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THE DEVELOPMENT AND TESTING OF THE *WILTRONICS T-H FINE FUEL MOISTURE METER*

Research Report No. 46

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SUMMARY:

The *Wiltronics T-H Fine Fuel Moisture Meter* measures electrical resistance of a fine fuel sample, and converts this to a moisture content. This meter was developed specifically for the measurement of vegetation fuels, as opposed to grains and wood. There are numerous meters and methods available to measure or estimate moisture content, however there are none that are portable, accurate and capable of measuring below 10% and above 50% oven dry weight.

This report describes the *Wiltronics T-H Fine Fuel Moisture Meter*, the procedure for operation of the meter, the testing of the meter, and the calibration procedure. Relationships between fuel moisture content and electrical resistance were established for nine dead surface fuel types. Two linear relationships for each fuel type were found, one for moisture contents less than 9% oven dry weight, and the other for moisture contents between 9 and 200% oven dry weight. Relationships between the conductivity of leachate of the different fuel types and coefficient/intercept values for the fuel moisture content calibration curves were also found. Conductivities of leachate of an additional thirty dead surface fuel types were measured. Using the relationships between the coefficient/intercept values and conductivities of the original nine fuel types, fuel moisture content calibration curves were obtained for the additional fuel types. The effects of temperature and the method of grinding the fuel samples were found not to have a significant effect on the relationship between resistance and moisture content. However the uniformity and fineness of the ground material did influence the amount of variation between individual observations. Field testing was carried out for a limited range of fuel types, and under restricted weather conditions. It was found that observations varied by 1% in the field as long as the average of at least three measurements is taken. The majority of the testing, both in the laboratory and in the field, is limited to dead surface fuels only. However, the *Wiltronics T-H Fine Fuel Moisture Meter* has the potential to measure live fuel moisture contents.

The *Wiltronics T-H Fine Fuel Moisture Meter* is portable, accurate and capable of measuring moisture contents between 3 and 200% oven dry weight for a wide range of fuel types, including live and dead fuels of pine, eucalypts and shrubs.

INTRODUCTION:

The moisture content of forest fuels plays an important role in determining fire behaviour (Dexter and Williams 1976, Viney and Hatton 1989, Viney and Hatton 1990, Eron 1991); with respect to probability of ignition, forward rate of spread, rate of combustion, fire intensity, and success of spotting. Subsequently, fire managers measure or estimate the moisture content of fine fuel, and the majority of fire behaviour models take into account the fuel moisture content or an estimation of it. Fuel moisture content is the weight of moisture, expressed as a percentage, of the oven-dry weight of the fuel. This is referred to as the "dry-weight" moisture content.

Dead fuels can have a range of moisture contents from about 2% oven dry weight to over 200% oven dry weight (Cheney 1981). Moisture contained in fuels has a cooling effect on a fire (Pompe and Vines 1966) by reducing radiative heat transfer (Luke and McArthur 1978) and by absorbing heat through latent heat vaporisation. This has a large impact on fire behaviour (Pompe and Vines 1966), because it encourages partial combustion (which means more energy is used in the process of evaporation rather than radiation). Consequently the heat yield decreases and ignition becomes more difficult. If the moisture content is great enough, it may even extinguish the fire.

Just as fire spread and combustion rates are influenced by surface fine fuel moisture content, flame heights and crownfire formation are also influenced by surface fine fuel moisture content (McArthur 1967), however these two components of fire behaviour are also influenced by elevated fuels and bark fuels. The success of spotting is also determined primarily by the surface fine fuel moisture content. McArthur (1967) states that only large flaming firebrands will be effective in starting new fires if moisture content is above 7% oven dry weight (Luke and McArthur 1978), and very small embers would have little trouble starting a fire if surface fine fuel moisture content was 4% oven dry weight or less.

There are five main fuel types available to a fire in a forest. They include surface and profile fine fuel, elevated fine fuel (both dead and alive), bark fuel and coarse fuels. Fine fuel (any dead plant material less than 6 mm thick and any live material less than 2 mm thick) burns in the flaming zone of a fire front and hence influences a fire's rate of spread and flame height, i.e. it is the primary fire carrier (Blank *et al.* 1985). The profile moisture content of a fuel bed influences the amount of fuel available for burning, and surface fuel moisture affects the rate of heat release. The material at the top of the fuel bed is generally different physically and chemically from the material at the bottom of the fuel bed, thus affecting fuel availability. Elevated fine fuels will increase flame height and fire intensity. Bark fuel is the bark that is held (loosely or tightly) on the trees. Bark of many eucalypt species has the potential "to spot" (send burning bark embers ahead of the main fire front and start another fire). Coarse fuels are those fuels greater than 25 mm thick, in particular branches and boles of fallen trees. These fuels are only important in the mopping up stages, as these fuels can continue to burn well after a control line has been established around a fire.

Currently there are numerous methods for determining fuel moisture content. These include both direct and indirect techniques (some of which can be used in the field) and indirect predictive models. The direct and indirect methods include oven-drying, chemical pressure

chambers, resistance meters, dielectric meters, distillation, titration, hazard sticks and hazard bags. These methods for measuring fuel moisture content reduce the dependence on unreliable weather predictions (Dexter and Williams 1976). The predictive models, on the other hand, rely on empirical observations relating fuel moisture content to environmental variables (Dexter and Williams 1976, Viney and Hatton 1989) and are used as broadscale planning tools. These environmental variables include temperature, relative humidity, wind speed, cloud cover, crown shading, slope, aspect, soil moisture and season or day of the year. (All techniques available for measuring fuel moisture content are reviewed in Appendix 1.)

All techniques currently available to measure moisture content are described in Appendix 1, and summarised in Table 1. Table 1 demonstrates that electrical resistance methods provide the best measurements of moisture content over a wide range of moistures and that these methods are quick, accurate and easily measured in the field. This is due to electrical conductivity being used to create calibration curves relating electrical resistance to fuel moisture contents. There are currently four meters available that use resistance as a measure of moisture content: *Marconi*, *Protimeter*, *Granitec* and *Wiltronic T-H Fine Fuel Moisture* meters.

Fire managers at wildfires or prescribed fires need to be able to measure fuel moisture content quickly and accurately at the site of the fire. There are numerous methods available to measure fuel moisture content in the field, but none simultaneously measure fuel moisture content accurately lower than 9% oven dry weight, have an automatic calibration for different fuel types, have an internal power source, and are portable and field-based.

The aims of this report are to briefly describe the *Wiltronics T-H Fine Fuel Moisture Meter* (hereafter referred to as the *Wiltronics* meter), the testing of the meter with various fuel types at various moisture contents (both inside and outside of the laboratory), the procedure for operation of the meter, and the calibration procedure. Field testing was carried out, however 90% of the measurements were within the range of 9 and 30% oven dry weight. This range was limited due to the weather conditions when testing.

This study has a number of limiting factors, the first being that only dead surface litter was examined. The *Wiltronics* meter has the potential to measure the moisture content of live fuel, and further testing should be aimed in this direction. Secondly, the electrical resistance of a fuel type is determined by both moisture content and chemical composition of the fuel. This study only examines the relationship between resistance and the combined effect of moisture content and chemical composition. While temperature is known to affect the resistance of a material, preliminary investigations found that temperature does not significantly affect the estimated moisture content when moisture contents are less than 60% oven dry weight and when air temperatures range between 0 and 45°C. Previous work also showed that the method of grinding does not significantly affect the average result, but the finer the material is ground, the less variation there is between individual observations.

Table 1. Summary of features and requirements of the direct and indirect methods available to estimate fuel moisture content.

PRINCIPLE	METHOD	Direct estimate	Fine fuels (<6mm thick)	Coarse fuels (>6mm thick)	Fuel ground / prepared	Destructive sampling	Field operational	Manual calibration	External power supply	Chemicals required	Scales required	Data storage	Time delay for setup *	Time delay for sampling *	ODW range
Oven-drying	Conventional oven	✓	✓	✓		✓			✓		✓			✓	0 - ∞%
	Microwave oven	✓	✓	✓		✓			✓		✓			✓	2 - ∞%
	Pressure plates - *Neosystems*	✓	✓				✓		✓				✓		2 - ∞%
Electrical	*Marconi Moisture Meter*		✓		✓	✓	✓	✓							10 - 30%
	Protimeter		✓		✓	✓	✓	✓							12 - 40 %
	Granitec		✓		✓	✓	✓	✓							10 - 30%
	T-H Fine Fuel Moisture Meter		✓		✓	✓	✓					✓			3 - 200 %
	Capacitance Meter		✓	✓			✓	✓							2 - 30 %
	Power-loss Meter		✓	✓			✓	✓							15 - 30 %
	Capacitance Admittance Meter		✓	✓			✓	✓							2 - 30 %
Mechanical	Leaf bending		✓			✓	✓	✓							4 - 20%
Chemical	*Speedy Moisture Meter*	✓	✓		✓	✓	✓	✓		✓	✓		✓		7 - 50 %
	Karl-Fischer titration	✓	✓		✓	✓				✓	✓			✓	0 - ∞%
	Xylene distillation	✓	✓		✓	✓				✓	✓			✓	0 - ∞%
Meteorological	NFDRS		✓	✓			✓	✓				✓	✓		5 - 200%
	KBDI - McArthur			✓			✓	✓				✓	✓		
	RH/Temperature - McArthur		✓				✓	✓				✓			3 - 19%
	Red Book		✓				✓	✓				✓			5 - 200%
Analogues	Hazard sticks			✓	✓		✓				✓		✓	✓	0 - ∞%
	Hazard bags		✓		✓		✓				✓		✓	✓	0 - ∞%
Remote Sensing	Satellite		✓					✓				✓	✓	✓	0 - ∞%
Burning Leaf	Burning Leaf		✓			✓	✓	✓							4 - 20 %

* time delay of greater than 5 minutes

(Refer to Appendix 1 for a written review on all of these methods.)

METHODS:

The *Wiltronics* meter measures electrical resistance of a fine fuel sample, which is determined by the fuel moisture content and chemical composition. This meter is based on the principle of electrical resistance, as are the *Marconi, Protimeter* and *Granitec* moisture meters. Whereas these three meters are not sensitive enough for fire management operations, the *Wiltronics* meter can measure resistance up to 10 teraohms (10×10^{12} ohms), which is equivalent to a fuel moisture content of approximately 3% oven dry weight.

Fuel samples are ground to homogenise the moisture through the sample, and to allow good contact between the electrodes and the fuel. As the moisture content of different parts of leaf can be quite variable, it is necessary to homogenise the sample before measuring. This is done by finely grinding the leaves. The method of grinding does not significantly affect the average result. As each sample only requires about five leaves, this only takes a few seconds, and it allows the fuel good contact with the electrodes. The compression of the fuel sample is important as it eliminates any air which may be moister or drier than the fuel sample and compression ensures that the fuel sample is brought to a uniform state.

Electrical resistance is the opposition to the flow of electric current, measured in ohms (Ω). Resistance is measured as the ratio of the voltage across a component to the resulting current through a component. The ratio is expressed by Ohm's Law

$$V = I*R \qquad (1)$$

where: V = voltage (volts)
I = current (amps)
R = resistance (ohms)

Dry wood acts as an excellent electrical insulator, however moisture within the wood has an inverse effect on the wood's electrical resistance. As moisture content of wood increases, electrical resistance through the wood decreases. Thus there is a direct inverse relationship between moisture content and resistance.

The resistance of most materials is also affected by a change in temperature. There is a linear relationship between temperature and the resistance of most metals (in general) over a broad temperature range. That is, as temperature increases, resistance also increases. This is known as a positive temperature coefficient of resistance. This linear relationship is expressed as Equation 2.

$$R_t = R_o(1 + \alpha t) \qquad (2)$$

where: R_t = resistance at t°K
R_o = resistance at 273°K (0°C)
α = temperature coefficient of resistance
t = temperature, t°K.

