

The Design and Development of a Low Cost Wood Moisture Sensor

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Stove Efficiency Testing

- Water boiling test
- Effective calorific value of the fuel varies with moisture content (MC)

$$C_{eff} = \frac{LHV - m * (80 * 4.186 + 2260)}{M}$$



Wood Moisture Content - Defined

- The amount of water moisture present
- Expressed as a percentage
- Wet or dry basis

$$m = \frac{(mass_{wet}) - (mass_{dry})}{mass_{wet}} * 100$$

$$m = \frac{(mass_{wet}) - (mass_{dry})}{mass_{dry}} * 100$$



Methods of Determining MC

- Oven-dry (ASTM D4442)
- Capacitance methods
- Resistance methods



<http://www.extechstore.com/ProductImages/407777.jpg>



Oven-dry Method - Limitations

- Weighing a sample before and after drying
- Directly calculates MC
- Destructive test
- Impractical for field use
- Can require more than 24 hours



Commercially available MC meters

- Most are expensive (\$300)
- Display MC directly (for a specific species)
- MC for other species by using a conversion table
- Most do not include temperature compensation



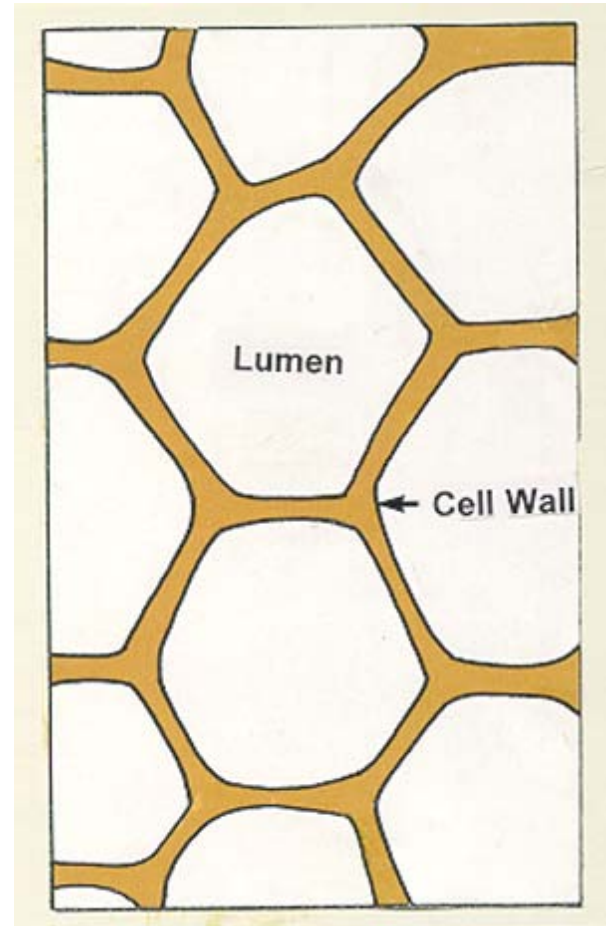
<http://www.extechstore.com/ProductImages/407777.jpg>



Resistance MC Meters – How they work

Wood Biology

- Bound / free water
- Stored in cell wall or cell cavities (lumens)
- Fiber saturation point (fsp)
- Absorption / desorption
- Relative humidity
- Governs swelling / shrinking



<http://www.geocities.com/Yosemite/Campground/5660/a1di.jpg>



Resistance MC Meters – How they work

- Electrical resistance varies consistently below the FSP
- Electrical resistance is temperature and species dependant
- Good regression models ($R^2 > 0.9$)

$$\log(\log(R + 1)) = a \times u + b$$

$$u_{corr} = -\frac{0.00147T(\ln(10) + \ln(\exp(au_{meas} \ln(10) + b \ln(10)) + 1) - 1.075 \ln(10))}{\ln(10)(0.000158T + 0.0262)}$$



