | 3.5 | *0.9* | *1.7* | *-0.1* | *-0.3* |

To recreate the 50-pound fuel load used in practice to carry out an advanced hydronic heater stove emissions and energy performance test, 10 individual specimens each weighing about 5 pounds were used. Since 5 pounds is very close to the average weight of the cordwood pieces of this project (Table 5), an exercise was undertaken to randomly select 10 pieces from the ones in the table to simulate what might be done during a fuel burn test. It is anticipated that this method will bring into the report confidence as to characterization of achievable accuracy.

Because specific interest is in %MC wood over the 17 to 25% MC range, only those pieces (from Table 5) that were predicted to be in that range using the moisture meter method were set up into a list of that data with a random number generator. There were 94 total data choices which were then randomized in different order 10 different times into new lists. From these 10 new lists, 10 pieces were sequentially selected, as would be done with selecting pieces for test burns, nine different times. This provided 90 independent sets of wood which would theoretically be utilized. Table 6 shows the results. Key is that average weight was 5.2 pounds, so 10 pieces would provide the approximately 50-pound fuel load desired. Average actual moisture of the 10 pieces in each of the 90 sets was 21.5% (18.3 to 24.4% range).

Of note, the average moisture meter prediction of 20.9% was quite close to actual (19.4 to 23.0% range). Although the moisture meter in the range of concern on an individual piece basis had a relatively qualitative dynamic accuracy of about ± 3 to 5%, considering 10 pieces together appears to provide quite achievable and reproducible accuracy of less than 1%.

**Table 6. Creating 50 pound fuel loads**

90 examples of average of 10 specimens, %MC determination and error.