Conductance is the reciprocal of resistance $\left(\frac{1}{\text{resistance}}\right)$, and is measured in mhos.

Nine fuel types were collected for the calculation of fuel moisture content calibration curves. Five fuel types were collected in Spring 1995 and the other four fuel types were collected in Autumn 1996. The fuel types were: *Eucalyptus obliqua* (brown litter[1]), *E.obliqua* (two week old green slash), *E.obliqua* (two year old brown slash), *E.sieberi* (grey fragmented litter), Gippsland coastal mixed species (grey fragmented litter), *E.sideroxylon* (brown litter), *E.microcarpa* (grey litter), *Pinus radiata* (brown litter) and *Acacia pycnantha* (brown litter). Gippsland coastal mixed species and *E.sieberi* fuel types were both collected in East Gippsland, whilst all other fuel types were collected at Creswick, Clunes or Barkstead (in west/central Victoria). The fine fuel was finely ground using a grinder developed from the *Mouli Parsmint* cutter. Various amounts of distilled water were added to the fuel samples to increase their moisture content. Samples were then allowed to sit in open aluminium trays, and reach a uniform moisture content before being tested for resistance and fuel moisture content.

Resistance of each sample was measured using the *Wiltronics* meter. Each sample was analysed two or three times, and 20-30 g of the sample placed in an oven so that the actual oven dry weight moisture content could be calculated. All species were tested over a broad range of moisture contents (2-300% oven dry weight). In the preliminary studies (prior to 1995), it was found that the cell temperature had a significant effect on the resistance of a sample at a given moisture content. Knowing this, and the relationship between resistance and temperature (Equation 2), cell and air temperature were both recorded when each sample was measured for resistance.

E.delegatensis (from NE Victoria) was also tested, however only enough leaf material for three samples was provided, and thus three data points did not provide sufficient data to analyse and produce a moisture content calibration curve.

For each fuel type the moisture content (oven dry weight) and the reciprocal logarithm ($\log_{10}$) of the resistance (as measured by the *Wiltronics* meter) were plotted. From these graphs,

[1] Each fuel type was classified according to the stage of leaf decay (i.e. the amount of leaching that had occurred). Green slash having only recently been felled, with leaves still green in colour, but not alive. This material will have experienced little or no rain. Brown slash having been felled in the previous four months, but leaves are still retained on the branches or heads of the trees, and not having experienced heavy rainfalls. Brown litter is surface litter that is brown in colour, but little decomposing has occurred. Grey litter is surface litter that has been leached to a pale brown or fawn colour, but the leaves are still intact. Grey fragmented litter is surface litter that is in an advanced state of decay; and is in small fragments.

linear regression was used to obtain calibration curves for each fuel type. The best fit was found to be between the $\log_{10}$ of moisture content and the reciprocal $\log_{10}$ of resistance. The nine calibration curves were then plotted with moisture content (log scale) against the reciprocal $\log_{10}$ of resistance. Linear regression techniques were also used to examine the relationship between air temperature and resistance.

Conductivity tests were run on each of the nine fuel samples, and the relationship between conductivity and the calibration curve equation coefficients and intercepts were also studied.

The leaf samples were finely ground, as was done when measuring resistances. Seven grams of the ground fuel was mixed with 70 ml of distilled water, and shaken vigorously on a mechanical shaker (at approximately 180 rpm) for a total of five minutes[2]. The solution was then filtered using hardened ashless #541 filter paper, and the filtrate analysed. The conductivity meter used was a *Radiometer Type CDM2d Conductivity Meter.* Each fuel type was sampled twice, and the average conductivity calculated. For each fuel type, the average conductivities were plotted according to species and stage of leaf decay.

The relationships between conductivities and fuel moisture content calibration curve coefficients, and conductivities and fuel moisture content calibration curve intercepts were analysed for the nine fuel types that were originally examined. Using these four relationships (each relationship for 0-9% oven dry weight and 9-200% oven dry weight), equations were formed so that the intercepts and coefficient values could be calculated from the average conductivity measurement. These relationships allowed easy determination of the fuel moisture content calibration curves for the other fuel types.

The conductivity of filtrate from 39 fuel types, in addition to the nine fuel types tested for resistance, were measured. These fuel types varied in species, location of collection and stage of leaf decay (i.e. green slash, brown slash, brown surface litter, grey surface litter and grey fragmented litter). These 39 fuel types were tested in 1993 and/or 1996. Majority of fuel samples tested in 1993 were retested in 1996. Table 2 shows a summary of the fuel types tested.

A sensitivity analysis was carried out on the relationship between conductivity and the indicated moisture contents. The conductivities of the fuel types tested ranged between 90 to 138 μmhos, so the range of conductivity examined was from 100 to 140 μmhos, and resistances between 5×10^2 and 5×10^{12} Ω. The difference in moisture content for a 10% and 20% change in conductivity was examined for each resistance. A sensitivity analysis was also carried out on the conductivity ranges of each of the fourteen fuel groups and the indicated moisture contents. The difference in moisture content from the extreme conductivities and the mean conductivity for each fuel group was examined.

When testing the prototype meter in 1993, the method of grinding was examined to determine if the method had a significant effect on the relationship between resistance and moisture content. Two types of grinders were tested: the *Rishworth* hand grinder and the *Mouli Parsmint* cutter. Fuel material was prepared using both methods, and then allowed to reach

[2] In 1993, testing showed that there was no significant increase in the conductivity of the filtrate if the solution was shaken for more than five minutes.

the required temperature and moisture content. The relationships between moisture content and resistance for each grinder were compared.

Table 2. Summary of the 48 fuel types used to determine electrical conductivity properties and to develop calibration curves relating resistance to moisture content.

	FUEL TYPE				
SPECIES	Green slash	Brown slash	Brown surface litter	Grey surface litter	Grey fragmented litter
Eucalypts :					
E.accidens					✓
E.baxteri				✓	
E.consideniana				✓	
E.cypellocarpa				✓	
E.delegatensis				✓	
E.diversicolor				✓	
E.fastigata				✓	
E.globoidea				✓	
E.leucoxylon			✓		
E.microcarpa				✓	
E.obliqua	✓	✓	✓	✓	✓
E.pilularis				✓	
E.polyanthemos			✓	✓	
E.radiata			✓	✓	
E.regnans				✓	
E.rubida			✓	✓	
E.sideroxylon			✓	✓	
E.sieberi			✓	✓	✓
Gippsland Coastal Mixed Spp.					✓
Grey Box Mixed Spp.				✓	
N.S.W. Gum Mixed Spp.				✓	
N.S.W. Box Mixed Spp.				✓	
Other species :					
Acacia pycnantha			✓		
Banksia grandis			✓		
Pinus radiata			✓		
Pinus pinaster			✓		

The relationship between temperature and resistance was examined, to determine whether temperature still had a significant effect on resistance, and to then incorporate temperature into the calibration equations. As both cell and air temperature were found not to have a significant effect on resistance, neither were included in the calibration equations.

As well as extensive testing in the laboratory, the *Wiltronics* meter was tested in the field. Moisture contents of various species and fuel ages were measured using the *Wiltronics* meter,

and samples taken back to the laboratory for oven-drying. The oven dry weight moisture content and the moisture content measured by the *Wiltronics* meter were compared. The results from these field tests are also presented in this report.

RESULTS:

Resistance :-

Appendix 2 contains the raw data of the resistances measured and the observed moisture contents (oven dry weight) for the ten original fuel types. When moisture content (on a $\log_{10}$ scale) is plotted against the reciprocal $\log_{10}$ of resistance, all fuel types showed a similar pattern (see Figure 1). There was a steep linear relationship between moisture content and resistance for moisture contents between 0 and 9% oven dry weight, and a gentler sloped linear relationship for moisture contents greater than 9% oven dry weight.

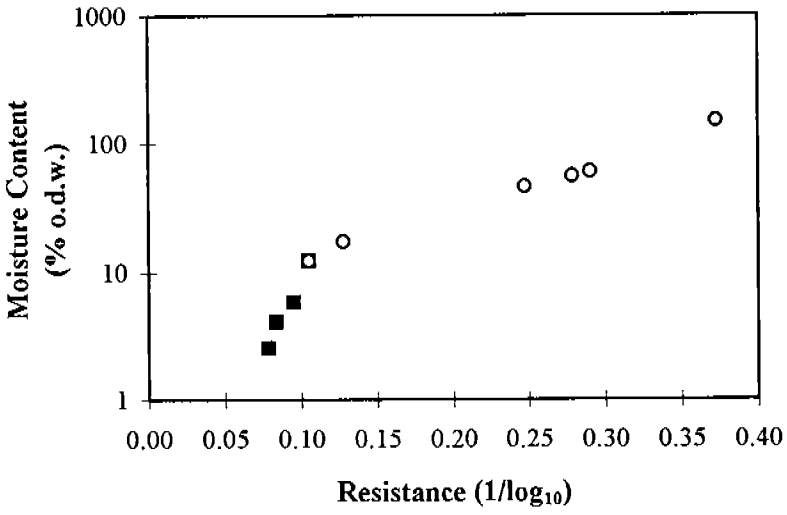


Figure 1. The typical linear pattern shown by all species tested for fuel moisture content. The observed data points for *Acacia pycnantha* are shown by ■ for data points less than 9% oven dry weight, and by O for data points greater than 9% oven dry weight.

Due to this pattern, the data for each fuel type were analysed in two data series; those with moisture contents below 9% oven dry weight and those above 9% oven dry weight; and the moisture content that was closest to 9% oven dry weight was analysed in both data series. Consequently two linear equations (both based on Equation 3) were found to give better predictions of moisture content for each of the nine fuel types, than a single curvilinear equation.

$$\log_{10}(mc) = \frac{a}{\log_{10}(R)} + b \qquad (3)$$

where: mc = fine fuel moisture content (%)
R = resistance (ohms)
a = coefficient
b = intercept

The coefficient (a) and intercept (b) values for the these nine fuel types can be found in Table 3. The *Wiltronics meter* is programmed to use the calibration equation for 0-9% oven dry weight first, and if this produces a moisture content greater than 9% oven dry weight, then the meter automatically uses the calibration equation for 9-200% oven dry weight.

Table 3. Coefficient and intercept values for the fuel moisture content calibration curves for the nine species tested for fuel moisture content using Equation 3.

Species	Moisture content range (% odw)	Coefficient (a)	Intercept (b)	r^2	Sample size (n)
Eucalyptus obliqua -brown	0-9	65.75336	-4.7219	0.60	6
	9-200	5.3497	0.4908	0.98	13
Eucalyptus obliqua - brown slash	0-9	32.86962	-2.27663	0.86	4
	9-200	4.827026	0.563378	0.98	17
Eucalyptus obliqua - green	0-9	28.83226	-1.90826	0.89	8
	9-200	3.805443	0.63083	0.95	17
Eucalyptus sieberi	0-9	30.40978	-1.97226	0.80	8
	9-200	5.5293	0.4089	0.98	14
Eucalyptus sideroxylon	0-9	32.91722	-2.2532	0.76	8
	9-200	4.396289	0.596167	0.93	20
Eucalyptus microcarpa	0-9	25.27472	-1.52153	0.93	4
	9-200	4.656125	0.58727	0.97	6
Coastal Mixed Spp.	0-9	85.39928	-6.47819	0.67	6
	9-200	5.5245	0.4022	0.97	14
Pinus radiata	0-9	132.5022	-9.3518	0.76	10
	9-200	5.6389	0.4527	0.93	14
Acacia pycnantha	0-9	23.28527	-1.38776	0.95	9
	9-200	3.821527	0.709392	0.99	14

Although conductivities of each species showed that there were differences between species and stage of leaf decay, the calibration curves for the nine fuel types are not distinct from each other (see Figure 2).