Species of wood	Moisture content (pcf)																			
	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	
	Resistance (MΩ)																			
Conifers																				
Baldcypress	12,600	3,980	1,410	630	265	120	60	33	18.6	11.2	7.1	4.6	3.09	1.78	1.26	0.91	0.66	0.51	0.42	
Douglas-fir (coast region)	22,400	4,780	1,660	630	265	120	60	33	18.6	11.2	7.1	4.6	3.09	2.14	1.51	1.10	.79	.60	.46	
Fir, California red	31,600	6,760	2,000	725	315	150	83	48	28.8	18.2	11.8	7.6	5.01	3.31	2.29	1.58	1.15	.83	.63	
Fir, white	57,600	15,850	3,980	1,120	415	180	83	46	26.9	16.6	11.0	6.6	4.47	3.02	2.14	1.55	1.12	.86	.62	
Hemlock, eastern	—	120,000	20,000	4,300	1,300	450	200	100	45.0	25.0	14.0	8.8	5.40	3.50	2.30	1.60	1.10	.78	.57	
Hemlock, western	22,900	5,620	2,040	850	400	185	98	51	28.2	16.2	10.0	6.0	3.89	2.52	1.58	1.05	.72	.51	.37	
Larch, western	39,800	11,200	3,980	1,445	560	250	120	63	33.9	19.9	12.3	7.6	5.02	3.39	2.29	1.62	1.20	.87	.66	
Pine, jack	450,000	52,000	9,500	2,800	1,000	440	210	110	60.0	35.0	21.0	13.0	8.80	5.80	3.80	2.60	1.80	1.30	.98	
Pine, longleaf	25,000	8,700	3,160	1,320	575	270	135	74	41.7	24.0	14.4	8.9	5.76	3.72	2.46	1.66	1.15	.79	.60	
Pine, red	700,000	100,000	17,000	4,300	1,300	470	210	100	52.0	28.0	16.0	10.0	6.80	4.40	2.80	1.90	1.20	.91	.67	
Pine, white	20,900	5,620	2,090	850	405	200	102	58	33.1	19.9	12.3	7.9	5.01	3.31	2.19	1.51	1.05	.74	.52	
Pine, ponderosa	39,800	8,910	3,310	1,410	645	300	150	81	44.7	25.1	14.8	9.1	5.62	3.55	2.34	1.62	1.15	.87	.69	
Pine, shortleaf	43,600	11,750	3,720	1,350	560	255	130	69	38.9	22.4	13.8	8.7	5.76	3.80	2.63	1.82	1.29	.93	.66	
Pine, sugar	22,900	5,250	1,660	645	280	140	76	44	25.7	15.9	10.0	6.6	4.36	3.02	2.09	1.48	1.05	.75	.56	
Redwood	22,400	4,680	1,550	615	250	100	45	22	12.6	7.2	4.7	3.2	2.29	1.74	1.32	1.05	.85	.71	.60	
Spruce, black	700,000	90,000	16,000	4,300	1,400	580	250	120	68.0	38.0	23.0	14.0	9.60	6.30	4.30	3.00	2.10	1.40	1.00	
Spruce, Sitka	22,400	5,890	2,140	830	365	165	83	44	25.1	15.5	9.8	6.3	4.27	3.02	2.14	1.58	1.17	.91	.71	
Hardwoods																				
Ash, black	14,000	2,300	600	200	85	40	20	10	6.0	3.4	2.1	1.3	.90	.60	.42	.32	.25	.20	.17	
Ash, white	12,000	2,190	690	250	105	55	28	14	8.3	5.0	3.2	2.0	1.32	.89	.63	.50	.44	.40	.40	
Aspen, bigtooth	300,000	24,000	4,000	1,100	360	150	60	30	16.0	8.6	5.0	3.1	2.00	1.30	.88	.61	.43	.33	.26	
Basswood [†]	36,300	1,740	470	180	85	45	27	16	9.6	6.2	4.1	2.8	1.86	1.32	.93	.69	.51	.39	.31	
Birch [†]	87,000	19,950	4,470	1,290	470	200	96	53	30.2	18.2	11.5	7.6	5.13	3.55	2.51	1.78	1.32	.95	.70	
Birch, paper	200,000	24,000	5,000	1,400	550	230	110	57	30.0	17.0	10.0	6.0	4.00	2.50	1.70	1.10	.81	.59	.43	
Elm, American	18,200	2,000	350	110	45	20	12	7	3.9	2.3	1.5	1.0	.66	.48	.42	.40	.40	.40	.40	
Hickory,	—	31,600	2,190	340	115	50	21	11	6.3	3.7	2.3	1.5	1.00	.71	.52	.44	.40	.40	.40	
Khaya [‡]	44,600	16,200	6,310	2,750	1,260	630	340	180	105.0	60.2	35.5	21.9	14.10	9.33	6.16	4.17	2.82	1.99	1.44	
Magnolia [†]	43,700	12,600	5,010	2,040	910	435	205	105	56.2	29.5	16.2	9.1	5.25	3.09	1.86	1.17	.74	.50	.32	
Mahogany (<i>Swietenia</i>)	20,900	6,760	2,290	870	380	180	85	43	22.4	12.3	7.2	4.4	2.69	1.66	1.07	.72	.49	.35	.26	
Maple, sugar	72,400	13,800	3,160	690	250	105	53	29	16.6	10.2	6.8	4.5	3.16	2.24	1.62	1.23	.98	.75	.60	
Oak, northern red [†]	14,400	4,790	1,590	630	265	125	63	32	18.2	11.3	7.3	4.6	3.02	2.09	1.45	.95	.80	.63	.50	
Oak, white	17,400	3,550	1,100	415	170	80	42	22	12.6	7.2	4.3	2.7	1.70	1.15	.79	.60	.49	.44	.41	
Philippine mahogany (<i>Shorea</i> Spp.)	2,890	690	220	80	35	15	9	5	2.8	1.7	1.1	.7	.45	.30	.21	.16	.12	.09	.07	
Sweetgum	38,000	6,460	2,090	815	345	160	81	45	25.7	15.1	9.3	6.0	3.98	2.63	1.78	1.26	.87	.63	.46	
Tupelo, black [†]	31,700	12,600	5,020	1,820	725	275	120	58	27.6	13.0	6.9	3.7	2.19	1.38	.95	.63	.46	.33	.25	
Walnut, black	51,300	9,770	2,630	890	355	155	78	41	22.4	12.9	7.3	4.9	3.16	2.14	1.48	1.02	.72	.51	.38	
Yellow-poplar [†]	24,000	8,320	3,170	1,260	525	250	140	76	43.7	25.2	14.5	8.7	5.76	3.81	2.64	1.91	1.39	1.10	.85	

