INTRODUCTION

The control of final moisture content is critical in maximizing the quality of kiln dried lumber and minimizing drying costs. Lumber that is underdried will not meet grade criteria with respect to moisture content and may cause problems in later processing. If lumber is overdried, however, the result will be excessive degrade losses. These losses can equal from $4-$6 per thousand board feet for each one percent reduction in average final moisture content. In order to minimize losses, average final moisture content should be kept as high as possible within limitations dictated by the applicable grading rules and subsequent processing.

In-line moisture meters are integral tools in the control of the final moisture content of kiln dried lumber and in the implementation of redry programs. Their primary function has traditionally been the identification of boards that exceed some maximum acceptable moisture content. When the meter identifies a "wet" board it will either mark the board so that it may be manually pulled or it will activate a drop out to divert the board from the flow of acceptable boards. Boards identified as "wet" are then either returned to the kilns for redrying or down-graded. The identification of "wet" boards allows lumber to be dried to a relatively high average final moisture content without risking that an unacceptable percentage of the boards being sent on for surfacing and shipping exceed an acceptable moisture content. The second function of the in-line meter is that of a data acquisition tool. Models currently available store measurements, and provide the operator with compiled information on the average moisture content and the moisture content distribution. This information is used for monitoring the consistency of the drying process and in determining the effects of process modifications. The data acquisition capability of the in-line moisture meter makes it an integral component in quality control programs.

Limited data is available on the performance of both handheld and in-line moisture meters. Salamon (1971) reported the correlations between reading from resistance and power loss moisture meters and oven dry moisture content. Resistance meter readings were not corrected for species. Ninety-five percent tolerance intervals for the resistance meter were +2.8% for white spruce and +1.5% for lodgepole pine. Corresponding intervals for the power loss meter were +3.1% and +1.7% respectively. The correlations between resistance and power loss meter readings and the oven dry moisture content of kiln dried hemlock dimension lumber was reported by Kozlik (1971). Correlation coefficients
for the resistance and power loss meters were 0.82 and 0.78 respectively. Prediction intervals were not given. A general discussion of proposed performance criteria for in-line moisture meters was given by McLauchlan (1975) along with a general discussion of in-line moisture meter operating principles. While no criteria are suggested for meter accuracy in predicting the moisture content of a single board, it is proposed that an in-line meter should be capable of measuring the average moisture content of a sample within 2%. Beall et al (1983) reported upon the operation and performance of an in-line moisture meter under development. Meter accuracy, based on the correlation between meter readings and moisture content as determined by oven drying, was compared to that for a resistance meter. The standard error for the in-line meter, based on the average reading from 3 sensor heads, was \( \pm 1.3\% \). The corresponding standard error for the resistance meter was \( \pm 2.1\% \) based on a single reading per board and \( \pm 1.0\% \) when based on 12 readings per board.

The overall objective of the study reported upon here was to evaluate the performance of in-line moisture meters relative to that for hand held resistance and power loss moisture meters.

**STUDY OBJECTIVES**

1. Determine the relationship between oven dry moisture content and electric moisture meter readings for hand held and in-line moisture meters.
2. Determine the potential accuracy of in-line moisture meters relative to that of hand held resistance and power loss meters (meter accuracy being defined as the meter's capability to determine "true" moisture content, as determined by oven drying.)
3. Determine the precision of in-line moisture meters relative to that for hand held resistance and power loss meters (precision being defined as the meter's capability to give reproducible readings irrespective of meter accuracy).
4. Determine the capability of in-line moisture meters to sense variability in moisture content across the width of a board and to recognize the presence and extent of wet streaks.

**BACKGROUND - PROBLEMS ASSOCIATED WITH MEASURING MOISTURE CONTENT IN LUMBER**

The potential accuracy of any method for determining moisture content in lumber has inherent limitations. These limitations must be considered in any evaluation of methods and/or instruments for determining moisture content.

1. Within board moisture content variability - moisture content within a board may vary along the length, across the width and through the thickness. Within board variability may be caused by the presence of both heartwood and sapwood within a board, wet pockets and streaks, or moisture gradients that remain after drying. Gradients typical for kiln dried lumber were measured by James et al (1984) and Pfaff et al (1978). James et al (1984) reported moisture content increasing from the surface to the core.
from approximately 9.5% to 14.5% in high temperature dried 2x4 southern pine and from 10% to 28% in white fir dimension. In the same material moisture content varied from the edge to the core from 8% to 12.5% and 10% to 20% respectively. Pfaff et al (1978) reported shell and core moisture contents for kiln dried spruce and pine studs as 13.4% and 22.4% and 12.3% and 20.5% respectively.