| | weight lbs | actual %MC | 3-wafer %MC | meter %MC | 3-wafer error | meter error |
|---|---|---|---|---|---|---|
| | 6.2 | 23.7 | 29.3 | 21.5 | 5.5 | -1.8 |
| | 4.7 | 20.0 | 23.1 | 22.0 | 3.1 | 2.1 |
| | 4.5 | 20.3 | 23.9 | 21.1 | 3.6 | 0.9 |
| | 5.7 | 21.7 | 25.3 | 19.5 | 3.6 | -2.2 |
| | 5.3 | 21.2 | 24.9 | 21.0 | 3.7 | -0.2 |
| | 5.3 | 21.2 | 24.6 | 19.7 | 3.3 | -1.5 |
| | 5.0 | 20.9 | 24.9 | 21.7 | 4.0 | 0.8 |
| | 4.4 | 20.4 | 23.6 | 21.3 | 3.2 | 0.8 |
| | 5.7 | 22.7 | 26.9 | 20.3 | 4.2 | -2.4 |
| | 4.8 | 20.2 | 23.5 | 20.2 | 3.3 | 0.1 |
| | 4.4 | 20.1 | 23.6 | 20.4 | 3.5 | 0.3 |
| | 5.8 | 22.6 | 27.3 | 20.3 | 4.7 | -2.3 |
| | 6.3 | 23.9 | 29.3 | 21.6 | 5.4 | -2.3 |
| | 5.4 | 23.5 | 27.0 | 20.7 | 3.4 | -2.8 |
| | 4.1 | 18.3 | 21.6 | 21.5 | 3.4 | 3.2 |
| | 5.2 | 22.3 | 26.4 | 21.6 | 4.1 | -0.7 |
| | 5.5 | 21.2 | 25.5 | 19.5 | 4.3 | -1.7 |
| | 5.1 | 21.1 | 24.3 | 22.3 | 3.2 | 1.3 |
| | 5.6 | 21.9 | 25.3 | 21.2 | 3.4 | -0.6 |
| | 4.6 | 21.5 | 25.3 | 20.1 | 3.8 | -1.5 |
| | 5.4 | 21.0 | 24.8 | 19.4 | 3.8 | -1.6 |
| | 5.6 | 21.4 | 25.0 | 20.1 | 3.6 | -1.3 |
| | 4.5 | 19.8 | 23.3 | 21.7 | 3.5 | 1.9 |
| | 5.6 | 21.9 | 26.8 | 21.1 | 4.8 | -0.9 |
| | 5.2 | 22.3 | 27.3 | 21.9 | 4.9 | -0.5 |
| | 4.9 | 21.6 | 25.2 | 21.7 | 3.6 | 0.1 |
| | 5.5 | 21.0 | 24.4 | 20.2 | 3.4 | -0.8 |
| | 5.6 | 20.9 | 24.9 | 20.8 | 4.0 | -0.1 |
| | 4.6 | 19.9 | 23.0 | 21.4 | 3.2 | 1.5 |
| | 5.7 | 22.5 | 26.2 | 20.9 | 3.8 | -1.6 |
| | 5.2 | 21.4 | 25.9 | 20.8 | 4.4 | -0.7 |
| | 6.1 | 23.0 | 27.2 | 20.7 | 4.2 | -2.3 |
| | 4.7 | 20.0 | 23.6 | 21.7 | 3.5 | 1.7 |
| | 5.2 | 22.5 | 27.2 | 19.9 | 4.7 | -2.7 |
| | 5.3 | 22.6 | 26.9 | 20.9 | 4.3 | -1.6 |
| | 4.7 | 20.8 | 24.0 | 21.6 | 3.1 | 0.8 |
| | 5.3 | 21.3 | 24.7 | 21.6 | 3.4 | 0.4 |
| | 5.3 | 22.5 | 26.3 | 20.8 | 3.8 | -1.7 |
| | 4.6 | 20.3 | 24.5 | 21.8 | 4.2 | 1.5 |
| | 5.5 | 21.7 | 26.4 | 23.0 | 4.7 | 1.2 |
| | 5.7 | 22.7 | 26.6 | 21.2 | 3.9 | -1.5 |
| | 5.3 | 21.5 | 25.5 | 19.6 | 4.1 | -1.8 |
| | 5.1 | 21.2 | 25.2 | 19.7 | 4.0 | -1.5 |
| | 5.5 | 22.7 | 27.2 | 20.1 | 4.5 | -2.6 |
| | 4.5 | 19.8 | 23.3 | 20.9 | 3.4 | 1.1 |
| | 5.5 | 22.1 | 25.7 | 21.9 | 3.6 | -0.2 |