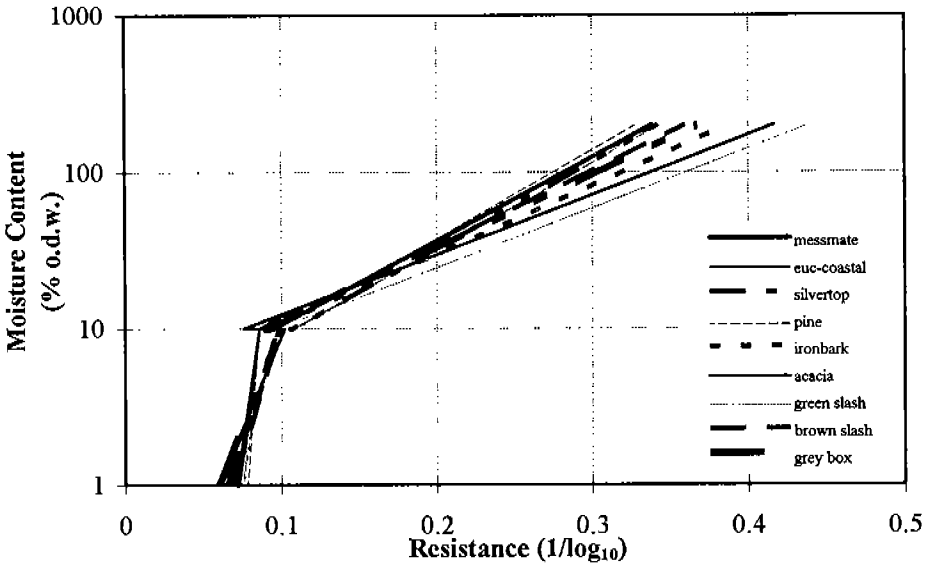


Figure 2. Calibration curves for the nine fuel types. These curves are based on the values shown in Table 2.

Using the resistance (calculated from the inverse of the conductivities shown in Appendix 3), it was found that the resistance of *E.sieberi* is 0.7 times the resistance of *E.obliqua*. Resistance of other eucalypt species range from 0.4 to 2.2 times the resistance of *E.obliqua*, indicating that *E.obliqua* is about the median of the range of all eucalypts measured. *A.pycnantha* had a resistance of less than one third of the resistance of *E.obliqua*, and *P.radiata* had a resistance of 1.8 times that of *E.obliqua*. This variation indicates that there is an inherent difference in the resistance of species, regardless of moisture content.

Similar variation can be seen when comparing the effect stage of leaf decay has on resistance. The resistance of green slash was one fifth of the resistance of brown litter, whereas the resistance of brown slash was almost 0.9 of the resistance of brown litter. Grey litter has a resistance of 1.5 that of brown litter, and grey fragmented litter had a resistance of 2.1 times that of brown litter. This could indicate that the nutrient content of the fuel is an important factor when measuring resistance. That is, the mineral 'salt' content of the litter could affect the moisture content determination.

The time of collection (i.e. season) of leaves related quite well to the stage of leaf decay. One hundred per cent of fuel types categorised as brown surface litter were collected in Autumn (March through to May), whilst 66% the grey surface litter were collected in Spring (September through to November). This relates to the amount of leaching that has occurred since leaf fall. Attiwill *et al.* (1978) reported that in Victoria, 75% of litter fall occurs during summer (December to February), implying that litter collected in Summer and Autumn has

only recently fallen to the ground, thus leaching and decomposition of the leaves has only just begun, whereas the litter collected in Spring has been more leached due to the winter rainfall.

In 1993 when the prototype of the meter was being tested, the method of grinding was examined to determine if the method had an effect on the relationship between resistance and moisture content. It was found that for samples having moisture contents between 13.1 and 23.1% oven dry weight, the method of grinding did not have a significant effect on the relationship. However the method of grinding influenced the amount of variation between individual observations.

Both cell temperature and air temperature were recorded when measuring resistance of the fuel samples. Preliminary results showed that the inclusion of either cell temperature or air temperature in the log-log relationship between moisture content and resistance accounted for 1-2% of the variation in the indicated moisture content in the range of 5 to 40% oven dry weight. However subsequent tests over a much wider range of moisture contents (2 to 300% oven dry weight), showed that temperature did not make a significant difference on the log-log relationship between fuel moisture content and resistance. Given that the resistance is proportional to the temperature (in °K), the difference in resistance between 0°C (273°K) and 40°C (313°K) is only 14.7%, which in Equation 3 is less than 0.1% moisture content for moisture contents less than 9% oven dry weight and less than 1% moisture content for moisture contents up to 60% oven dry weight. Therefore the importance of temperature in the preliminary results was an artefact of the data collection where low moisture contents were only recorded at high temperatures. Temperature does not significantly affect the indicated moisture content for readings less than 60% oven dry weight.

Conductivity:-

The conductivities for each fuel type tested in 1993 and 1996 are shown in Appendix 3. The average conductivity for each fuel type was calculated and plotted. The fuel types were then grouped into 14 groups on the basis of their conductivities, and were described according to bark types (i.e. stringybark, gum bark, box bark, ash bark, etc.) and the three stages of leaf decay (green, brown and grey). The fuel type groupings (Figure 3) show the differences in conductivities between species and stage of leaf decay.

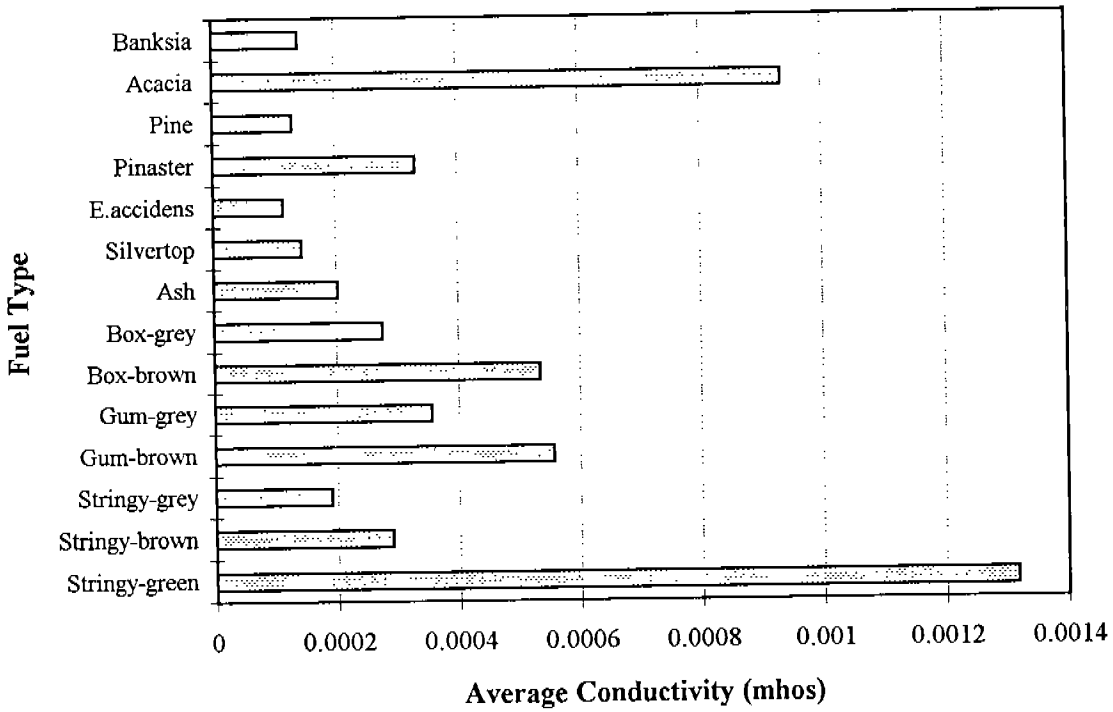


Figure 3. Conductivities of the 14 fuel type groupings determined by species and stage of leaf decay.

With the nine fuel types used to construct the calibration curves, the coefficients and intercept values of the fuel moisture content calibration curves and the relevant conductivities were analysed. For all the variables, except the intercept values from the 9-200% fuel moisture content calibration curves, the relationships between the coefficient or intercept values and conductivities showed a logistic relationship. The relationship between the intercept value from the 9-200% fuel moisture content calibration curve showed an exponential association. These equations are expressed as Equations 4-7, and Figure 4 shows these four relationships respectively.

$$\text{Coefficient}(0-9\%\ \text{fmc}) = \frac{20.901726}{(1 - 1.0922295 \times e^{(-2853.4098 \times c)})} \quad (4)$$

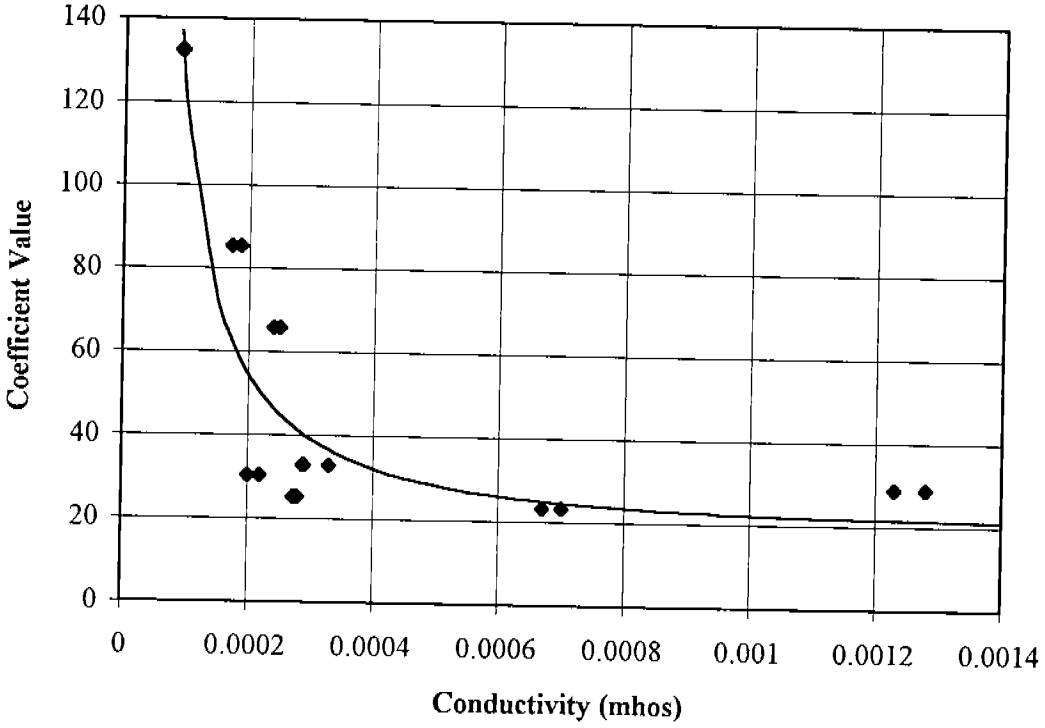
$$\text{Coefficient}(9-200\%\ \text{fmc}) = \frac{3.5099961}{(1 - 0.47862763 \times e^{(-1922.6661 \times c)})} \quad (5)$$

$$\text{Intercept}\ (0-9\%\ \text{fmc}) = \frac{-0.0045805621}{(1 - 1.0001241 \times e^{(-6.229308 \times c)})} \quad (6)$$