2. Measurement sampling method - the measurement of moisture content of a board almost always involves taking sample measurements and from one or more measurements, inferring the board's moisture content. As a result, the potential accuracy of any method used to determine moisture content is affected by the scheme used to sample measurements. As the sampling scheme is changed to sample an increasing amount of the board, the accuracy of the method being used will approach some finite value. The potential accuracy of any method used to determine moisture content is therefore directly affected by the size of the zone sensed by each measurement and the number of measurements taken on each board. To illustrate this, one may compare the resistance moisture meter to an in-line moisture meter. The resistance meter senses a narrow zone approximately an inch long while the in-line meter senses a zone approximately two feet long and several inches wide. It could be expected that a single reading taken with an in-line meter with a single sensor head would be more accurate than one taken with a resistance meter assuming that both were to have equal sensitivity to moisture. This effect is suggested by data reported by Beall et al (1978). In an evaluation of one type of in-line meter, three resistance meter readings averaged together were required to achieve accuracy equal to that for an in-line meter with a single sensor head. It was further shown that the resistance meter's standard error in predicting the oven dry moisture content of a board decreased from approximately 2.1% to 1.0% as the number of readings taken per board increased from one to twelve.

3. Interpretation of multiple measurements - when more than one moisture content measurement is taken on a board, the most common method of interpreting the multiple measurements is to calculate an average value in which all individual measurements are weighted equally. This method may not be appropriate for all applications, particularly when large within piece variability in moisture content exists. For example, if 4 measurements were taken on a 16 foot long board and the presence of a relatively small localized wet pocket caused one reading to be high, the average reading could be affected enough to cause the board to be rejected even though the moisture content of most of the board was well within acceptable limits. In situations such as the one just described, interpreting multiple measurements using some type of statistical algorithm may be preferable to calculating a simple average. The use of a statistical algorithm for interpreting multiple measurements for an in-line meter was reported by Beall et al (1983). In some applications the average meter reading may be of less concern than are the extreme readings which may indicate conditions that will cause problems in later processing or when lumber is put in service. An example would be that of lumber to be used for glulam production. Any zone of high moisture content will cause failures in gluing. Identifying the
presence of such zones is of primary concern. The average moisture content of lumber for this product, though still important is of secondary concern.

4. Depth of measurement - electric moisture meters' sensitivity to moisture in a board changes with the distance from the board's surface at which the moisture is located. In the case of the resistance meter, the depth of the meter's sensitivity is dependent on the depth to which pins are driven. The depth of sensitivity for the power loss meters cannot be readily controlled. It has been shown that these meters are predominantly sensitive to moisture located near the lumber surface (Mackay, 1976). The effect of depth on the sensitivity of in-line meters has not been established.

5. Effect of density - the two electrical properties of wood that are detected by lumber moisture meters are resistance and capacitance. Meters that measure predominantly capacitance, sense absolute moisture content or weight water per unit volume of wood. The accepted definition for lumber moisture content, however, is the ratio of the weight of water in a piece of wood to the wood's oven dry weight. Assuming that moisture content (oven dry basis) is kept constant an increase or decrease in wood density will cause a corresponding increase or decrease in electrical capacitance and a corresponding increase or decrease in the reading of capacitance based moisture meters. Resistance is not greatly affected by density.

6. Calibration accuracy - the actual accuracy of a given moisture meter is dependent on the meter being properly calibrated for the species being measured and temperature. Proper calibration requires that lumber with which the moisture meter is calibrated is representative of that upon which the meter will be used and that once the meter is calibrated, its calibration will not drift over time.

EQUIPMENT AND MATERIALS

The moisture meters evaluated in this study were a hand held resistance meter, a hand held power loss meter, a low frequency in-line meter and a high frequency in-line meter. The low frequency meter used two frequencies, 312.5 Hz and 10 kHz, while the high frequency meter operated at a single frequency. Both in-line meters were tested with single heads only.