| | 5.7 | 22.1 | 26.9 | 21.8 | 4.7 | -0.3 |
| | 5.0 | 21.7 | 27.3 | 20.8 | 5.6 | -0.9 |
| | 5.0 | 21.5 | 24.8 | 22.2 | 3.3 | 0.7 |
| | 5.3 | 20.6 | 24.9 | 20.1 | 4.3 | -0.6 |
| | 5.0 | 20.9 | 24.3 | 20.5 | 3.4 | -0.4 |
| | 5.3 | 21.8 | 25.1 | 20.0 | 3.3 | -1.9 |
| | 4.8 | 21.5 | 25.7 | 20.6 | 4.2 | -0.9 |
| | 5.0 | 20.6 | 23.9 | 20.4 | 3.3 | -0.2 |
| | 5.3 | 21.2 | 24.9 | 22.4 | 3.8 | 1.2 |
| | 5.5 | 22.1 | 26.3 | 21.4 | 4.1 | -0.7 |
| | 5.5 | 21.1 | 24.1 | 20.3 | 3.0 | -0.7 |
| | 4.4 | 20.4 | 24.7 | 20.9 | 4.3 | 0.4 |
| | 5.1 | 21.5 | 25.0 | 19.7 | 3.5 | -1.8 |
| | 5.9 | 23.7 | 29.0 | 20.8 | 5.2 | -3.0 |
| | 5.4 | 21.9 | 26.0 | 20.4 | 4.1 | -1.5 |
| | 4.7 | 21.7 | 25.7 | 22.0 | 4.0 | 0.3 |
| | 5.0 | 19.8 | 23.2 | 19.9 | 3.4 | 0.1 |
| | 4.7 | 20.5 | 24.8 | 20.2 | 4.3 | -0.3 |
| | 4.7 | 20.5 | 24.4 | 20.7 | 3.9 | 0.2 |
| | 6.0 | 23.2 | 27.7 | 20.9 | 4.5 | -2.3 |
| | 5.4 | 21.9 | 25.4 | 20.1 | 3.5 | -1.8 |
| | 5.4 | 22.2 | 26.4 | 21.0 | 4.2 | -1.3 |
| | 5.6 | 21.1 | 24.2 | 20.3 | 3.1 | -0.8 |
| | 4.8 | 21.1 | 24.3 | 21.8 | 3.2 | 0.8 |
| | 5.0 | 20.9 | 25.2 | 21.3 | 4.3 | 0.5 |
| | 5.0 | 22.0 | 26.1 | 21.8 | 4.1 | -0.2 |
| | 4.6 | 19.2 | 22.4 | 21.2 | 3.2 | 2.0 |
| | 5.4 | 22.6 | 26.7 | 20.3 | 4.1 | -2.3 |
| | 4.2 | 18.5 | 21.5 | 21.1 | 3.0 | 2.5 |
| | 5.0 | 22.5 | 26.6 | 20.8 | 4.1 | -1.7 |
| | 6.2 | 22.2 | 26.0 | 20.2 | 3.8 | -1.9 |
| | 5.4 | 21.6 | 24.9 | 20.2 | 3.3 | -1.4 |
| | 4.5 | 21.3 | 24.6 | 20.8 | 3.3 | -0.5 |
| | 4.8 | 20.7 | 25.1 | 21.3 | 4.3 | 0.6 |
| | 6.3 | 24.4 | 30.0 | 21.5 | 5.7 | -2.9 |
| | 5.5 | 22.6 | 27.0 | 21.5 | 4.4 | -1.1 |
| | 4.9 | 21.4 | 26.6 | 21.7 | 5.2 | 0.3 |
| | 4.6 | 20.0 | 23.7 | 19.8 | 3.7 | -0.2 |
| | 5.7 | 21.5 | 24.9 | 20.9 | 3.4 | -0.5 |
| | 5.2 | 21.9 | 26.2 | 21.7 | 4.2 | -0.2 |
| | 5.8 | 21.5 | 24.7 | 20.6 | 3.2 | -0.9 |
| | 4.7 | 20.9 | 25.0 | 20.6 | 4.1 | -0.4 |
| | 5.2 | 21.7 | 25.4 | 19.8 | 3.7 | -1.9 |
| | 5.1 | 21.6 | 25.0 | 21.1 | 3.4 | -0.6 |
| | | | | | | |
| Avg. | 5.2 | 21.5 | 25.4 | 20.9 | 3.9 | -0.6 |
| Std.Dev. | 0.5 | 1.1 | 1.6 | 0.8 | 0.6 | 1.3 |
| Min. | 4.1 | 18.3 | 21.5 | 19.4 | 3.0 | -3.0 |
| Max. | 6.3 | 24.4 | 30.0 | 23.0 | 5.7 | 3.2 |

