THE SHIGOMETER AND ELECTRICAL RESISTANCE STUDIES OF PAPER BIRCH

by

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ABSTRACT

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Key Words: Ion accumulation, paper birch, red heart, Shigometer, wounding.

The Shigometer was evaluated as an instrument for detecting red heart of paper birch. The Shigometer accurately detected the presence of red heart at a 50% decrease from the maximum reading rule but sometimes failed to precisely define its outer limits. Although it did not always correctly detect the presence or precise location of discoloured wood, it was able to correctly detect the presence of discoloured wood within a few centimetres in approximately 85% of attempts. There was a general increase in ion concentrations in the red heart as compared to the clear wood. The ions appear to accumulate in vessels along the clear wood to discoloured wood transition zone, in the ray parenchyma in the transition zone and in the discoloured wood. Following wounding there was an increase in soluble and insoluble potassium. The Shigometer readings were found to be correlated with mobile ion concentrations of potassium and magnesium. Because few microorganisms were found in association with the red heart, it is felt that the initial accumulation of ions may be a wound response by the tree.

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INTRODUCTION

Methods for determining the presence of stain and decay in wood in service (e.g. utility poles), in living trees, and in cut wood are always in demand. Although many instruments have been developed to determine the internal condition of wood, some are more practical and effective than others. The Shigometer is an instrument that detects the presence of stain and decay in wood on the basis of the resistance of the wood to an electrical current.

Paper birch (*Betula papyrifera* Marsh.) can be a valuable species (e.g. plywood, finished veneer). However, it quite frequently has a discolouration commonly known as "red heart". It would be useful to find a method for quickly and accurately determining the quality of the wood in living paper birch trees before they are cut, or a general survey of the quality of the wood in a stand. The Shigometer may be a good instrument to detect the presence of the "red heart" in paper birch without damaging the tree.

Following a literature review, this study first attempts to determine to what degree of accuracy the Shigometer can be used to detect the "red heart" of paper birch. It also examines the theory of the Shigometer operation, particularly as it pertains to paper birch and its "red heart". This will be accomplished by comparing Shigometer readings taken from standing trees with the actual extent of stain and decay. Examined as well, will be the accumulation of soluble and insoluble ions in clear and discoloured wood, the location of the ionic accumulations within the wood, and their origins.

This thesis is divided into six chapters. The first chapter is a general literature review of electrical conductance in wood, the Shigometer and its ability to detect discoloured wood, and the "red heart" of paper birch. The second chapter is a description of the "red heart" in the trees that were studied. The third chapter is an evaluation of the accuracy of the Shigometer. The fourth is an examination of the ions that accumulate and their locations of accumulation in clear wood and red heart. The fifth chapter is an examination of the ion accumulations after wounding. The final chapter summarizes the general conclusions of the research work. Each chapter, excluding the first and last, are presented as individual studies. The final chapter draws the four experimental studies together and makes some general conclusions.

CHAPTER I: LITERATURE REVIEW

The effects of electricity on plants has been studied for over 100 years (Tattar and Blanchard, 1976). The use of electricity to determine plant health or condition has been studied for almost as long. According to Tattar and Blanchard (1976), in the late 19th century and early 20th century there were several investigations into the stimulatory effects of applying a current to the soil in greenhouse beds. Some of the results were correlated with reduced incidence of mildew, increased seed germination, increased growth rates, increased yields, and increased root elongation in crop plants. Other studies demonstrated an increase in the growth of bacteria and yeasts with the stimulus of electrical currents.

Stone (1914), while studying the deleterious effects of uninsulated power lines in contact with tree branches, examined the electrical resistance properties of the woody tissue of living trees. He found that electrical resistance was lowest at the cambium and that cambial resistance could be used as a measure of tissue viability. Healthy tissue had a low resistance and dead tissue had a substantially higher resistance.

Osterhout (1922) attempted to quantify the changes in membrane permeability with degree of injury by measuring the associated electrical conductivity. The loss of selective permeability of electrolytes and resultant increased tissue conductivity became a basic principle in plant electrophysiology (Tattar & Blanchard, 1976).

If the injury results in cell death, the release of ions from the cell will cause a local increase in ion concentration (Wheeler & Hanchey, 1968).

Williams *et al.* (1964), while attempting to measure the resistance of cell membranes in *Nitella translucens*, used small pulses of direct current so that there would be little effect on the tissue by the applied voltage, which might otherwise create an artifact.