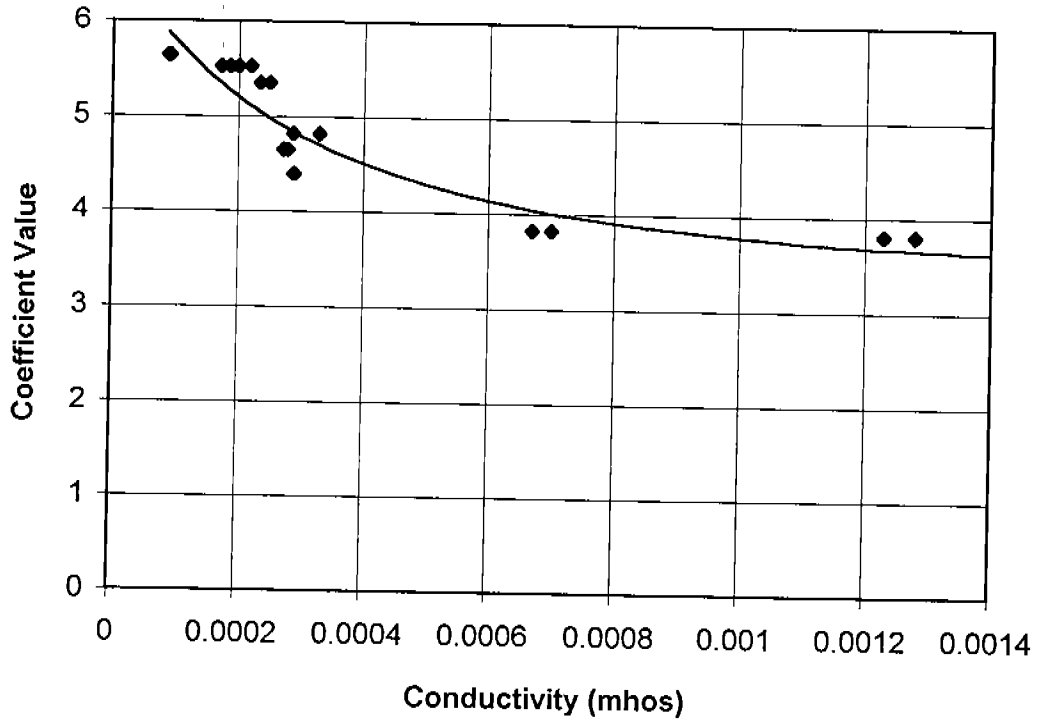
$$\text{Intercept}\ (9-200\%\ \text{fmc}) = 0.0481 \times (1.67 - e^{(-3757.3757 \times c)}) \quad (7)$$

where: c = conductivity (mhos)

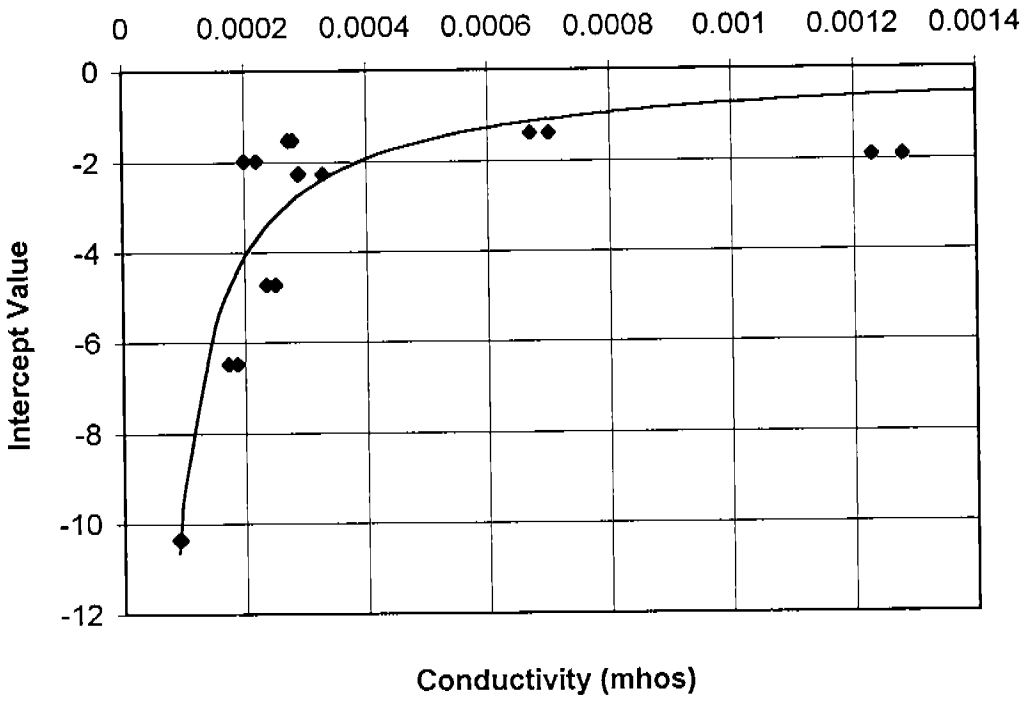
(a) coefficient value for 0-9% oven dry weight



(b) coefficient value for 9-200% oven dry weight



(c) intercept value for 0-9% oven dry weight



(d) intercept value for 9-200% oven dry weight

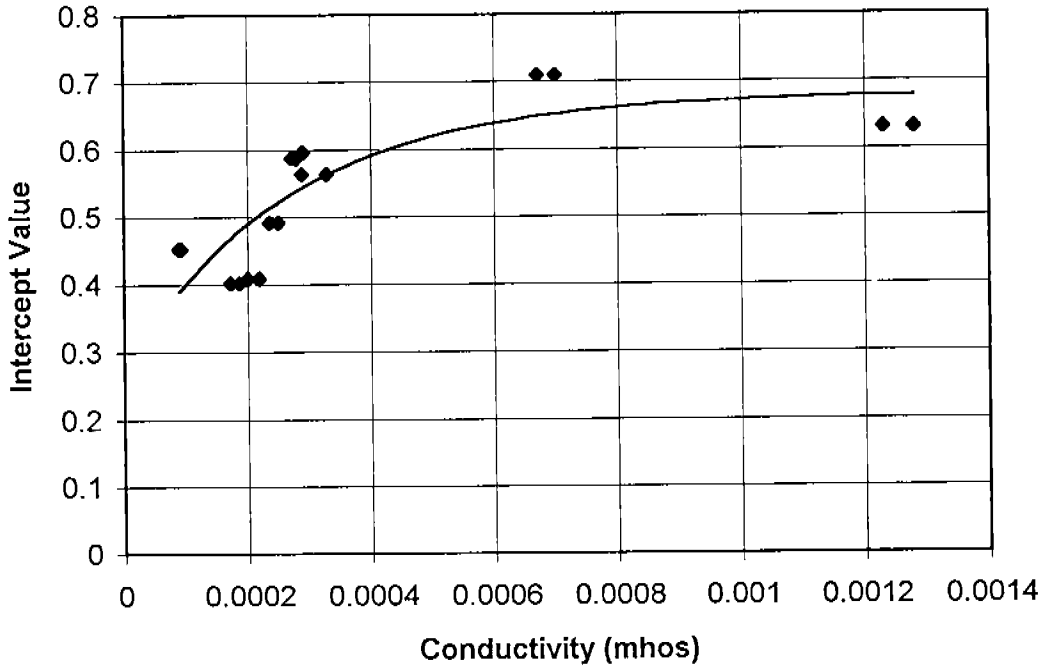


Figure 4. The relationships between the coefficient and intercept values for each moisture content range and the conductivities for the original nine fuel types examined. The observed data points are marked individually by ♦, and the predicted models are shown by a line (—).

With these four relationships, calibration curves were calculated for each fuel type, and for each fuel type group. (The coefficient and intercept values for each fuel group can be found in Appendix 4.) These calibration curves are now available to be used on the *Wiltronics* meter.

The results from the sensitivity analysis carried out on conductivity and the indicated moisture content are summarised in Table 3 (a and b). For moisture contents of less than 40% oven dry weight, less than 0.5% error in moisture content was found with a 20% change in conductivity when conductivities ranged between 100 and 250 µmhos, and between 850 and 1400 µmhos. When conductivities ranged between 250 and 850 µmhos, there was less than 0.5% error in moisture content for a 10% change in conductivity. For moisture contents ranging between 0 and 9% oven dry weight, less than 1.0% error in moisture content can be expected for a 20% change in conductivity. For all moisture contents below 200% oven dry weight, less than 10% error in moisture content can be expected with a 10% change in conductivity.

Table 3. Results of sensitivity analysis on conductivity and indicated moisture content. Conductivity ranges are shown in µmhos for the change in per cent in conductivity.

(a) with a change by 20% in conductivity.

Moisture content range (%)	**Maximum potential error in moisture content**				
	0.5%	**1.0%**	**2.0%**	**5.0%**	**10%**
0 -9	100 - 250 850 - 1400	250 - 450	450 - 850	-	-
9 - 20	100 - 1400	-	-	-	-
20 - 40	-	950 - 1400	150 - 950	-	-
40 - 80	-	100 - 150	-	-	-
80 - 200	-	-	-	1250 - 1400	800 - 1250

(b) with a change by 10% in conductivity.

Moisture content range (%)	**Maximum potential error in moisture content**				
	0.5%	**1.0%**	**2.0%**	**5.0%**	**10%**
0 -9	100 - 450 800 - 1400	450 - 800 -	800	-	-
9 - 20	100 - 1400	-	-	-	-
20 - 40	250 - 300 1000 - 1400	150 - 250 300 - 1000	-	-	-
40 - 80	100 - 150	150 - 180	-	-	-
80 - 200	-	-	-	850 - 1400	350 - 850

The results of the sensitivity analysis on the conductivity ranges of the fourteen fuel groups and the indicated moisture contents are shown in Appendix 5. The conductivity ranges for some of the fuel groups are quite large, ranging between 50 and 165% of the mean conductivity. Those fuel groups that had a range of ±10% of the mean conductivity (i.e. gum - brown) were found to have less than ±0.5% error in the indicated moisture content for moisture contents less than 40% oven dry weight, and less than ±10.0% error in the indicated moisture content for moisture contents between 100 and 200% oven dry weight. For fuel groups with a range of ±20% of the mean conductivity (i.e. *E.accidens*) were found to have less than ±0.5% error in the indicated moisture content for moisture contents less than 20% oven dry weight, and less than ±2.0% error in the indicated moisture content for moisture contents between 20 and 40% oven dry weight.

Field Testing :

The *Wiltronics* meter was tested in the field as well as in the laboratory. The results from these tests are shown in Table 4. Most of the tests in the field were done on an ad-hoc basis, in that testing of the meter occurred in a very limited range of environmental conditions and with a limited variety of fuel types. By referring to Table 4, most measurements are between 9 and 30% oven dry weight. Little testing was done in the extreme moisture contents (i.e. less than 9% and greater than 30% oven dry weight). Replications of samples were taken for the meter, but in most cases only one sample was measured for the oven dry weight reading.

Table 4. Results of casual field testing of the *Wiltronics T-H Fine Fuel Moisture Meter*, showing measured moisture content and the oven dry weight moisture content.