A system was constructed in which an expanded Rockwell AIM-65 microcomputer was used to accept measurements from the in-line meters while it concurrently operated a stepping motor driven laboratory scale dry chain that transported boards over the in-line meters' sensor heads. The system is schematically

1 The low frequency in-line meter was supplied by Weyerhaeuser Co., Tacoma, Washington and was essentially identical to that reported upon by Beall et al (1983). A commercialized version utilizing the same technology is currently available from Strandberg Engineering Laboratories, Greensboro, North Carolina. The high frequency in-line meter was a commercially available analog model manufactured by Wagner Electronics Products, Inc., Rogue River, Oregon.
illustrated in Figure 1. The high frequency meter was modified by the manufacturer so that its readings could be read by the computer as a 0-8 volt analog signal. The signal was processed by the computer through a 10-bit analog to digital converter. The low frequency meter was configured so that the actual meter reading was sent to the computer as a two-digit number via a serial interface. The dry chain handled boards four feet in length and was five feet long. During operation the chain, under computer control, accelerated a board up to a speed of 80 feet per minute and then carried the board over both sensor heads at that speed. From the point at which the leading edge of the board met the leading edge of a sensor head until the trailing edge of the board passed the trailing edge of the sensor head a reading was taken from the appropriate meter each .240 inches of board travel. Readings were stored for later analysis.

The lumber used in this study was 2x8 kiln dried white fir [Abies concolor (Gord. and Glend.) Lindl.]. It was used for several reasons. First, due to the presence of wet streaks and wet pockets, determining moisture content for white fir is more difficult than for many other species. As a result, moisture meter performance using white fir would represent one of the worst cases with respect to moisture meter accuracy and precision. Second, due to the wide variability in the drying time required for white fir boards and the resulting wide variability in final moisture content, white fir is a species with which redry programs, of which in-line meters are an integral part, may be beneficial. Lastly, it was felt that testing moisture meters on kiln dried rather than conditioned lumber would yield test results similar to those expected in the field.

PROCEDURE

The material used in this study was obtained green at a saw mill and kiln dried in a laboratory kiln using a relatively mild commercial schedule. The scheme used to process that material is illustrated in Figure 2. It was designed to generate a population of four foot long boards with a wide distribution of final moisture contents. The moisture contents of the four foot boards were evaluated by the hand held moisture meters, the in-line moisture meters and by oven drying. The procedure used for evaluating the moisture content of each board is as follows:

1. An average resistance meter reading was determined based on 3 individual measurements. One half inch long uninsulated pins were used.
2. An average power loss meter reading was determined based on three individual measurements.
3. A set of readings was taken as the board was carried by the dry chain over the low frequency in-line meter sensor and in turn the high frequency meter sensor. One reading was taken each .240 inches of board travel.
4. To test the precision of each meter, steps 1-3 repeated three times on one third of the
boards. The time between repeat measurements varied from 4 to 24 hours.

5. In order to quantify across the board moisture content variability, resistance meter readings were taken at one inch intervals across the width of half of the boards.

6. Three six inch long sections were cut from each board for oven drying. It should be noted that the hand meter readings were taken centered at zones from which oven drying samples were cut and that the oven drying samples were cut from that section of the board that traveled directly over the in-line meters' sensor heads.

The presence of values which represent full scale readings for the respective meters dictated one limitation with respect to analysis of the data. Full scale moisture content readings for the resistance, power loss, low frequency in-line and high frequency in-line meters were 30%, 22%, 25% and 30.7% respectively. Although the resistance meter's scale reads up to 80%, reading above 30% may be highly inaccurate. As a result, readings above 30% were considered full scale readings. Readings that were full scale were viewed as invalid with respect to the data analysis. If any of the three readings taken on a board with a hand meter was full scale, an average meter reading for that meter and board could not be calculated.

As already noted, with each board a set of readings was taken from each in-line meter as the board was carried over the respective sensor head. From this set of readings the actual reading for a given board was determined. Generally, an in-line meter will recognize the peak reading taken as a board passes over one of its sensor heads as the reading for that board. In this study the actual measurement associated with each board and in-line meter was determined two ways. First, the peak reading was determined. Second, the reading taken when the board was physically centered over the sensor head was used.