Skutt *et al.* (1972) used the theories of Stone (1914) and the direct pulsed current method used by Williams *et al.* (1964) to detect discoloured and decayed wood in living trees. Their meter was the forerunner of the Shigometer.

NATURALLY OCCURRING ELECTRICAL CURRENTS IN PLANTS

Electrical currents occur naturally within plant tissues and can be further induced to flow without applying an artificial external source of current.

Biopotentials

Different areas within a plant, such as on different sides of a membrane, can have different electrical potentials. These differences in relative electrochemical activity can be measured as biopotentials (Tattar & Blanchard, 1976). This in itself is not electrical conduction, but rather the potential for conduction. When something allows the ions to move, either naturally or man induced, the potential produces a bioelectric current.

Bioeletric Currents

A bioelectric current is a flow of charged ions. Bioelectric currents will occur naturally or can be caused by an electrochemical reaction created by the use of electrodes of opposite charge, which cause a polarization effect. This polarization is the flow of charged ions to the oppositely charged electrode (Levengood, 1973), where they will accumulate. No externally applied voltage is required to make the ions move.

Polarization of the electrodes through bioelectric currents can be avoided by using electrodes that are of the same charge. However, when a voltage is applied to measure the resistance, polarization will still occur as the charges accumulate at the ground electrode. This can be avoided by using an alternating current or short pulses of direct current which do not allow enough time for the electrodes to charge.

Tattar (1974) also noted that bioelectric currents increased in wood in progressive stages of discolouration and decay.

THEORIES ON ELECTRICAL CONDUCTION IN WOOD

Electrical conduction has been studied in textile materials, cellulose fibres and wood. In 1926, Hasselblatt found that in birch wood, the logarithm of the electrical resistance was linearly related to the moisture content of the wood, but only when it was below the fibre saturation point. Above the fibre saturation point, there was

very little change in electrical resistance with increased moisture content. Since this study, many authors have found the same relationship (Barakas *et al.*, 1943; Brown, 1962; Brown *et al.*, 1963; James, 1988; Lin, 1967).

Clark and Williams (1933) felt that conductance in wood was ionic and dependent on the number of bound and free ions. Likewise, Hearle (1952) concluded that electrical conduction in wood at high moisture contents was dependent on the concentration of conducting ions and their mobility. However, he felt that moisture was not a factor at these higher moisture contents but at lower moisture contents, the matter was more complex. Hearle (1952) theorized that breaks in the conduction path (i.e. continuous water paths) at lower moisture contents partly limited conduction, but the limited dissociation at these moisture levels also may be part of the answer.

Temperature in relation to electrical conductance has been considered mostly for wood that is below the fibre saturation point. Decreasing resistance with increasing temperature suggested that conduction is by charge carriers whose number or mobility are increased by thermal activity (James, 1988).

The number of charge carriers is a major factor from 0 to 20% moisture contents (Lin, 1965). At higher moisture contents, the mobility of the ions became more important and above the fibre saturation point the path for conduction shifts from the cell walls to the cell lumens. The electrical conductivity will increase gradually and continuously until the cell wall is saturated, beyond which there is little additional change (Siau,1984).

Yavorsky (1951) believed that there were two types of conductivity in wood. The first being free ion or direct current and the second being bound ion and polar molecule displacement.

ELECTRICAL RESISTANCE IN THE CAMBIAL ZONE

The electrical properties of the cambium have been used to determine tissue activity, vigour and condition. The "cambium" that is normally referred to in the literature includes the actual cambium, the phloem and the cork cambium. The first publication of the idea of using the electrical resistance of the cambium as a measure of tissue activity (sap flow, bud break, etc.) was by Fensom (1960) and the idea was later studied by many authors (Davis *et al.*, 1979; Dixon *et al.*, 1978; and Piene *et al.*, 1984b). Since then, many studies have been conducted to determine tree vigour and condition by measuring the cambial resistance (Glerum, 1973; Wargo and Skutt, 1975; Smith *et al.*, 1976; Tattar, 1976; Newbanks and Tattar, 1977; Shortle *et al.*, 1977; Carter and Blanchard, 1978; Shortle *et al.*, 1979; Cole and Jensen, 1980; Kile *et al.*, 1982b; Shortle and Ostrofsky, 1983; Piene *et al.*, 1984a; and Gagnon *et al.* 1987).