[†]Resistance measured in megohms at 80 °F between two pairs of needle electrodes spaced 1-1/4 inches apart and driven to a depth of 5/16 inch. The reciprocals of these data are conductance in micro siemens.

[‡]Exact species unknown.

[§]Known in the trade as "African mahogany."

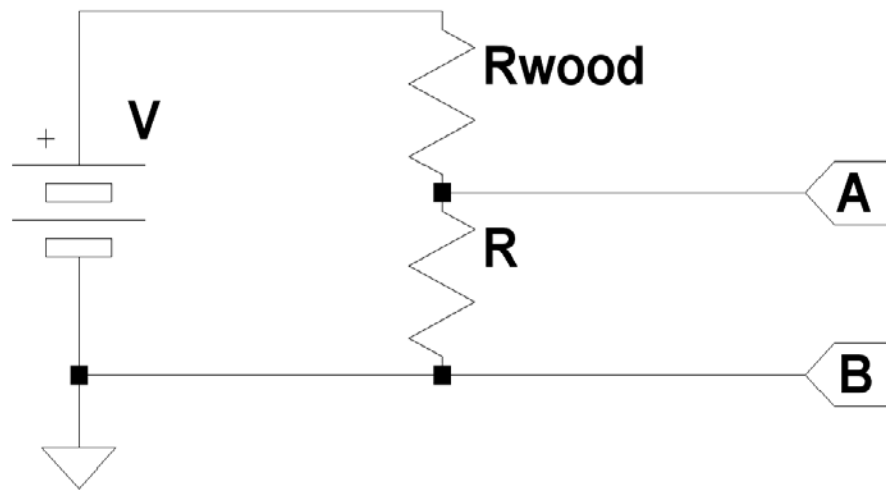
^{††}The values for this species were calculated from measurements on veneer.