# 6 Practical Issues and Example

On an individual piece basis, use of resistance wood moisture meters when over 25% MC should be considered qualitative with expected accuracy from 3 to 10% with actual moisture of more than 35%. Below the 15 to 18% MC range, where moisture gradients will not be as steep and will be less variable, meter accuracy in predicting actual %MC is much closer to 1%. However, this research determined that less than 2% error was obtainable with sets of 10 kiln-dried split red oak cordwood pieces in the 17% to 25% MC range (even with normal and not specifically predictable shell to core and end to center moisture gradients) by averaging the four values obtained from shell and core parallel to grain readings about one inch from the end and the specimen center. Partially predrilling the holes to about 75% of depth prior to core moisture determination was found to be simple, fast, and significantly prolonged moisture meter pin life with almost no pin breakage.

With regard to developing fuel for testing of advanced cordwood hydronic heaters, data show that the moisture meter can be used to predict actual wood %MC to within ± 2% when checking and averaging each of 10 individual pieces. By using the method of preboring the holes for core %MC, each of the 10 pieces for a test run could be characterized for weight and %MC in less than 30 minutes. A suggested method (Butcher 2013) of averaging oven drying wafers from one-quarter, center and three-quarter zones appears to generally over predict actual %MC and seems less accurate on a 10 specimen basis than the meter. This seems likely due to an over influence of core moisture. Another problematic aspect of this method is that it sacrifices the piece and assumes other pieces in a pile are comparable, which might be quite incorrect.

Another very important and practical issue for wood fuel is that kiln drying to the desired %MC can at the same time also heat-treat the material (Xiping et al. 2011). Wood that has not been heat-treated is typically restricted from being moved greater than 50 miles from its source, which means sourcing of fuel material, especially of particular dimensions, species, and %MC could be difficult.

Knowledge of the uncertainty of fuel energy value due to %MC difference between predicted and actual values is a primary benefit of the results of this research. For example, red oak is typically considered to have 8,700 Btu per dry pound (Ince 1979, Maker 2004). If true moisture of a piece is 20%MC, the energy value for red oak is reduced to 6,960 Btu per pound. If, however, a moisture meter is used to predict the moisture as 20% and the actual is 22% MC, the true energy value would then be 6,786 Btu per pound. If the actual moisture content is 18%, then the true energy value would be 7,134 Btu per pound. These values indicate that with a dynamic accuracy of ±2% at 20% target moisture content, true energy content of split red oak cordwood may vary from predicted by ±2.5%.

# 7 U.S. EPA New Source Performance Standards

On February 3, 2014 the U.S. Environmental Protection Agency (EPA; EPA 2014) issued proposed New Source Performance Standards (NSPS) which, among other items, address standards for the performance of new residential wood and hydronic heaters. Three issues relevant to this research are proposals to tighten specifications on wood test fuel moisture content (page 6342, 5.), to use a specific procedure for moisture measurement (page 6343, 9.) and that use of kiln dried wood is not allowed (page 6397, 12.2).

The proposed tightening of allowable wood moisture content is from a range of 19% to 25%, to 22.5% ±1%. Although it is perhaps desirable to have such a specifically precise and accurate prediction of wood fuel %MC, this research has demonstrated that achieving this is not only practically difficult but scientifically impossible. For example, a 22.5% wood moisture level requires extended equilibration to relative humidity conditions of 95% RH (Table 1.) These conditions are too humid for meaningful drying to occur, and will also very likely result in growth of mold and related fungal microorganisms (Simpson 1988). The drying research on split red oak cordwood carried out during this work has shown that drying will not occur without surface moisture content conditions below 15% EMC, corresponding to approximately 70% RH. This characteristic will result in split cordwood having, by necessity, moisture gradients where end and surface faces are drier than core regions. So when an individual piece might be 22.5% MC, its shell could be 15%MC while its core is 35%MC. Knowing that the moisture was 22.5% within ±1.0%MC is virtually impossible to achieve, whether by actual determination via oven drying or prediction using a moisture meter. To illustrate with example from this research project work, from 24 pieces of wood that were specifically prepared by careful and controlled drying to target moisture level of between 19% and 25% (Table 7.) the average was close to 20% actual predicted moisture while individual values ranged from 10% to more than 30%.

On page 6343, section 9, of the NSPS, a procedure for predicting split cordwood moisture using a wood moisture meter has been proposed that requires averaging at least five separate moisture readings. Insulated pin electrodes are to be used with the pins parallel to the grain and with penetration into the wood of one-quarter of the thickness or three quarters of an inch, whichever is less. Three of the measurements came, one each, from each of three sides of a fuel wood piece, with one each about 3 inches from each end and one from the center. Two additional measurements are to come at approximately one-third the thickness and were made centered between the other three locations. This methodology might reasonably be expected to predict wood moisture content in split cordwood pieces that had very uniformly distributed and even moisture with a very minimal moisture gradient.