Wilner (1960) measured the resistance of water extracts, (what he called "diffuse electrolytes"), to determine relative and absolute ratings of frost hardiness. Wilner (1967) found that the water extracts from severed shoots or frozen roots had lower cambial resistances than intact tissues. Glerum (1973) used the electrical impedance (a.c.) to detect frost hardiness in a similar manner.

The cambial resistance of trees have been used to determine the presence of vascular wilts (Tattar, 1976), determining the extent of cankers (Sylvia & Tattar, 1978), monitoring water potential (Dixon *et al.*, 1978; Gagnon *et al.*, 1987), and monitoring seasonal physiological changes within the tree (Davis *et al.*, 1979; Fensom, 1960).

As the tree goes into dormancy, the cambial zone begins to decrease in thickness and as the zone decreases, the cambial electrical resistance increases. When trees start to grow in the spring, the cambial electrical resistance usually decreases (Shigo and Shortle, 1985).

The biggest use of cambial resistance has been for the determination of tree vigour. Glerum (1970) used the ratio of the electrical impedance measured at different frequencies to determine vigour. Several studies have shown that the cambial resistance was higher for defoliated trees than for non-defoliated trees (Wargo & Skutt, 1975; Piene *et al.*, 1984a; Shortle & Ostrofsky, 1983; MacDougal *et al.*, 1988). Smith *et al.* (1976) found that by measuring the cambial resistance, one could differentiate between non-released, released, and released & fertilized trees. Piene *et al.* (1984a and b) discovered that cambial resistance was correlated with the amount of foliar biomass.

Shigo and Shortle (1985) felt that the Shigometer simply measures the thickness of the cambial zone (phloem, cambium and phellogen) and therefore the vigour. All of these other factors would be either a response to a thicker cambial zone or factors that would cause a thicker cambial zone.

Several studies have shown that the cambial resistance is correlated with vigour classes, but can only statistically differentiate between extreme vigour classes (Newbanks & Tattar, 1977; Kile *et al.*, 1982b; Kostka & Sherald, 1982). Growth rate, another function of vigour, also has been correlated with the cambial resistance (Shortle *et al.*, 1977; Shortle *et al.* 1979).

FACTORS AFFECTING ELECTRICAL CONDUCTANCE IN WOOD

The amount of electrical conductance in wood can be dependent on the amount of moisture present, the temperature, physical properties of the wood, the presence of ions and the type of voltage used to measure the conductance/resistance.

Moisture Content

The effect of moisture content on electrical conduction in wood is an important concept to understand. Moisture will either have a strong effect or almost no effect depending on the gross moisture content being considered. The fibre saturation point is the critical moisture content level in the conduction of electricity in wood. Below the fibre saturation point, conduction of an electrical current is highly dependent on the moisture content of the wood (Stamm, 1927; Barakas *et al.*, 1943; and Siau, 1984). The moisture content has been shown to be linearly related to the logarithm of the electrical resistance. Above the fibre saturation point conduction of an

electrical current is weakly and erratically associated with the moisture content (Brown *et al.*, 1963; Lin, 1967; and James, 1988).

Temperature Effects

Ambient air temperature has an effect on resistance readings when the moisture content is below the fibre saturation point but plays a much smaller role when above. Below the fibre saturation point, temperature is inversely related to the logarithm of the resistance (Hearle, 1952; Davidson, 1958; and James, 1988). Above the fibre saturation point, temperature becomes less critical (Lin, 1967). At the freezing point, the resistance dramatically increases (Glerum, 1969) because ions are no longer capable of moving freely.

Couture and Hill (1974) felt that ohmic heating, the heating of wood by passing a large or prolonged current or a high frequency current through it, would tend to decrease the observed electrical resistances.

Physical Properties of the Wood

The physical attributes of wood, its structure and density, can have an effect on electrical conduction. The direction of the wood grain can have an effect on the resistance to an electrical current. Resistance measured along the grain is lower than the resistance across the grain. This effect is directly related to the number and amount of physical barriers that must be passed (i.e. the cell walls) (Hart, 1964; Skarr, 1964; Lin, 1967; and James, 1988). Specific gravity (density) also is thought to have an effect on the resistance (Yavorsky, 1951).