Location	Fuel type	Meter moisture content (A) (avg%, n, SE)	Oven dry weight moisture content (B) (avg%, n, SE)	Difference (B-A)
Creswick	*Eucalyptus obliqua*	10.7 (25, 0.22)	12.3 (2, 0.25)	1.6
Creswick	*Pinus radiata*	11.2 (23, 0.13)	14.2 (2, 0.55)	3.0
Daylesford	*E.obliqua*-brown slash	13.4 (6, 0.83)	14.9 (2, 2.00)	1.5
Daylesford	*E.obliqua*-brown slash	11.9 (6, 0.18)	13.3 (2, 1.55)	1.4
Daylesford	*E.obliqua*-brown slash	12.5 (3, 0.15)	12.9 (1, 0.00)	0.4
Daylesford	*E.obliqua*-brown slash	23.9 (4, 2.84)	20.5 (1, 0.00)	-3.4
Little Desert NP	Eucalypt	9.4 (1, 0.00)	9.7 (1, 0.00)	0.3
Little Desert NP	Dead Casuarina	10.2 (1, 0.00)	11.7 (1, 0.00)	1.5
Little Desert NP	Live Casuarina	70.0 (1, 0.00)	74.2 (1, 0.00)	4.2
N.S.W.	Black Butt	11.0 (2, 0.00)	11.5 (2, 1.50)	0.5
N.S.W.	Black Butt	17.0 (1, 0.00)	17.0 (1, 0.00)	0.0
N.S.W.	Box - Ironbark	11.0 (1, 0.00)	10.0 (1, 0.00)	-1.0
N.S.W.	Box - Ironbark	12.0 (1, 0.00)	14.0 (1, 0.00)	2.0
N.S.W.	Stringybark - grey	10.0 (2, 0.00)	10.0 (2, 1.00)	0.0
N.S.W.	Stringybark - grey	13.5 (2, 0.50)	14.0 (2, 0.00)	0.5
N.S.W.	Stringybark - brown	10.0 (1, 0.00)	7.0 (1, 0.00)	-3.0
N.S.W.	Stringybark - brown	14.0 (1, 0.00)	14.0 (1, 0.00)	0.0
N.S.W.	Box - Ironbark	11.0 (2, 0.00)	10.5 (2, 0.00)	-0.5
N.S.W.	Box - Ironbark	13.0 (2, 0.00)	15.5 (2, 0.00)	2.5

The *Wiltronics* meter over-predicted on four of the nineteen occasions (20%), overpredicting by 0.5 to 3.4%. For the most part however, the *Wiltronics* meter underpredicts, underpredicting by an average of 1.3%. The meter reading that underpredicted by 4.2% was for live Casuarina (*Allocasuarina* spp.) for which there was no relevant calibration curve at the time of measurement.

DISCUSSION:

The *Wiltronics* meter measures moisture contents between 3 and 200% oven dry weight. Cheney (1993) states that the "range of moisture in dead fuels is from about 2% oven dry weight to over 200% in saturated litter beds containing free water". Therefore the range covered by this meter covers the majority of the range possible to find in the environment. This enables fire managers to use the meter under varying climatic conditions, and for various operations (i.e. prescribed fire and wildfire).

A two-phase calibration curve (made up of two linear equations) is used for all species. A possible explanation for this two-phase curve could be explained by the material that is being measured by the *Wiltronics* meter. When moisture content is 9% oven dry weight or below, the electrical current is only measuring the resistance of the moisture in the cell walls of the fuel, whereas above 9% oven dry weight, the meter is measuring the moisture and electrolytes within and between the cells of the fuel.

There are three sources of error or variation in using the *Wiltronics* meter. There is firstly the meter itself. The meter cell may not be clean - therefore allowing the electrical current to take a path through the dirt rather than through the fuel. This source of error can be detected by using the test button on the meter. It will tell you whether there is an error occurring, and if so, this can be eliminated by cleaning the cell with acetone. Another source of error is the fuel. Moisture content can vary within a single leaf, as well as between leaves. This is especially so when the fuel is not at equilibrium with the environment. It is therefore important to carefully grind the fuel to ensure maximum contact with the electrodes. It is also important to take at least three samples at any particular site. The average of these three samples should be representative of the overall fuel moisture content. The final source of variation is the user. Despite the fact that the *Wiltronics* meter is very simple to use - there are a number of small things that the operator could do to obtain an incorrect reading.
These are:

- the wrong fuel type could be selected;
- an unrepresentative sample of fuel could be collected;
- there could be no replications in sampling; and
- there may be incomplete grinding.

Preparation of the sample is important. Each sample should be prepared in the same way, and samples should be prepared immediately after collection so that the moisture content of the sample should not be altered in any way.

In the laboratory, testing showed that observations varied by 1% about the mean, and in the field, observations varied by 2% about the mean. This variation can be reduced to about 1% if the average of three measurements is taken. This amount of variation is similar to the natural variation found in the moisture content of fuels in the field. At moisture contents above 30%, such variation should not be a problem, as most fuels will not even ignite, let alone sustain a fire. Various relationships have been found between rate of spread of fire and moisture content of fuel, however they all indicate a rapid increase in rate of spread when surface fuel moisture contents drop below 10% oven dry weight (McArthur 1967). Moisture contents below 7% oven dry weight (McArthur 1967) also allows mass spot fires to develop ahead of the fire front, which can have a significant effect of fire behaviour.

It is important to remember that the natural variation of fuel moisture content can be at least 1% by itself. Therefore by only measuring one sample, you may only be picking up an extreme value of moisture content. If however you take three or more samples, you are likely to pick up on this natural range of variation. For example, 11.3, 11.7, 11.9, 14.9 and 14.6 were measured as moisture contents for one area. There is greater than 3% difference in these readings. If you only took the first sample, then your reading for fuel moisture content would be 11.3%. If however you take the average of three samples, the moisture content reading would be 11.6%, and of five samples - 12.9%. It is easy to see that by only taking one sample it would be very easy to underestimate or overestimate the true moisture content, simply due to natural variation.

As mentioned previously, a source of error may be the selection of the wrong fuel type calibration. This error may be due to species and/or stage of leaf decay. An error such as this can mean a difference in moisture content of up to 4% for moisture contents less than 30% oven dry weight, and greater than 20% for moisture contents greater than 30% oven dry weight. Therefore it is important to select the correct fuel type. By taking more than one sample, such an error may be found, and the incorrect reading not taken into account.

The *Wiltronics* meter has the potential to measure moisture contents of live fuels. However, all the testing done so far has concentrated on dead surface litter, as in most cases this is the primary fire carrier (Blank *et al.* 1985). In areas of dense elevated fuels, heathlands and at crown fires, it is also important to know the moisture content of live fuels as well, so as to determine the total amount of fuel available to the fire. Calibration curves need to be constructed for a variety of live fuels. It has been found so far when measuring live fuel moisture contents that care needs to be taken when grinding the fuels, to produce a homogenous sample is obtained.

Due to the *Wiltronics* meter being so quick and easy to use, portable and accurate, the *Wiltronics* meter is ideal for measuring fuel moisture content in the field. All the sources of error or variation found in this meter, are inherent in other meters using electrical resistance to measure fuel moisture content. Not only can it be used when planning a prescribed fire, but it can also be used at wildfires. This will enable operations staff to more accurately predict forward rates of spread and other aspects of fire behaviour. As moisture contents drop below 10% oven dry weight, fire behaviour intensifies. Many of the previously available methods of measuring fuel moisture content cannot reliably measure this low, and so warnings of extreme fire behaviour have not been readily available.

CONCLUSIONS:

The *Wiltronics* meter is a meter that measures electrical resistance of fine fuel samples, automatically calculating the measured resistance into a moisture content reading. The meter is portable and capable of measuring moisture contents between 3% and 200% oven dry weight.

Fuel moisture content is influenced by chemical composition and moisture. The chemical composition is a function of the species of plant from which it comes and the stage of decay and thus, chemical leaching. Calibration curves have been calculated for numerous fuel types, enabling the *Wiltronics* meter to be programmed to have calibration curves relevant to local conditions. A quick and accurate method for determining calibration curves has been developed, involving the measurement of conductivity of the fuel sample.

With good measurement technique a fuel moisture reading in the range of 3 to 30% can be expected to be within ±2% of the oven dry determined moisture content. The size of this variation is due to natural variability in moisture content in litterbeds and variations in calibration curves. At moisture contents above 60%, these two sources of variation can be quite large which may present a problem for measuring the moisture contents of live fuels. The meter is however, most accurate in the critical moisture content range.

Being able to accurately predict fuel moisture content enables fire managers to predict fire behaviour more accurately. These predictions may be either for a prescribed fire or a wildfire. This knowledge will enable fire managers to make decisions regarding the timing, pattern and method of lighting prescribed fires, and suppression strategies for wildfires more quickly and easily.

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APPENDIX 1.

Techniques of Measuring Fuel Moisture Content : A Review

By Karen Chatto

Since the 1930's, fire researchers have been trying to develop an easy and accurate method for determining fuel moisture content in the field. Currently there are numerous methods for determining fuel moisture content, which rely on direct techniques (some of which can be used in the field) or indirect predictive models. These methods include oven-drying, electrical, mechanical, chemical, meteorological, analogues and remote sensing techniques.

Direct methods for measuring fuel moisture content (such as oven-drying and chemical techniques) reduce the dependence on unreliable weather predictions (Dexter and Williams 1976). The predictive models, on the other hand, rely on empirical observations relating fuel moisture content to environmental variables (Dexter and Williams 1976, Viney and Hatton 1989). These environmental variables include temperature, relative humidity, wind speed, cloud cover, crown shading, slope, aspect and season or day of the year. Although these models seem to work quite well under the conditions they were developed, they have not been tested over a wide variety of conditions. The models are also often inadequate due to the complexity of the fuel composition; a fuel complex can include grass, leaves, bark, twigs, branches, elevated fuels, etc.. A different species may cause errors in the predictions, due to differences in the chemical composition between species. According to Viney and Hatton (1990), current fuel moisture models underpredict fuel moisture content as they do not consider condensation, and the authors maintain that condensation is an important parameter and should be incorporated into these models. Field testing has indicated that the predictive models are not as accurate as the direct methods (Blank *et al.* 1983).

Oven-drying :

Conventional oven-drying is the most frequently used method of measuring fuel moisture content directly. It is considered to be accurate and the most reliable method, and is used as the benchmark for assessing the accuracy of other methods and/or models (Hartley and Marchant 1988). However, Buck and Hughes (1939) found that the results obtained from oven-drying were significantly influenced by the location of the sample within the oven and the relative humidity of the air surrounding the oven. The major problems with this method are the time delay of 24 to 48 hours, depending on the oven and fuel moisture content; it requires a high energy output (Blank *et al.* 1985); it is not practical for field measurements; and overestimation of fuel moisture content may occur if the fuel contains significant amounts of volatile material (which evaporates under heating). This effect is generally not large enough to be important (Hartley and Marchant 1988), except perhaps at very low fuel moisture contents.

In recent years, there has been an inclination to try microwave ovens for oven-drying in preference to conventional ovens. Although the drying time for the samples is much faster, there are a number of precautions that must be taken. The basic problem is that the fuel can easily char or even explode. Hartley and Marchant (1988) state that "[m]icrowave energy is absorbed preferentially by the water molecules in the fuel, producing heat." As the moisture within the fuel evaporates, more heat is generated. If the fuel is in a desorption cycle (the

interior is moister than the exterior), then the interior may heat up more rapidly than heat can be taken away. This may cause charring, or if the process builds excess vapour pressure, it may result in an explosion. The use of a turntable helps to eliminate these "hot spots". Norman (1986) and Hartley and Marchant (1988) suggest placing a bowl of water inside the oven whilst drying, so the oven is not damaged as the fuel reaches oven-dry weight. Periods of heating and cooling should alternate until a constant weight is achieved, however the length of the period is determined by "trial and error" (Hartley and Marchant 1988). Norman (1986) found that it took anywhere between 10 and 36 minutes for drying, depending on the initial fuel moisture content. Both Norman (1986) and Hartley and Marchant (1988) found that by using a medium heat setting (or less) charring did not occur. As for a conventional oven, microwave ovens also require an external power source, and are not very practical for field work.