James, 1988



Resistance Measurement Techniques

- Differ only from a standard ohmmeter by the large resistance values (700,000 M Ohms)
- Voltage divider circuit and high impedance voltmeter (expensive)



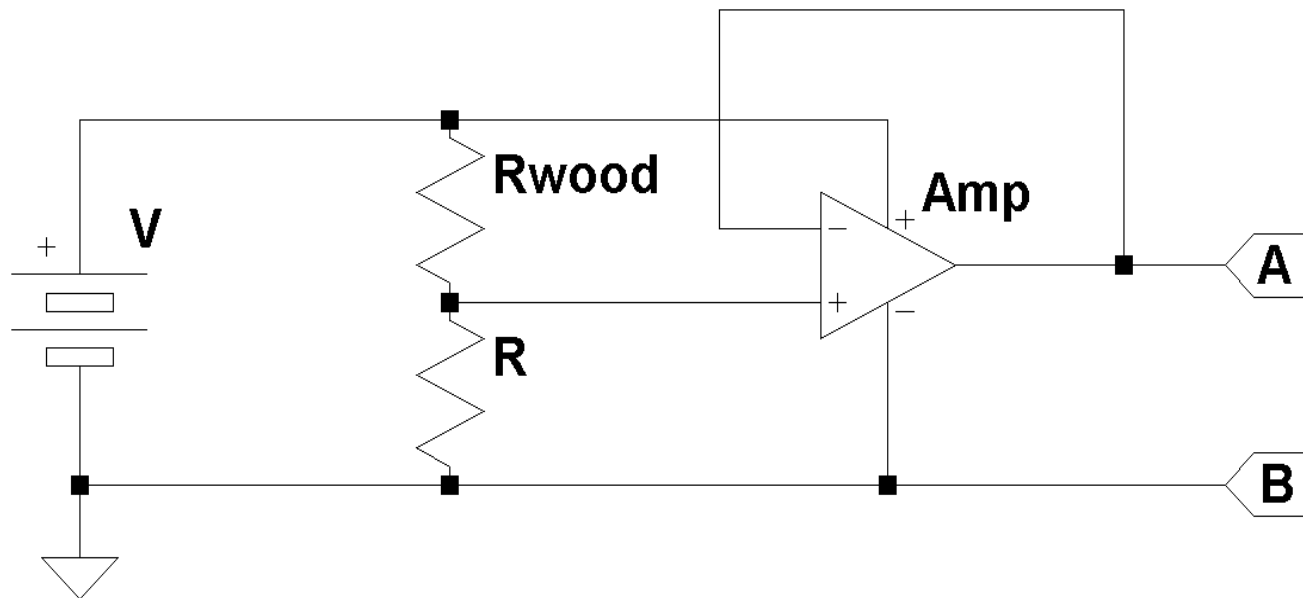
$$V_{ab} = V \times \left(\frac{R}{R + R_{wood}} \right)$$

$$R_{wood} = R \times \left(\frac{V}{V_{ab}} - 1 \right)$$



Buffer Op-amp Solution

- An inexpensive, high impedance op-amp can be added to the circuit, allowing the use of a standard digital multi-meter



Testing Results

- Performed well
- Signs of degradation at 1 T Ohm

Experimental Data														
Test	R_{wood}		Meter Range	R		V	V _{ab} (meas.)	V _{ab} (theo.)	Min V (-tol)	Max V (+tol)	Calculated Resistance (M Ohm)	% Error	Max % Error	Notes
1	5,000	1%	A	5,000	1%	10.06	5.02	5.03	4.98	5.08	5,020	0.40%	2.01%	
2	15,000	1%	A	5,000	1%	10.06	2.50	2.52	2.48	2.55	15,120	0.80%	1.88%	
3	25,000	1%	A	5,000	1%	10.06	1.68	1.68	1.65	1.70	24,940	0.24%	1.94%	
4	35,000	1%	A	5,000	1%	10.06	1.26	1.26	1.24	1.28	34,921	0.23%	1.61%	
5	40,000	1%	A	5,000	1%	10.06	1.12	1.12	1.10	1.14	39,911	0.22%	1.82%	
6	45,000	1%	A	5,000	1%	10.06	1.01	1.01	0.99	1.02	44,802	0.44%	1.80%	
7	1,000,000	10%	A	5,000	1%	10.02	0.07	0.05	0.04	0.06	710,714	28.93%	24.75%	Op-amp performance degrading