Ions

The presence of ions that can carry charges is important to conduction in wood. Ions are considered to be the principal contributor to conduction in wood (Clark and Williams, 1933; Fensom, 1966; and Tattar *et al.*, 1974). The quantity of ions and the type of ions will generally determine the amount of conduction (Fensom, 1966). The greater the number of ions, the more conduction that can take place. Different ions carry different amounts of charge and have different mobilities; thus, the type of ion also can affect the amount of current conducted through the wood (Lin, 1965; and Yavorsky, 1951).

Current Type Used

Resistance is affected by the voltage and frequency used and whether direct current (d.c.) or alternating current (a.c.) is used. Higher voltages will tend to give lower resistance readings, a phenomenon sometimes referred to as the Evershed Effect (Yavorsky, 1951; and Davidson, 1958). A higher frequency will cause a lower resistance reading (Yavorsky, 1951).

The current type used also affects the polarization of the electrodes, which is a problem in making resistance measurements of wood. Polarization can be avoided by using an output signal that reverses the voltage, or a signal that turns the voltage on and off. This type of signal is a pulsed signal, it uses d.c. voltage in short small pulses rather than a constantly applied unvarying voltage (Brown, 1962; Williams *et al.*, 1964; and Skutt *et al.*, 1972).

ACCUMULATION OF IONS IN STAINED AND DECAYED WOOD

Because ions play such a major role in conduction above the fibre saturation point, it becomes important to understand when the ion types and concentrations change.

Total ash content (inorganic ion content) has been shown to be greater in discoloured and decayed wood as opposed to clear wood (Tattar *et al.*, 1971). Scheffer (1939) found an increase in ash content in the discoloured wood associated with tap holes, and Shigo and Sharon (1970) found an increase in ash content in discoloured wood associated with wounds.

Shevenell and Shortle (1986) working with red maple (*Acer rubrum* L.) and Shortle and Ostrofsky (1982) with balsam fir (*Abies balsamea* (L.) Mill.) also determined H^+ concentrations in discoloured wood and clear wood and found no difference.

Ross (1961) found an increase in bark Mn concentrations in red oak (*Quercus rubra* L.) trees that had cankers, and he found higher concentrations at the canker itself.

Shevenell and Shortle (1986) found that soluble K, Ca, Mn, and Mg were higher in the discoloured wood than in the clear wood, with Mg being highest at the clear wood boundary. They also found that some organic anions also were higher in the discoloured wood (acetate, malate, oxalate, and formate). They also found that K and Na were readily extracted with water, whereas Ca, Mg and Mn were not.

The general findings of these studies are summarized in Table 1.1.

Shortle and Shigo (1973) found that discoloured wood that yielded many hymenomycetes had a higher total Mn concentration than the adjacent clear wood. However, the discoloured wood that yielded few hymenomycetes had Mn concentrations similar to the adjacent clear wood.

Some authors have indicated that the boundary between the clear wood and discoloured wood has the highest concentrations of some ions (Shevenell & Shortle, 1986).

Ring shakes also have been shown to have a build up of Ca, Mg and K in the vicinity of the shake (McGinnes, 1971).

Table 1.1. Comparisons of ion levels between clear and discoloured wood.

Author	K	Ca	Mg	Na	Mn	Fe	Total Ash
Increases with wound associated discoloured wood:							
Blanchard *et al.*, 1978		*		*		*	
Safford *et al.*,1974	*	*	*	?	*		
Scheffer, 1939							*
Shigo & Sharon, 1970	*						
Increases with decayed wood:							
Ellis, 1959	*	*	*	*	*	*	
Increases with discoloured wood:							
Tattar *et al.*, 1971							*
Malia & Tattar, 1978		*	*	?	*		
Tattar *et al.*, 1972	*	*					
Good *et al.*, 1955	*	*					
Hart, 1968	*	*	*				
Shortle & Ostrofsky, 1983			*				
No change in ions:							
Tattar *et al.*, 1972				*			
Wilkes & Heather, 1982a			*	*	*	*	*
Wilkes & Heather, 1982b							*
Hart, 1968					*	*	
Shevenell & Shortle, 1986	*	*	*		*		

* Differences reported.
? Possible differences reported.

MOISTURE METERS

The amount of moisture in wood below the fibre saturation point can be determined by an ohmeter that is calibrated for this purpose. Moisture meters measure the very high resistances associated with predominately moisture limited conduction in wood below the fibre saturation point and not the predominately ion limited conduction that is associated with wood that is above the fibre saturation point (Tattar and Blanchard, 1976).