Unfortunately, because drying a piece of split red oak (or for that matter, any other hardwood or softwood species) cordwood to a target near 20%, 22.5% or a 19% to 25%MC range average moisture level requires that the shell be much drier, while the core is still wet. The resulting natural moisture gradient, due to actual piece size, geometry, grain orientation, presence of bark, and anatomical structure can be quite unpredictable, especially with split cordwood because primary direction for moisture movement is likely longitudinal, parallel to the grain, from the piece ends. This is in specific contrast to rectangular shaped slender lumber, where drying is primarily from surfaces, not ends. So while inserting insulated pins into a board about one-quarter of the thickness has been found to accurately predict moisture in boards, which have a two-dimensional (core to shell) moisture gradient, it will not work well in split cordwood because that has three-dimensional moisture gradients (core to shell, and end to center to end). Of particular importance and interest is that our work during this research has found good moisture predictability that is able to account for the three-dimensional moisture gradient in split cordwood by averaging four values, shell and core measurement from the center of a piece and shell and core measurement from an end. Accuracy has been shown to be quite good, within 1% to 2% MC, especially when averaging sets of several pieces that would typically be included in a fuel charge.

This research project work has also found that the alternative proposal that BNL developed, where sample wafer slices are cut, and then oven dried from the center (middle) and one- quarter and three-quarter zones along the length of a piece of split cordwood, was not especially accurate (Table 6). Though its results were more precise than measurement with a moisture meter, with a standard deviation of 0.6 instead of 1.3, the method tended to over predict true moisture by about 4%. This method also kills a specimen for actual test burning and assumes that other pieces will have comparable moisture, which due to many unknown variables can actually have a high degree of uncertainty. Interestingly, a subsequent review of data available from this work has shown much greater accuracy can be achieved with this wafer method if just two sample wafers are taken: one from the center and one from the end.

The NSPS also notes that kiln-dried material should not be used. In practice, this restriction is quite problematic for no discernable reason. This project work has demonstrated that controlled drying in a lumber kiln can bring moisture content to desired levels in a period of just several days, which greatly facilitates production of consistent and uniform wood fuel for both test and general consumer heating purposes. Also, phytopathology regulatory restrictions on movement of cordwood will require heat treatment, which for practical purposes might as well continue drying.

# 8 Proposed Method to Determine %MC of Split Cordwood Using a Resistance-Based Wood Moisture Meter

## 8.1 Current Method 28 WHH

6.7 Wood Moisture Meter – Calibrated electrical resistance meter capable of measuring test fuel moisture to within 1% moisture content. Must meet the calibration requirements specified in 10.4

12.2 Fuel ………………… The use of kiln dried fuel is not allowed.

12.2.1 Using a fuel moisture meter as specified in 6.7 of the test method, determine the fuel moisture for each test fuel piece used for the test fuel load by averaging at least five fuel moisture meter readings measured parallel to the wood grain. Penetration of the moisture meter insulated electrodes for all readings shall be ¼ the thickness of the fuel piece or 19 mm (3/4 in.), whichever is lesser. One measurement from each of three sides shall be made at approximately 3 inches from each end and the center. Two additional measurements shall be made centered between the other three locations. Each individual moisture content reading shall be in the range of 18 to 28% on a dry basis. The average moisture content of each piece of test fuel shall be in the range of 19 to 25%. It is not required to measure the moisture content of the spacers. Moisture shall not be added to previously dried fuel pieces except by storage under high humidity conditions and temperature up to 100°F. Fuel moisture shall be measured within four hours of using the fuel for a test.

## 8.2 Proposed Revision for Method WHH

On the basis of the research presented in this report, the authors propose the following revisions.