More recently, *Neosystems*[3] have designed a portable oven that is based on the conventional oven method, using two pressure plates. This method measures moisture content directly and eliminates the need for calibrations for each species. The oven relies on a fuel sample being compressed between two hot plates, and a vacuum pump that removes the moisture-laden air from the oven. Although this meter is based on the conventional oven technique, there are a number of practical disadvantages. The oven requires a car battery to operate, and subsequently is really only vehicle-based. Although each measurement only takes three to four minutes, the oven takes approximately 15 minutes to 'warm-up'. Due to the inclusion of a precision balance within the meter, the meter needs to be sitting on a flat horizontal surface, with as little movement (i.e. wind) as possible. As yet this meter is not commercially available. It is currently being tested by the Department of Conservation and Land Management in Western Australia.

Electrical Meters :

Although electrical moisture meters are considered to be direct methods of measuring moisture content, they actually rely on the direct relationship between moisture content and the electrical properties of the fuel. These meters are generally quick, accurate and reliable. There are two types of electrical meters:

(i) resistance meters; and
(ii) capacitance meters.

Both types of meters have advantages and disadvantages, however resistance meters are more suitable for more forestry applications according to Hartley and Marchant (1988).

Dry wood acts as an excellent electrical insulator, however moisture within the wood has an inverse effect on the wood's electrical resistance. Electrical resistance is directly influenced by the moisture content of the fuel. This effect is most obvious at moisture contents below 30% (fibre saturation point for most species) according to Hartley and Marchant (1988). Moisture contents above 30% have a poorer relationship with resistance than do the lower moisture contents. This limit is not serious, as fire behaviour is low to moderate when fuel moisture content is above 15% (Luke and McArthur 1978). The lower fuel moisture contents are important, as it is at these levels that fire behaviour is high to extreme. However it is difficult to measure low moisture contents (less than 10%) due to the very high electrical resistances

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involved. Resistance is measured by applying a current between two electrodes that are in contact with the fuel. The resistance of the fuel sample is balanced with an internal reference resistance. The user must rely on the manufacturer to determine an accurate relationship between the moisture content of the fuel and resistance (Hartley and Marchant 1988). This relationship may change due to different species of fuel, degree of nutrient leaching from the fuel and temperature, therefore some further calibration may still be required.

Dielectric meters determine moisture content by measuring the dielectric constant and/or the dielectric loss factor of fuel samples. There are three types of dielectric meters; capacitance meter, power-loss meter and the capacitance admittance meter. These three types of meters all measure the mean moisture content, and are therefore more reliable when moisture is evenly distributed through the fuel. These meters can read to zero moisture content, although accuracy is lost in the low extremes. According to Hartley and Marchant (1988), dielectric meters are not as accurate as resistance meters, although they do suit some applications (such as timber veneer moisture determination) better. These methods are quick, reliable and non-destructive.

The *Marconi Moisture Meter* was developed to measure the moisture content of grains, so the designers had no requirement to design a system which was able to measure moisture contents below 10% oven dry weight. The measurement is manually determined, after calibration for temperature and fuel type (i.e. species). Generally the average of three measurements is calculated, and is used as the fuel moisture content measurement. The meter is basically a wheatstone bridge, relying on relatively simple electronics. It is quick, accurate and reliable, but its range is limited to 10-30% moisture content. This meter is widely used in Western Australia, and is no longer being manufactured.

The *Protimeter* is also an electrical resistance meter. Although similar to the *Marconi Moisture Meter*, it does have some additional advantages in that it is fully automated, measures air temperature automatically, and is specially calibrated for different fuel types (however this may still require use of calibration tables depending on the fuel type). It is easy and quick to use, practical for field work, and gives immediate results. It's range is limited; measuring only down to 12% oven-dry weight for eucalypt fuel and 14% oven-dry weight for pine fuel. Buckley (1988) found that the moisture content of eucalypt fuels (collected in Victoria) were variable and consistently underpredicted by at least 2% oven-dry weight. Such variable results for eucalypt fuels are unacceptable for fire management decision making (Buckley 1988).

The *Granitec Meter* uses electrical conductivity to determine moisture content, and was designed for agricultural crops. The *Granitec Meter* has similar characteristics to the *Protimeter*.

The capacitance meter measures only the dielectric constant. (The dielectric constant is the ability of the fuel to absorb and store energy (James 1975)). This is measured by calculating the ratio between the capacitance of a capacitor containing fuel between its plates and the capacitance of a capacitor containing empty space. James (1975) and Hartley and Marchant (1988) found that the dielectric constant increases as the fuel moisture content increases. The dielectric constant also increases when wood density and wood temperature increase.

The power-loss meter measures the dielectric loss factor only. This is the measure of the proportion of stored energy that is lost (Hartley and Marchant 1988). As with the dielectric constant, as moisture content increases, the loss factor increases (James 1975, Hartley and Marchant 1988). However the relationship between the loss factor and moisture content is quite complex, relying on temperature, frequency and wood density (Hartley and Marchant 1988).

The capacitance admittance meter measures both the dielectric constant and the loss factor. When the electrode (capacitive element) is in contact with the fuel, capacitance and the loss factor increases causing an imbalance in the circuit. This imbalance is measured. Wood density has a significant effect on these readings, therefore the meter should be calibrated accordingly. It is also important to know the reference temperature for the meter. The accuracy of the readings is naturally limited due to the considerable normal variation in density. With coarse fuels, orientation of the grain can cause errors.

Mechanical :

The leaf bending technique was developed in Western Australia for *Pinus pinaster* needles, and is a crude technique for estimating fuel moisture content (Burrows 1991). It relies on how much a needle will bend without breaking; the greater the moisture content of the needle, the further the needle will bend without breaking. Preliminary investigations on the use of this technique for eucalypt leaves had shown promise (Burrows 1991).

Chemical :

The *Speedy Moisture Meter* is a chemical method of measuring fuel moisture content. It is a pressure cylinder to which is added a known weight of fuel and calcium carbide. The calcium carbide reacts with the moisture in the fuel, releasing acetylene gas. The gas pressure within the chamber is then measured directly and this is converted to a moisture content. The fuel must be minced finely before being added to the pressure cylinder. The finer the particle size, the higher the surface area to volume ratio, allowing for complete reaction between the water in the fuel and the calcium carbide. Care must be taken in mincing, so as not to overheat the fuel (causing moisture loss) nor take too long in mincing (possibly causing moisture change), and to maximise the grade of mince (Dexter and Williams 1976). All the equipment must be clean, otherwise inaccurate measurements will be recorded. The cylinder must be completely sealed and tightened before mixing the fuel and absorbent (calcium carbide) together, otherwise readings will be underestimated. Care must be taken when releasing the pressure, as the gas is highly flammable. Calcium carbide should not be left exposed to the air or allowed to become moistened, otherwise deterioration will occur and moisture reading underestimated. The final reading must be corrected for fuel type (species) and for being of "wet-weight" basis rather than "dry-weight" basis. The *Speedy* moisture meter measures between 7% and 50% oven dry weight. This method provides a reliable direct estimate using inexpensive equipment to determine moisture content in the field, and is currently being used throughout Victoria.

The xylene distillation method relies on the principle that the boiling characteristics of the liquid are changed when boiled in a mixture with another liquid with which it is immiscible (Buck and Hughes 1939). This method requires the use of complicated apparatus, and is therefore not very practical in the field. It is, however, a reliable method when measuring fuel

that has significant amounts of volatile materials (Hartley and Marchant 1988). Special precautions must also be taken to ensure the safe use of xylene. Toluene or benzene can also be used as the solvent, however xylene was found to give repeatable results, results were obtained more quickly, it is the least miscible with water, and it is slightly safer to use (Buck and Hughes 1939).

The Karl-Fischer titration method, with the use of iodine, pyridine and methanol, is considered to be the most accurate method for measuring fuel moisture (Hartley and Marchant 1988). However due to its impracticality in the field and the extensive chemical knowledge required, it is very rarely used today.

Meteorological :

The meteorological models available are based on empirical observations relating fuel moisture content to environmental variables (Dexter and Williams 1976, Viney and Hatton 1989). A number of different weather conditions are required as input parameters for these models; including temperature, relative humidity, wind speed, slope, aspect, cloud cover, crown shading, season and day of the year. Although these models seem to work quite well under the conditions they were developed, they cannot be used over a wide variety of conditions. The models are also often inadequate due to the complexity of the fuel composition (Viney and Hatton 1989); a fuel complex can include grass, leaves, bark, twigs, branches, elevated fuels, etc.. According to Hatton and Viney (1988) and Viney and Hatton (1990), current fuel moisture models underpredict fuel moisture content as no models take into consideration condensation. Some models even require keeping a record of relevant weather observations from late spring/early summer (Rothermel *et al.* 1986). The majority of the meteorological models (except the Red Book (Sneeuwjagt and Peet 1985)) do not take into account the natural variation found in moisture content of different species (Hatton and Viney 1988).

The National Fire Danger Rating System (NFDRS) is a fire danger rating system that contains a fuel moisture content estimator within the system. This estimation requires 21 inputs for the weather record (Deeming *et al.* 1978), which is used to estimate fuel moisture content. This estimation requires daily bookkeeping, and predicts fuel moisture content for both live and dead fuels (Deeming *et al.* 1978). Viney and Hatton (1989) found that the NFDRS model severely underpredicted fuel moisture content in the early afternoon of various litter types. However when comparing this model to other meteorological models, Viney and Hatton (1989) found the smallest error associated with NFDRS compared to other models for leaves and bark. This model divides fuel into four classes; 1-hour, 10-hour, 100-hour and 1000-hour. This is in reference to the time the fuel takes to equilibrate to environmental conditions (Carlson *et al.* 1996)

The Keetch-Byram Drought Index is a systematic method of estimating the progress of drought (Keetch and Byram 1968), based on soil moisture. The KBDI represents the net effect of evapotranspiration and precipitation, indicating cumulative moisture deficiency in deep duff or upper soil layers, and is thus a good indicator of coarse fuel availability and deep litter fuel availability. The KBDI is calculated using the maximum air temperature and total rainfall in the previous 24 hours (Keetch and Byram 1968). It is a simple bookkeeping procedure, but does require to be started when the soil is at field capacity (i.e. KBDI=0), which is generally before the fire season starts. The scale is between 0 (soil is fully saturated)

and 200, although 100 is considered to be the critical point and indicates 100% fuel availability to fire.

McArthur's Forest Fire Danger Meter MkV (1975) uses the relationship between temperature and relative humidity to indirectly determine fuel moisture content in dry sclerophyll forests. The meter itself does not give a moisture content reading. This meter was specifically developed for dry sclerophyll forests however it is used extensively throughout Australia. This relationship assumes no moisture time lag (Viney and Hatton 1989), but McArthur does account for the time lag in Leaflet No. 107 (McArthur 1968) in which the fire danger meter is first presented. Viney and Hatton (1989) also comment that the meter's predictions of fuel moisture content are only suitable between 1 pm and 6 pm (McArthur 1968).

The Red Book (Sneeuwjagt and Peet 1985) was developed for the jarrah (*Eucalyptus marginata*) forests of southern Western Australia. The tables are very fuel type specific, however they have been adapted to other fuel types, including karri (*E.diversicolor*), *Pinus radiata* and *P.pinaster*. Fuel moisture content is estimated using the overnight rainfall, overnight RH count, forecast maximum temperature, forecast minimum relative humidity, yesterday's minimum moisture content and a drying factor.