THE SHIGOMETER AND ITS THEORETICAL OPERATION

The Shigometer is a resistance meter or ohmeter that is used to measure the decreased resistance associated with the discolouration or decay of wood. The Shigometer uses an output signal that is a d.c. pulsed current, with a square wave output signal that is 0.5 uA, 0.5 ms in duration, occurring at intervals of 10 ms. This output signal will avoid the problems of higher voltages and the polarization effects associated with continuous signals, as previously described.

The Shigometer will only give accurate readings above the fibre saturation point, just as a moisture meters operational range is below it (Delmhorst Instrument Co., 1988; and Shigo and Shortle, 1985). The Shigometer measures the amount of resistance to an applied voltage. The current, above the fibre saturation point, is conducted presumably by the mobile cations that are present. Therefore, it is the quantity and type of mobile cations that will

determine the amount of resistance (Hearle, 1952; and Shigo and Shortle, 1985). Generally it is assumed that K, Ca, Mg, and Mn are the main cations that are responsible for electrical conduction in wood that is above the fibre saturation point.

The Shigometer operates between 0° and 60° C. No conversions are necessary for temperatures between 5° and 20° C. (Osmose Wood Preserving Co., 1980). There is some question as to the heating of the wood during drilling (Wilson *et al.*, 1982). However, the heat generated by the friction of the drill bit is dissipated rather quickly, and will not affect the readings. The physical damage that occurs to the cells while drilling, however, may have some effect on the readings (Wilson *et al.*, 1982).

Physical properties of the wood can have some effect on the readings (Yavorsky, 1951; Hart, 1964; Skarr, 1964; Lin, 1967a; and James, 1988). However, when the twisted wire probe is used, the grain orientation is of little significance, if the orientation of the hole is radial. When the needle probes are used, they should be oriented vertically, so that there are no cross grain measurements which will affect the readings.

Extremes in moisture content can also have an effect on the readings (Shigo and Shortle, 1985), such as when there is dry decay or "wet wood". If the wood is below the fibre saturation point the meter will not read correctly. In the case of "wet wood", the drill hole will be flooded and give very low resistance readings. Otherwise trees that are alive, and wood in service in ground contact, will generally have moisture contents above the fibre saturation point.

The season of the year has some effect on the use of the Shigometer. In the winter, the Shigometer can not be used since the wood is frozen, and little conduction will occur through ice, except at very high voltages. Also, just prior to leaf senescence in the fall, there will be an excess of moisture in the xylem, and the readings obtained will tend to be lower and little difference between readings of clear and discoloured wood will be detected. The flow of sap in the spring can also cause increased readings that will not necessarily be diagnostic of the wood condition.

The needle probes can also be used to differentiate between sound discoloured wood and discoloured wood associated with advanced decay in the ends of logs (Shigo and Shortle, 1985). The defective zones in the wood will tend to hold moisture longer than the sound wood, and over time the difference between the ER of sound and defective wood becomes greater (Shigo and Shortle, 1985).

Tree Vigour Assessment with the Shigometer

The number of ions that are present in the cambium, phloem and phellogen (referred to simply as the "cambium" in the literature) can be diagnostic of tissue activities in the tree as well as vigour.

When the Shigometer is used with the needle probes to detect vigor in trees, the meter will detect the ions associated with the cambial zone. When there is a large active cambial zone there will be a lower resistance (Carter and Blanchard, 1978; and Cole and Jensen, 1980). Therefore trees with a large, healthy, cambial zone will give lower resistance readings than will a tree that is growing slowly (Shortle *et al.*, 1977; and Tattar and Blanchard, 1977), or is

suppressed or diseased (since it will have a smaller cambium). There also may be a difference in the type and amount of ions present in healthy as opposed to diseased cambial zone.

The season will also alter the readings from the Shigometer. In the spring, when the buds are flushing, and as long as there is active growth, the resistance will be lower. Later in the summer and especially into the fall, the resistances will be higher (Piene *et al.*, 1984b; Kile *et al.*, 1982a).