In determining the centered reading for the low frequency meter only, seven consecutive readings consisting of the true centered reading and three readings taken before it and three readings taken after it, were averaged. The seven readings represent readings taken over one and one half inch of board travel. The reason for not selecting only the true centered reading as the centered reading was that the resolution of the low frequency meter was limited by the configuration of the meter's internal software to provided readings to the nearest percent moisture content. The error imposed by this limitation would be most pronounced when the meter readings was fluctuating between two whole numbers. The intent in averaging seven consecutive readings was to minimize the error that would be caused by such fluctuations. It should be pointed out that readings were generally stable or fluctuating within a 1% range as the board approached and passed the centered position.

The correlations between oven dry moisture content and in-line meter readings were determined using in-line meter readings as determined by each of the two methods, i.e. peak reading and centered reading. The high frequency meter showed
slightly better correlation when the peak reading was used, therefore the results reported here are based on using the peak reading as the actual reading from the high frequency meter. With the low frequency meter slightly better correlation was obtained using the readings taken with the board centered over the sensor head. Therefore, results reported here with respect to the low frequency meter are based on using the centered reading as the actual reading.

RESULTS AND DISCUSSION

In-line Meter Response Wet Streaks

Figure 3 illustrates the response of each of the in-line meters to a board with relatively uniform moisture content across the width. The meter readings plotted are those taken as the board is passed over the sensor head. "Relative position" refers to the board position relative to that where the leading edge of the board meets the leading edge of the sensor head. Resistance meter readings taken at one inch intervals across the width are also shown. The plot shows that as the board enters the field of the sensor head the meter reading begins to rise to some maximum reading and then drops off.

The response of the in-line meters to a board with nonuniform width wise moisture content is shown in Figure 4. The high moisture content on one edge suggest the presence of a wet zone or streak. This asymmetrical moisture content distribution is seen by the in-line meter since the peak reading occurs sooner than it would with a board with uniform across the width moisture content. While it appears that a nonuniform moisture content distribution as caused by a wet streak may be identifiable when the total response of the meter is analyzed, it is doubtful that the meter could be used to clearly define the size and severity of any given wet streak.

Further investigation of the effect of wet streaks and pockets on the performance of in-line meters are planned and will be reported upon in a later paper.

Meter Accuracy

The accuracy of a given moisture meter is dependent on it being properly calibrated. It was not the intent of this study to directly address the problem of properly calibrating lumber moisture meters. As a result, no extensive effort was made to accurately calibrate the meters specifically for the material being evaluated. The power loss and high frequency in-line methods were used with the calibrations supplied by the manufacturers for white fir. The resistance and low frequency in-line meters were calibrated for Douglas-fir only. For all meters it was assumed that the potential accuracy of a meter would be indicated by the degree of correlation between meter readings and "true" moisture content as determined by oven drying. If a good correlation existed, true accuracy should be attainable by adjusting the gain and offset of each meter.

Linear regressions of moisture meter readings versus oven dry moisture content and for in-line meter readings versus resistance meter readings were calculated. Meter readings are plotted
against oven dry moisture content in Figures 5 through 8 for the resistance, power loss, low frequency in-line and high frequency in-line meters respectively.

Regression coefficients, correlation coefficients and 95% prediction intervals are summarized for all regressions in Table 1. It should be noted that the 95% prediction intervals have been adjusted to apply to a regression of unity slope. This is necessary since the standard error, and therefore the prediction interval, will depend on a meter's gain setting. When the gain is changed during calibration, the standard error will change. The correlation coefficient, however, is independent of meter gain. In the regression analyses, only boards for which all four meters gave valid readings, i.e. less than full scale, were included. The rationale being that all meters should be evaluated using the same set of boards. This limited the range of oven dry moisture contents over which the meters could be evaluated to 8 through 21%.

The prediction intervals indicate that the in-line meters had better accuracy with respect to predicting oven dry moisture content than did the hand held meters. The high frequency meter was able to predict, with 95% confidence, the oven dry moisture content of a board within 2.9% moisture content while the low frequency meter was able to predict it within 3.3% moisture content. This indicates that both in-line meters are equally viable instruments for monitoring the final moisture content of dried lumber as far as accuracy is concerned. There is a significant difference however in the correlations between in-line meter readings and those of the resistance meter. The low frequency in-line meter readings showed a much higher degree of correlation with the resistance meter readings than did those from the high frequency meter. This may be of importance in considering meter calibration procedures.