6.7 Wood Moisture Meter – Calibrated electrical resistance meter capable of measuring test fuel moisture to within 1% moisture content. Must meet the calibration requirements specified in 10.4

12.2 Fuel ………………………….. The use of kiln dried wood is allowed if the wood meets the moisture content requirements of Section 12.2.1

12.2.1 Using a fuel moisture meter as specified in 6.7 of the test method, determine the fuel moisture for each test fuel piece used for the test fuel load by averaging four moisture meter readings measured parallel to the wood grain. The moisture readings will include two core measurements and two shell measurements. One of the core measurements and one of the shell measurements shall be made at the center of the length of each piece. The second core measurement and the second shell measurement shall be made approximately one inch from one end of each piece. Either end may be selected for this measurement. The shell measurements shall be made with a penetration of the moisture meter insulated electrodes of ¼ inch. The core measurements shall be made with a penetration of the moisture meter insulated electrodes to the center of the piece or a distance of 1.125 inch, whichever is less. For the core measurements, a pilot hole, not greater than twice the diameter of the insulated electrode may be drilled to a distance of not greater than ¼ inch less than the target penetration distance. Each individual moisture content reading shall be in the range of 10 to 35%MC on a dry basis. The average moisture content of each piece of test fuel shall be in the range of 19 to 25%. It is not required to measure the moisture content of the spacers. Moisture shall not be added to previously dried fuel pieces except by storage under high humidity conditions and temperature up to 100°F. Fuel moisture shall be measured within four hours of using the fuel for a test.

**Table 7. Red oak split cordwood %MC data and determination using a Delmhorst resistance moisture meter with insulated pins in accordance to the newly proposed methodology.**

Method includes averaging one-quarter-inch deep shell and 1.125 inch deep core readings from end and center of each piece; notes to the left indicate samples with bark, that likely resulted in slower drying and pieces remaining wet, and weights of the 12 pieces selected for a test burn.

| Cordwood Moisture Content Determination | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Test # | | | | Name/s: | | | | | | | | | |
| Date: | | | | Moisture Meter: | | | | | | | | | |
| | Weight | A - end | | B - center | | C - end | | ***Predicted Piece %MC*** | | | | | Weight |
| Piece # | g / lbs | shell | Core | shell | Core | shell | Core | ***A-B*** | ***B-C*** | ***A-B & B-C*** | | | g / lbs |
| 1 | 5.7 | 16 | 33.2 | 31.7 | 45.2 | 12.1 | 27.6 | 27.6 | 29.2 | 28.4 | bark | | |
| 2 | 2.25 | 10.9 | 12.1 | 16.1 | 22.7 | 11.1 | 14.4 | 15.5 | 16.1 | 15.8 | | | 2.25 |
| 3 | 2.5 | 11.9 | 15.2 | 21.5 | 32.1 | 16.7 | 21.9 | 20.2 | 23.1 | 21.6 | | | 2.5 |
| 4 | 5.5 | 12.2 | 15.2 | 13.3 | 32.1 | 12.2 | 20 | 18.2 | 19.4 | 18.8 | | | 5.5 |
| 5 | 9.1 | 15.2 | 26.1 | 19.6 | 38.3 | 16.7 | 22.7 | 23.1 | 24.3 | 23.7 | bark | | 9.1 |
| 6 | 4.1 | 11.9 | 20.2 | 14.1 | 29.7 | 12.2 | 20.1 | 19.0 | 19.0 | 19.0 | | | 4.1 |
| 7 | 7.9 | 14.7 | 35.4 | 21.8 | 42 | 15.3 | 41.1 | 28.5 | 30.1 | 29.3 | | | |
| 8 | 6 | 15.1 | 31.1 | 22.2 | 48.3 | 17.4 | 29.8 | 29.2 | 29.4 | 29.3 | bark | | |
| 9 | 6.4 | 14.1 | 31.7 | 26.2 | 43.5 | 14 | 33.9 | 27.2 | 29.4 | 28.3 | bark | | |
| 10 | 4.2 | 12.2 | 23.4 | 22.2 | 40.7 | 12.7 | 19 | 24.6 | 23.7 | 24.1 | | | 4.2 |
| 11 | 8.2 | 15.3 | 36.3 | 21.5 | 40.5 | 12.3 | 29.5 | 28.4 | 26.0 | 27.2 | | | |
| 12 | 6.4 | 14.3 | 34.2 | 16.8 | 41.8 | 16.8 | 35 | 26.8 | 27.6 | 27.2 | | | |
| 13 | 5.8 | 12.7 | 10.7 | 10.6 | 13.3 | 11.9 | 13.3 | 11.8 | 12.3 | 12.1 | | | |
| 14 | 3.3 | 9.7 | 10 | 9.7 | 10.7 | 9.7 | 10.8 | 10.0 | 10.2 | 10.1 | | | |
| 15 | 4.1 | 10.1 | 10.3 | 10 | 11.6 | 9.7 | 9.7 | 10.5 | 10.3 | 10.4 | | | |
| 16 | 4.9 | 10.1 | 10.6 | 9.2 | 13.6 | 9.6 | 13.2 | 10.9 | 11.4 | 11.1 | | | |
| 17 | 6.1 | 9.7 | 10 | 10.1 | 21.1 | 9.2 | 12.7 | 12.1 | 13.3 | 12.7 | | | |
| 18 | 6.4 | 9.7 | 9.6 | 9.2 | 13.1 | 9.6 | 10.2 | 10.2 | 10.5 | 10.4 | | | |
| 19 | 6.7 | 9.1 | 32.6 | 17.3 | 35.8 | 12.3 | 12.9 | 20.0 | 19.6 | 19.8 | | | 6.7 |
| 20 | 6.2 | 11.7 | 13.4 | 13.6 | 25.1 | 10.6 | 15.2 | 14.9 | 16.1 | 15.5 | | | 6.2 |
| 21 | 3.1 | 15.2 | 29.3 | 10 | 34 | 10.7 | 22 | 20.2 | 19.2 | 19.7 | | | 3.1 |
| 22 | 8.9 | 17.2 | 42.1 | 12 | 45.1 | 11 | 36.3 | 27.3 | 26.1 | 26.7 | | | 8.9 |
| 23 | 5.1 | 10 | 24 | 13.1 | 37.8 | 14.7 | 32.2 | 22.0 | 24.5 | 23.2 | | | 5.1 |
| 24 | 6.6 | 10.9 | 29.6 | 13.1 | 41 | 10.3 | 32.5 | 22.9 | 24.2 | 23.6 | | | 6.6 |
| ***Sum*** | 135.5 | | | | | | ***Average*** | 20.0 | 20.6 | 20.3 | | | 64.3 |