Evaluation of the Shigometer

Although the theoretical basis for the Shigometer appears to be sound, the proof of its usefulness as a tool in the detection of stain and decay is in actual trials. The Shigometer has been shown to be effective for the detection of decay in utility poles (Shigo *et al.*, 1977; Shortle *et al.*, 1978; Thornton *et al.*, 1981; Zabel *et al.*, 1982). It has been shown to be able to detect many problems in different trees. The Shigometer has been used to detect discoloured and decayed wood in ash (*Fraxinus* sp.), horse chestnut (*Aesculus hippocastanum* L.), and sitka spruce (*Picea sitchensis* (Bong.) Carr. (Mercer, 1979). It has also been demonstrated to be able to detect watermark disease, caused by *Erwinia salicis* (Day) Chester in willow (*Salix alba* var. *caerula* Sm.) (Miller-Jones *et al.*, 1977), decay associated with *Fomes annosus* (Fr.) Karst. in red pine (*Pinus resinosa* Ait.) (Shigo & Berry, 1975), injury associated ring shake in black walnut (*Juglans nigra* L.) (McGinnes & Shigo, 1975). It also was able to detect discolouration and decay in soil-block decay tests of giant sequioa (*Sequoia sempervirens* (D. Don) Endl.) and white fir (*Abies concolor*

(Gord. & Glend.) Lindl. (Piirto & Wilcox, 1978), in *Pinus radiata* (Thornton, 1979a), and *Dyera costulata* (Thornton, 1979b).

There is some question still of having to make a hole , a wound, in the tree and the possibility of spreading infections between trees on the unsterilized drill (Miller-Jones *et al.*, 1977).

Trees may sometimes require more than one hole to detect the presence of a defect (Miller-Jones *et al.*, 1977). Wilson *et al.* (1982), working with red beech (*Nothofagus fusca* (Hock. f.) Oerst. felt that the drilling process altered the wood from the "natural" condition and altered it disproportionately. The Shigometer is actually measuring the resistance in a drill hole and not the wood in its natural state. The drill hole may have torn or compressed tissue, and loose fragments. The drilling process alters the wood differently from the outside of the beginning of the drill hole, where the drill bit will be present for a much greater time than at the end of the drill hole.

The Shigometer on its own will be of little value unless you have some knowledge of the patterns of defect that might be expected and some experience in interpreting the readings (Mercer, 1979; Shortle, 1979; Mercer, 1987). Thornton *et al.* (1981) proposed that the Shigometer is a good instrument for detecting internal defects but it should be used in conjunction with other techniques and should not be used as the sole determinator.

One of the advantages to using electrical resistance is the supposed ability of detecting discolouration and decay in its very early stages, before it can be visually detected (Zabel *et al.*, 1982; and Shortle *et al.*, 1978).

OTHER METHODS OF DETECTING STAIN AND DECAY

Several other methods have been designed to detect decay, specifically in utility poles, but are applicable to living trees. The simplest of methods combine visual evidence with resonant soundings, drilling (torque), picking, and the extraction of cores. These techniques can give good results but are dependent on personal judgements and experience. Therefore, an instrument that can quantify the results might be better.

Eslyn (1968) reported on an instrument that measured the force required to push a blunt pin into wood. The instrument is large and bulky, and will not detect discolourations or incipient decay, unless associated with a strength loss, or decay pockets less than 1 cm. Barret *et al.* (1987) reported a hand held compression strength meter. It, also, will not detect discolouration or the early stages of decay unless it has an associated strength loss. The probe creates a larger wound than other compression instruments or the drill hole for the Shigometer. Zabel *et al.* (1982) tested an impact energy absorption technique (Pilodyne), where a spring loaded pin is driven into the wood. That study found that the instrument correctly diagnosed 65 (+-12)% of the utility poles tested. The wood density, which will vary between and within species will have an effect on the results of all compression strength methods.

There are several types of borers that have been used to detect decay. The Pressler borer and the French Design auger both make

fairly large holes (Mercer, 1987). The French Design auger produces wood chips which are difficult to interpret. Borers, including increment borers, require visual examinations and the wood may appear sound even though it may actually be in the early stages of decay.

Some chemical tests have been developed to indicate the presence of decay (Eslyn, 1979). However, the colour changes may be subtle and confused further by the original colour of the wood. It is also difficult to interpret extent of decay from colour reactions. The chemical tests are also not necessarily universal, and therefore different chemicals may have to be used for different decay organisms and possibly even tree species.