Analogues :

Hazard sticks must be of the same dimensions as the fuel components, and must be exposed to the identical site (Dexter and Williams 1976, Eron 1991). Therefore a variety of hazard sticks must be used to represent the whole fuel complex (Wilson 1958). Placement of the sticks should be representative of the fuels being assessed (Eron 1991). There are strict specifications in the selection of suitable timber for use as hazard sticks. Oven-dry weight of the sticks must be known before positioning in the field, and sticks need to be calibrated before being used. Hazard sticks must be positioned in advance (Blank *et al.* 1985), with a minimum of two weeks exposure suggested by Eron (1991), allowing the sticks to come into equilibrium with the surrounding fuel. This is not possible in a wildfire situation. According to Eron (1991), hazard sticks should not be used in the field for more than a month, to avoid excessive weathering, weight loss, damage or excessive dirt accumulating on the sticks. However Carlson *et al.* (1996) suggest replacement of hazard sticks is dependent on the diameter of the sticks. Despite hazard sticks being fairly simple to use and easy to set up, their practical value is limited (Wilson 1958) as they are really only useful for prescribed fire situations.

Hazard bags are similar to hazard sticks, in that both are used to represent the fuel. The bags are generally made of terylene or fine mesh material (such as shade cloth), and a representative sample of fuel is placed inside. A subsample of the fuel is oven-dried before being placed in the field, and the oven-dry weight recorded. As for hazard sticks, hazard bags must be placed in advance, allowing the fuel to reach equilibrium with the surrounding fuel. Billing (pers. comm.) recommends that the bags must be exposed to at least one wetting cycle for the fuel to acclimatise to the site conditions.

Remote Sensing :

Remote sensing techniques are used to determine both fuel quantity and fuel curing (Williamson 1988) on a regular basis. However using satellite imagery for determining fuel moisture content is quite difficult and requires specialist knowledge. Although imagery is routinely collected, it is not on a daily basis (Williamson 1988). Cloud cover also continually causes a problem, as satellites cannot "see" through clouds. To overcome these problems, Barber (1987) used a combination of satellite imagery with GIS. There are currently three forms of satellite imagery available in south-eastern Australia: Landsat satellites (MSS), NOAA (AVHRR) and airborne systems.

Burning Leaf :

The burning leaf technique is a very crude technique of estimating fuel moisture content, and should only be used if previously mentioned techniques are not available. It relies on the burning rate of a leaf. The angle to which a burning leaf is tilted so that combustion is just sustained (a small flame will neither go out nor flare up (FC and TFS 1984)) will depend on the moisture content of the leaf (Burrows 1984). From the angle a crude estimate of fuel moisture content can be obtained.

Conclusion :

Fuel moisture content plays an important role in determining fire behaviour, as it is considered to be the primary fire carrier. It is therefore important that we are able to measure fuel moisture content quickly, easily, accurately and, most importantly, out in the field. Xylene distillation is the best technique available, but oven-drying is the most commonly used standard. However neither of these techniques are suitable out in the field. Although there is a wide variety of methods to measure fuel moisture content in the field, there are no current meters that meet the current requirements of accuracy, affordability, portability and capability of measuring fuel moistures between 3% and 200% oven dry weight.

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APPENDIX 2. Resistances as measured by the *Wiltronics T-H Fine Fuel Moisture Meter* and observed moisture contents (odw) for ten fuel types.

		Resistance			Fuel moisture
Site	Fuel type	Rep 1 (10^x Ω)	Rep 2 (10^x Ω)	Rep 3 (10^x Ω)	content (odw) (%)
Clunes	*Acacia pycnantha*	12.881	12.535		2.56
Clunes	*Acacia pycnantha*	12.131	11.594	12.043	4.07
Clunes	*Acacia pycnantha*	10.635	10.389		5.88
Clunes	*Acacia pycnantha*	9.462	9.573		12.26
Clunes	*Acacia pycnantha*	7.825	7.838		17.42
Clunes	*Acacia pycnantha*	4.051	4.040		46.06
Clunes	*Acacia pycnantha*	3.592	3.589		55.95
Clunes	*Acacia pycnantha*	3.438	3.293	3.612	60.28
Clunes	*Acacia pycnantha*	2.801	2.634	2.613	148.41
NE	*E.delegatensis*	11.025	11.556		13.75
NE	*E.delegatensis*	6.776	7.068		24.00
NE	*E.delegatensis*	2.910	2.937		144.00
Clunes	*E.microcarpa*	12.393	12.344		2.67
Clunes	*E.microcarpa*	13.104	12.282	12.356	2.82
Clunes	*E.microcarpa*	11.445	11.144		7.03
Clunes	*E.microcarpa*	8.654	8.682		15.86
Clunes	*E.microcarpa*	4.653	4.750	4.539	37.85
Clunes	*E.microcarpa*	4.612	4.191	4.097	44.51
Clunes	*E.microcarpa*	3.808	3.954	3.913	46.25
Clunes	*E.microcarpa*	2.862	2.887	2.828	204.11
Clunes	*E.microcarpa*	9.851	9.129	10.527	11.82
Creswick	*E.obliqua*	12.547	12.233		3.85
Creswick	*E.obliqua*	12.109	12.130		4.28
Creswick	*E.obliqua*	12.023	11.900		7.06
Creswick	*E.obliqua*	11.008	10.859		11.46
Creswick	*E.obliqua*	5.903	5.779		21.85
Creswick	*E.obliqua*	5.896	5.508	5.811	26.37
Creswick	*E.obliqua*	5.319	5.827	5.873	31.52
Creswick	*E.obliqua*	4.750	4.954	4.954	39.53
Creswick	*E.obliqua*	4.398	4.135	4.051	54.12
Creswick	*E.obliqua*	3.937	3.913		65.06
Creswick	*E.obliqua*	3.897	4.135	4.238	75.00
Creswick	*E.obliqua*	3.734	3.666		80.52
Creswick	*E.obliqua*	3.882	3.814		81.08
Creswick	*E.obliqua*	3.574	4.010	3.875	81.61
Creswick	*E.obliqua*	2.694	2.716		282.38

Site	Fuel type	Resistance Rep 1 (10^x Ω)	Rep 2 (10^x Ω)	Rep 3 (10^x Ω)	Fuel moisture content (odw) (%)
Creswick	*E.obliqua*	2.733	2.686		371.40
Creswick	*E.obliqua*	2.640	2.657		519.70
Creswick	*E.obliqua* -2wk slash	12.296	12.388		2.31
Creswick	*E.obliqua* -2wk slash	12.175	12.103		2.82
Creswick	*E.obliqua* -2wk slash	10.975	11.318		6.49
Creswick	*E.obliqua* -2wk slash	9.908	9.799		9.24
Creswick	*E.obliqua* -2wk slash	5.513	5.340	5.204	25.47
Creswick	*E.obliqua* -2wk slash	3.685	3.734	3.868	45.45
Creswick	*E.obliqua* -2wk slash	3.729	3.549	3.474	50.30
Creswick	*E.obliqua* -2wk slash	2.989	3.115	3.009	56.60
Creswick	*E.obliqua* -2wk slash	2.759	2.621	2.667	134.57
Daylesford	*E.obliqua*	12.367	12.446		1.56
Daylesford	*E.obliqua*	12.682	12.596		2.88
Daylesford	*E.obliqua*	10.924	10.724		6.87
Daylesford	*E.obliqua*	9.834	9.890		10.57
Daylesford	*E.obliqua*	5.706	5.492	5.247	28.76
Daylesford	*E.obliqua*	3.729	4.085	4.238	60.77
Daylesford	*E.obliqua*	3.662	3.808	3.847	64.94
Daylesford	*E.obliqua*	3.954	3.808	3.784	66.89
Daylesford	*E.obliqua*	2.893	2.809	3.165	163.89
Clunes	*E.sideroxylon*	12.545	12.440		1.63
Clunes	*E.sideroxylon*	11.494	11.568		6.45
Clunes	*E.sideroxylon*	10.971	10.644		7.04
Clunes	*E.sideroxylon*	9.872	9.822		9.93
Clunes	*E.sideroxylon*	5.302	5.470	5.482	27.92
Clunes	*E.sideroxylon*	4.449	4.331	4.374	34.69
Clunes	*E.sideroxylon*	4.122	5.850	4.374	42.94
Clunes	*E.sideroxylon*	3.457	3.608	3.359	58.19
Clunes	*E.sideroxylon*	3.539	3.636	3.666	60.76
Clunes	*E.sideroxylon*	2.758	2.767	2.739	188.19
E.Gippsland	*E.sieberi*	12.148	12.253		2.53
E.Gippsland	*E.sieberi*	12.372	12.342		2.97
E.Gippsland	*E.sieberi*	11.692	11.812		6.04
E.Gippsland	*E.sieberi*	10.201	10.185		9.52
E.Gippsland	*E.sieberi*	8.305	8.395		12.76
E.Gippsland	*E.sieberi*	7.625	7.863		13.98
E.Gippsland	*E.sieberi*	5.477	5.580		24.04
E.Gippsland	*E.sieberi*	3.890	4.222	4.423	47.37
E.Gippsland	*E.sieberi*	4.449	4.148	4.574	47.90
E.Gippsland	*E.sieberi*	4.222	3.946	4.162	61.68
E.Gippsland	*E.sieberi*	3.981	4.040		66.45

Site	Fuel type	Resistance Rep 1 (10^x Ω)	Resistance Rep 2 (10^x Ω)	Resistance Rep 3 (10^x Ω)	Fuel moisture content (odw) (%)
E.Gippsland	*E.sieberi*	3.671	3.653		78.31
E.Gippsland	*E.sieberi*	4.000	4.176	3.963	80.54
E.Gippsland	*E.sieberi*	3.275	3.410	3.352	81.18
E.Gippsland	*E.sieberi*	3.596	3.937	3.640	89.29
E.Gippsland	*E.sieberi*	2.771	2.679		276.92
E.Gippsland	*E.sieberi*	2.851	2.665		304.70
E.Gippsland	*E.sieberi*	2.697	2.776		332.90
E.Gippsland	Coastal Mixed	12.737	12.507		1.58
E.Gippsland	Coastal Mixed	11.977	11.642		4.65
E.Gippsland	Coastal Mixed	12.095	12.031		6.00
E.Gippsland	Coastal Mixed	10.309	10.300		10.72
E.Gippsland	Coastal Mixed	7.496	7.045	7.122	16.67
E.Gippsland	Coastal Mixed	6.951	6.596	6.698	16.92
E.Gippsland	Coastal Mixed	5.826	5.223	5.575	29.63
E.Gippsland	Coastal Mixed	4.352	4.574	4.574	39.58
E.Gippsland	Coastal Mixed	4.291	4.291		51.90
E.Gippsland	Coastal Mixed	3.709	3.570	3.739	62.14
E.Gippsland	Coastal Mixed	4.273	4.222		65.48
E.Gippsland	Coastal Mixed	3.790	3.724		80.19
E.Gippsland	Coastal Mixed	3.415	3.395		98.65
E.Gippsland	Coastal Mixed	3.175	3.468	3.368	103.57
E.Gippsland	Coastal Mixed	2.726	2.723		266.00
E.Gippsland	Coastal Mixed	2.781	2.723		300.00
E.Gippsland	Coastal Mixed	2.740	2.753		492.70
Creswick	*Pinus radiata*	12.494	12.445		1.35
Creswick	*Pinus radiata*	12.385	12.627		2.02
Creswick	*Pinus radiata*	12.294	12.079		3.38
Creswick	*Pinus radiata*	12.112	12.125		4.26
Creswick	*Pinus radiata*	11.937	12.101		5.03
Creswick	*Pinus radiata*	10.166	10.425		10.71
Creswick	*Pinus radiata*	9.212	9.296		13.73
Creswick	*Pinus radiata*	8.019	8.092		17.05
Creswick	*Pinus radiata*	7.729	8.039	8.016	17.33
Creswick	*Pinus radiata*	6.193	6.038		24.75
Creswick	*Pinus radiata*	5.027	4.539	4.750	35.96
Creswick	*Pinus radiata*	4.191	3.921	3.709	63.00
Creswick	*Pinus radiata*	5.301	4.331	5.212	64.20
Creswick	*Pinus radiata*	4.449	4.162	4.352	67.01
Creswick	*Pinus radiata*	3.734	3.890	3.585	87.78
Creswick	*Pinus radiata*	3.368	3.457		103.85

Site	Fuel type	Resistance			Fuel moisture content (odw) (%)
		Rep 1 (10^x Ω)	Rep 2 (10^x Ω)	Rep 3 (10^x Ω)	
Creswick	*Pinus radiata*	3.645	3.567		117.57
Creswick	*Pinus radiata*	3.413	3.379		176.36
Creswick	*Pinus radiata*	3.570	3.123	3.570	216.13
Creswick	*Pinus radiata*	2.882	3.035	2.881	244.27
Creswick	*Pinus radiata*	2.948	2.844	2.899	477.99

APPENDIX 3. Conductivities and locations of each fuel type tested.