# 9 Conclusions

The statistical analysis of the final verification data set (Tables 4, 5 and 6) suggests that the moisture meter can predict, to a 95% confidence level, actual red oak fuel wood moisture content within a range of about ±1 to 3%.

- When considering the entire data set of Table 4, the predicted moisture content was 17.418%, as compared to the actual of 15.620%, with a 95% confidence that the accuracy of the prediction is between 1.246 and 2.351% of the predicted values.
- When considering only the data in Table 4 with predicted moisture less than 25% and greater than 17%, the predicted moisture content was 20.408%, as compared to the actual of 19.871%. These values indicate a 95% confidence that the accuracy of the prediction is between -0.889 to + 1.964.
- Analysis of predicted %MC data with only 12 specimens is important because that is quite close to what would actually be used during a test operation. However with fewer specimen replicates predicted accuracy is not as good. From the results illustrated in group 3 (4.3) and group 4 (4.4), where 95% confidence intervals of predicted accuracy were between -1.294 and +3.044, and -1.997 and +2.397, respectively, it is suggested that practical predicted accuracy, including that inherent in the meter itself, for determining red oak split fuelwood %MC would be from -2% to +3%.
- Verification of the 50 additional pieces (Table 5) of the proposed method of averaging shell and core moisture value readings from the end and center of test fuel pieces showed good results, with overall averages when including 10 pieces selected from randomized groups (Table 6) typically quite close to actual %MC.

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# Evaluation of Wood Fuel Moisture Measurement Accuracy for Cordwood-Fired Advanced Hydronic Heaters

Final Report
March 2014

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