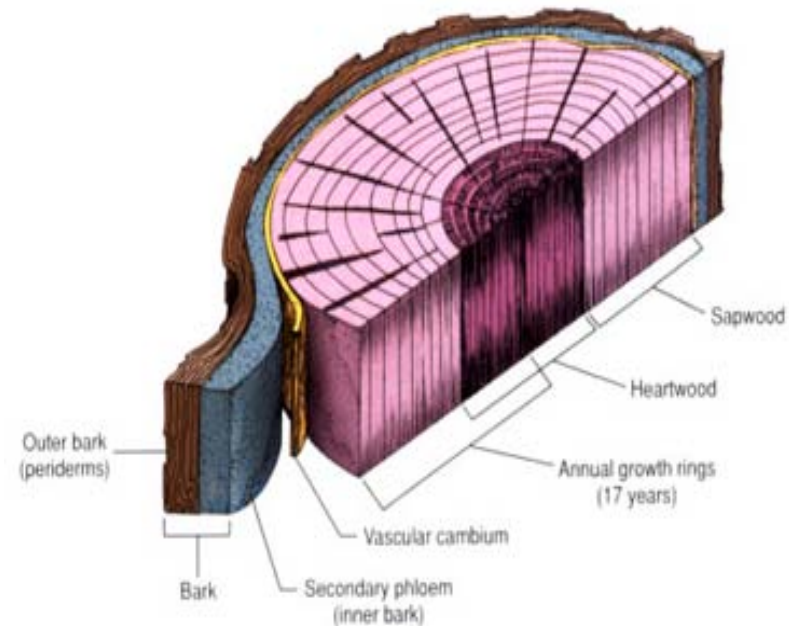
Other Factors – Measurement Location

- MC constantly changing – RH constantly changing
- Average MC at $1/3W$, $1/3L$, $1/3H$
- Insulated electrode shafts required



Other Factors

- Direction – negligible (with the grain)
- Heartwood vs. sapwood – minimal effect
- Electrode size – negligible (nail size)
- Electrode spacing – negligible (1.25”)



<http://www.nrru.ac.th/web/ancient/wood/images/wood05.jpg>



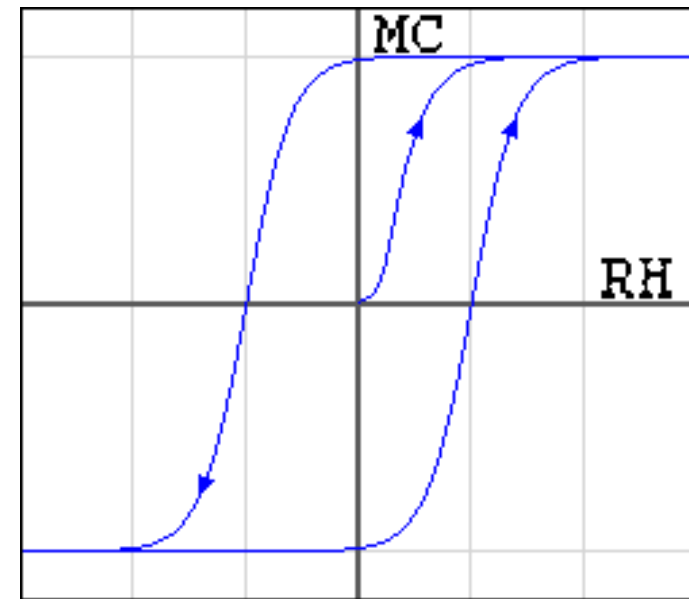
Species Characterization

- United States and European species-resistance values are well known
- Central and South American species-resistance values are not well known
- Characterized by correlating a resistance with a MC



Equilibrium Moisture Content (EMC)

- Samples should be at EMC
- MC at which neither absorption / desorption occurs
- Temperature and RH dependant
- MC depends on direction (absorption / desorption)



<http://en.wikipedia.org/wiki/Image:Hysteresiscurve.png>



Sample Conditioning

- Wood samples conditioned according to ASTM D4933
- Use water-acid or saturated salt aqueous solutions to maintain constant RH
- Endpoint determined by constant mass



Testing Procedure

- Condition samples from the same direction (all undergoing absorption or desorption)
- Measure resistance value parallel to the grain
- Calculate MC based on oven-dry method (ASTM D4442)
- Generate regression constants



Conclusions

- MC significantly affects stove efficiency calculations
- Most commercial MC meters are expensive
- Commercial MC meters require species and temperature corrections
- Inexpensive method developed using a standard multi-meter
- Species testing to be implemented in classroom