	Fuel type	Location	Conductivity 1	Conductivity 2
	Acacia pycnantha - brown	Clunes	0.001110	0.001100
*	*Acacia pycnantha* - brown	Clunes	0.001010	0.001020
*	*Acacia pycnantha* - brown	Clunes	0.000700	0.000670
	Banksia grandis - brown	W.A.	0.000137	0.000126
*	*Banksia grandis* - brown	W.A.	0.000153	0.000148
*	Coastal Mixed Spp. - grey	East Gippsland	0.000172	0.000187
	E.accidens - grey fragmented	W.A.	0.000097	0.000098
*	*E.accidens* - grey fragmented	W.A.	0.000120	0.000142
*	*E.baxteri* - grey	Serra Rd/Henham Tk	0.000178	0.000217
*	*E.consideniana* - grey	Orbost	0.000195	0.000194
	E.consideniana - grey	Orbost	0.000132	0.000125
*	*E.cypellocarpa* - grey	Bairnsdale	0.000330	0.000300
	E.cypellocarpa - grey	Bairnsdale	0.000290	0.000300
*	*E.delegatensis* - grey	Swifts Creek	0.000190	0.000182
	E.delegatensis - grey	Swifts Creek	0.000177	0.000191
	E.diversicolor - grey	W.A.	0.000330	0.000302
*	*E.diversicolor* - grey	W.A.	0.000255	0.000268
*	*E.fastigata* - grey	Orbost	0.000262	0.000251
	E.fastigata - grey	Orbost	0.000150	0.000152
*	*E.globoidea* - grey	Bairnsdale	0.000207	0.000186
	E.globoidea - grey	Bairnsdale	0.000205	0.000180
*	*E.globoidea / Angophora costata* - grey	Morisset, N.S.W.	0.000360	0.000348
*	*E.globoidea / E.cypellocarpa / Angophora floribunda* - grey	Morisset, N.S.W.	0.000312	0.000286
*	*E.globoidea / E.cypellocarpa* - grey	Morisset, N.S.W.	0.000385	0.000395
	E.leucoxylon - brown	Clunes	0.000580	0.000575
*	*E.leucoxylon* - brown	Clunes	0.000570	0.000550
*	*E.microcarpa* - grey	Clunes	0.000279	0.000272
*	*E.microcarpa* - grey	Clunes	0.000244	0.000243
*	*E.obliqua* - brown	Creswick	0.000305	0.000343
	E.obliqua - brown	Creswick	0.000250	0.000265
	E.obliqua - brown	Creswick	0.000340	0.000163
	E.obliqua - brown slash	Creswick	0.000311	
*	*E.obliqua* - brown slash	Daylesford	0.000288	0.000329
	E.obliqua - green slash	Creswick	0.001380	
*	*E.obliqua* - green slash	Barkstead	0.001280	0.001230

	Fuel type	Location	Conductivity 1	Conductivity 2
*	*E.obliqua* - grey	Stewarts Creek	0.000280	0.000309
*	*E.obliqua* - grey	Creswick	0.000235	0.000250
*	*E.obliqua* - grey	Bairnsdale	0.000170	0.000165
	E.obliqua - grey	Bairnsdale	0.000150	0.000146
*	*E.obliqua* - grey	Swifts Creek	0.000148	0.000138
	E.obliqua - grey	Swifts Creek	0.000105	0.000102
	E.obliqua - grey fragmented	Creswick	0.000130	
*	*E.pilularis* - grey	Morisset, N.S.W.	0.000127	0.000122
*	*E.pilularis* - grey	Morisset, N.S.W.	0.000123	0.000110
	E.polyanthemos - brown	Clunes	0.000820	0.000780
*	*E.polyanthemos* - brown	Clunes	0.000450	0.000505
	E.polyanthemos - grey	Bairnsdale	0.000345	0.000339
*	*E.polyanthemos* - grey	Bairnsdale	0.000290	0.000274
	E.radiata - brown	Creswick	0.000408	0.000380
*	*E.radiata* - brown	Creswick	0.000370	0.000394
*	*E.radiata* - grey	Serra Rd/Dunkeld	0.000281	0.000312
*	*E.regnans* - grey	Swifts Creek	0.000207	0.000219
	E.regnans - grey	Swifts Creek	0.000121	0.000115
*	*E.rubida* - brown	Creswick	0.000560	0.000570
	E.rubida - brown	Creswick	0.000520	0.000530
	E.rubida - grey	Swifts Creek	0.000439	0.000430
*	*E.rubida* - grey	Swifts Creek	0.000380	0.000423
	E.sideroxylon - brown	Clunes	0.000610	0.000600
*	*E.sideroxylon* - brown	Clunes	0.000550	0.000550
*	*E.sideroxylon* - grey	Clunes	0.000290	0.000289
*	*E.sideroxylon / E.acmenioides / E.robertsonii* - grey	Bulahdelah, N.S.W.	0.000450	0.000390
*	*E.sideroxylon / E.acmenioides / E.robertsonii* - grey	Buladelah, N.S.W.	0.000227	0.000213
*	*E.sieberi* - grey	Orbost	0.000185	0.000183
	E.sieberi - grey	Orbost	0.000170	0.000155
*	*E.sieberi* - grey	Orbost	0.000109	0.000106
	E.sieberi - grey	Orbost	0.000088	0.000087
*	*E.sieberi* - grey fragmented	East Gippsland	0.000200	0.000219
	Grey Box Mixed Spp. - grey	Castlemaine	0.000290	0.000255
*	Grey Box Mixed Spp. - grey	Castlemaine	0.000193	0.000191
*	*Syncarpia glomulifera / E.acmenioides / E.robertsonii* - grey	Morisset, N.S.W.	0.000230	0.000211
*	*Pinus pinaster* - brown	W.A.	0.000450	0.000450
	Pinus radiata - brown	Castlemaine	0.000170	0.000158
*	*Pinus radiata* - brown	Castlemaine	0.000146	0.000139
	Pinus radiata - brown	Creswick	0.000110	0.000155
*	*Pinus radiata* - brown	Creswick	0.000092	0.000089

* denotes those fuel types tested in 1996.

APPENDIX 4. Coefficient and intercept values for each fuel group based on conductivities.

Species	Fuel type	Moisture content range (% odw)	Coefficient *a*	Intercept *b*
Stringybark	green slash	0 - 9	21.44751	-0.56898
		9 - 200	3.648677	0.678637
Acacia pycnantha		0 - 9	22.61591	-0.80586
		9 - 200	3.81231	0.669364
Pinus pinaster		0 - 9	29.964821	-1.71203
		9 - 200	34.395664	0.606286
Gum	brown	0 - 9	26.8991	-1.37173
		9 - 200	4.198866	0.631171
Gum	grey	0 - 9	34.60485	-2.19303
		9 - 200	4.628151	0.574241
Stringybark	brown	0 - 9	39.94846	-2.71988
		9 - 200	4.833357	0.544525
Stringybark	grey	0 - 9	57.01426	-4.30149
		9 - 200	5.250935	0.482387
Pinus radiata		0 - 9	83.15404	-6.54116
		9 - 200	5.580964	0.433353
Silvertop	grey	0 - 9	77.11437	-6.03976
		9 - 200	5.522973	0.441911
Ash	grey	0 - 9	54.38616	-4.06532
		9 - 200	5.202084	0.489688
Box	brown	0 - 9	28.88177	-1.59466
		9 - 200	44.331046	0.614735
Box	grey	0 - 9	41.57708	-2.87657
		9 - 200	4.88635	0.536718
Banksia		0 - 9	77.53983	-6.07537
		9 - 200	5.527329	0.441267
Eucalyptus accidens		0 - 9	98.76789	-7.79758
		9 - 200	5.700234	0.415863

These values are used in Equation 3 to produce the calibration curves required for each fuel group.

$$\log_{10}(mc) = \frac{a}{\log_{10}(R)} + b \qquad \text{(Equation 3)}$$

APPENDIX 5. Percentage error in moisture content when comparing upper and lower conductivity limits with mean conductivity for each fuel group.

		Moisture content range (%)					
Fuel type		**1 - 9**	**9 - 10**	**12 - 13**	**17 - 18**	**29 - 43**	**107 - 340**
Stringy - green	**L**	±0.5	±0.5	±0.5	±0.5	±0.5	±5.0
(1317.5)	**U**	±0.5	±0.5	±0.5	±0.5	±0.5	±2.0
Acacia	**L**	±5.0	±0.5	±0.5	±1.0	±5.0	
(935.0)	**U**	±0.5	±0.5	±0.5	±0.5	±1.0	±10.0
Pinaster	**L**	±2.0	±1.0	±0.5	±0.5	±5.0	
(331.3)	**U**	±2.0	±0.5	±0.5	±0.5	±2.0	
Gum - brown	**L**	±0.5	±0.5	±0.5	±0.5	±0.5	±10.0
(556.9)	**U**	±0.5	±0.5	±0.5	±0.5	±0.5	±5.0
Gum - grey	**L**	±1.0	±0.5	±0.5	±0.5	±2.0	
(355.6)	**U**	±1.0	±0.5	±0.5	±0.5	±2.0	
Stringy - brown	**L**	±2.0	±1.0	±1.0	±0.5	±5.0	
(290.5)	**U**	±1.0	±0.5	±0.5	±0.5	±1.0	
Stringy - grey	**L**	±1.0	±1.0	±0.5	±0.5	±5.0	
(191.0)	**U**	±2.0	±1.0	±0.5	±0.5	±5.0	
Pine	**L**	±0.5	±0.5	±0.5	±0.5	±2.0	
(130.9)	**U**	±0.5	±0.5	±0.5	±0.5	±2.0	
Silvertop	**L**	±0.5	±0.5	±0.5	±0.5	±5.0	
(144.6)	**U**	±1.0	±0.5	±0.5	±0.5	±5.0	
Ash	**L**	±1.0	±1.0	±0.5	±0.5	±5.0	
(202.6)	**U**	±2.0	±1.0	±0.5	±0.5	±5.0	
Box - brown	**L**	±2.0	±0.5	±0.5	±0.5	±5.0	
(534.8)	**U**	±5.0	±0.5	±0.5	±1.0	±5.0	
Box - grey	**L**	±1.0	±0.5	±0.5	±0.5	±5.0	
(275.8)	**U**	±2.0	±1.0	±0.5	±0.5	±5.0	
Banksia	**L**	±0.5	±0.5	±0.5	±0.5	±1.0	
(141.0)	**U**	±0.5	±0.5	±0.5	±0.5	±1.0	
E.accidens	**L**	±0.5	±0.5	±0.5	±0.5	±1.0	
(114.3)	**U**	±0.5	±0.5	±0.5	±0.5	±2.0	

The mean conductivity ($x10^6$ mhos)for each fuel group is listed below fuel group names in brackets.

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