Meter Precision

The variability between repeat determinations of mean moisture content for sets of boards with nominal average moisture contents for the set of 20%, 15% and 10% are given in Table 2. The hand meters showed greater variability between repeat runs than did the in-line meters. Unfortunately, since boards with resistance meter readings over 30% moisture content are excluded, the effect of wet pockets and streaks on resistance meter readings is not fully reflected in the data presented. Inconsistently high resistance meter readings, which were most likely due to wet pockets or streaks, were common. The in-line meters' coefficients of variation between repeat determinations of mean moisture content in all cases of less than 1%. The maximum coefficient of variation between the three repeat in-line meter determinations for any single board was 4.9% and considerably less than that in most cases.

It should be emphasized that results reported here were obtained under laboratory conditions. Factors that were not addressed in this study and that may have significant effects on meter performance under mill conditions include the following:

1. Effect of surface moisture
2. Effect of moisture content gradients through the thickness.
3. Effect of varying ambient and lumber temperature
4. Effect of transfer chain speed
5. Effect of board width
6. Effect of varying board thickness
7. Effect of electrical coupling between lumber and transfer chains.

CONCLUSIONS

1. In-line moisture meters have greater potential accuracy with respect to predicting oven dry moisture content for kiln dried lumber than do resistance and power loss type hand meters.
2. Under laboratory conditions in-line moisture meters can predict oven dry moisture content with ±3.3% or better with 95% confidence.
3. In-line moisture meters gave reproducible measurements. Coefficients of variation between repeat determinations of the average moisture content of a set of boards was less than 1%, and less than 4.9% for repeat determinations on any single board.
4. It appears that the in-line moisture meters used in this study cannot readily be used to identify the presence and extent of wet streaks.

Accuracy and precision values reported here suggest that for most applications in-line meters are viable tools for the monitoring of moisture content in kiln dried lumber. The degree of viability of the meters for any specific application, however, will depend on the intended end use of the lumber. While with prediction intervals at the 95% confidence level of ±2.9% to ±3.3% in-line meters cannot be said to be highly accurate, their accuracy exceeds that for resistance and power loss hand held meters. This suggests that with respect to accuracy, in-line meters perform equal to or better than other methods available for monitoring moisture content in commercially kiln dried lumber.

REFERENCES


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<th>a</th>
<th>b</th>
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<th>Prediction Intervals²/</th>
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<td>Resistance³/</td>
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<td>.645</td>
<td>±3.96</td>
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1/Regression for each meter are based on the same set of boards; number of boards = 211.

2/Corrected to apply to regression with unity slope.


4/Reading for power loss, and high frequency meters corrected for species.
### TABLE 2. VARIATION IN AVERAGE MOISTURE CONTENT BETWEEN 3 REPEAT RUNS

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<th>Resistance</th>
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<td><strong>20% MC LEVEL</strong></td>
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<td>$\bar{X} = 17.8$</td>
<td>$\bar{X} = 14.2$</td>
<td>$\bar{X} = 16.8$</td>
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<td>$CV = 1.4%$</td>
<td>$CV = 0.6%$</td>
<td>$CV = 0.3%$</td>
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<td><strong>10% MC LEVEL</strong></td>
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Figure 1. Configuration of In-Line Moisture Meter System
Figure 2. Processing Steps For Generating Population of 4 Foot Kiln Dried Boards

- Sampling of 96 pieces 2" x 8" x 16' (green)
- End seal both ends of each piece
- Kiln dry lumber to approximately 20% average moisture content
- Cut 4 feet off from the end of each 16' long piece
- End seal remaining 12 foot long piece at the saw cut
- Return 12 foot pieces to kiln and dry to 15% average moisture content
- Cut 4 feet off from the end of each 12' long piece
- End seal remaining 8 foot long pieces at the saw cut
- Return 8 foot pieces to kiln and dry to 10% average moisture content
- Cut 4 feet off from the end of each 8' long piece

Evaluate moisture content of 4' long piece
RESISTANCE METER READINGS TAKEN AT 1" INTERVALS

Figure 3. In-Line Meter Response to a Board With Uniform Moisture Content Across the Width

RESISTANCE METER READINGS TAKEN AT 1" INTERVALS

Figure 4. In-Line meter Response to a Board with Non-Uniform Moisture Content Across the Width
Figure 5. Resistance Meter vs. Oven Dry

Figure 6. Power Loss Meter vs. Oven Dry
Figure 7. Low Frequency In-Line Meter vs. Ivey vs. Oven Dry

Figure 8. High Frequency In-Line Meter vs. Oven Dry vs. Oven Dry