Breuil *et al.* (1988) developed a technique using an enzyme-linked immunosorbent assay to detect staining by *Ophiostoma* sp. before the staining is visibly present. However, the technique is an involved laboratory procedure that requires specialized equipment and training, and is not suitable as a field technique.

Many ultrasonic detectors have been used to identify the internal conditions of utility poles. Methods have used longitudinal or transverse compression waves, resonance, and the acoustic velocity or damping is measured or resonance is measured (Dunlop, 1981). There are some technical difficulties with acoustic couplings, resolution, and response speeds but they are capable of differentiating a wide range of wood defects (Hailey and Morris, 1987).

Resonance techniques rely on the generation of longitudinal standing waves, when the frequency of excitation coincides with the

resonant frequency of the pole, which can then be detected (Smith, 1983; and Engineering Data Management Inc., n.d.). The results from these instruments are not easly interpreted in the field and the results, although correct, are a little vague (e.g. "heart rot area ratios").

Impulse radar has been investigated as a method of analysing the internal condition of trees (Canpolar Inc., 1987). Plots of radar echoes can be dificult to interpret and the instrumentation is not yet available in a portable package that is set up for inspecting trees.

X-ray and gamma-ray techniques also have been used to determine the internal condition of utility poles in the form of gross density mapping. These techniques, however, involve equipment that is usually not very portable (Mercer, 1987; McGinnes & Shigo, 1975). There is also a high cost and a high degree of training required to operate the equipment and interpret the results (McGinnes & Shigo, 1975; and Hailey and Morris, 1987). These radiographic techniques are not able to detect discolouration or incipient decay and work best at detecting large pockets of advanced decay and voids (Mercer, 1987; Zabel *et al.*, 1982; McGinnes & Shigo, 1975; and Hailey and Morris, 1987).

Magnetic resonance also has been investigated (Hailey and Morris, 1987). Magnetic resonance provides two-dimensional images of the chemical environment and proton (H^+) distribution. Although this method shows much promise, its cost and the great deal of experience required to operate and interpret the results detract from its usefulness.

Other methods that have been tried include: the use of "sniffer" dogs (Swedjemark, 1989), which apparently is reasonably effective; CO_2 detection (Hailey and Morris, 1987; Smith, 1983; and Zabel et al., 1982), which is not as easly conducted as it sounds; and the measurement of the moisture content (Hailey and Morris, 1987), which is not always correlated with extent of decay.

Although there are many techniques to detect the presence of decay, some are more effective than others and some take very advance technologies to make a complicated result of a simple answer. Magnetic resonance mapping, for example, is a very "exciting" technique but may be excessive if a visual inspection and an increment core will give the level of results desired.

THE "RED HEART" OF BIRCH

"Red heart" of birch has been recognized since at least the turn of the century. Dana (1909) thought that the red heart was the normal heartwood of birch. Fritz (1931) isolated *Torula ligniperda* (Willk.) Sacc. (later to be called *Trichocladium canadense* Hughes) from the red heart of birch. He inoculated sterilized wood blocks and got a similar discolouration, and he therefore concluded that *T. ligniperda* caused red heart.

Campbell and Davidson (1941) noticed that trees with well healed branch stubs had little red heart, whereas, trees that had course branch stubs, wounds, etc, were often badly "red hearted" . They also noted that trees less than 50 years old, regardless of

condition, had little "red heart". Shigo and Sharon (1968) considered red heart to be wound altered tissue, where organisms that could compete and infect the wound altered tissue would survive.

Siegle (1967) felt that red heart was the result of phenols, (pyrocatechol, coniferyl alcohol, pyrogallol, and catechin). He felt that the fungi associated with the red heart were the producers of the phenol oxidases which catalyze the discolouration process. He also felt that *T. canadense* was not able to catalyze the discolouration process, and was therefore, not responsible for the red heart. He extracted wood blocks with hot water and these blocks did not brown when inoculated with fungi, supposedly because the phenols were no longer present in the extracted wood. The phenolic compounds in extracts of clear wood were not found in extracts of discoloured wood.

WOOD DISCOLOURATION

Wood in a living tree will discolour for several reasons. As wood ages, the living parenchyma cells will eventually die. When this happens deposits may form in what is commonly termed "heartwood". Wounding will also cause discolouration in trees.

The source of the discolouration from wounding is alternately argued (by different authors) as being a response by the tree or is caused by microorganisms. An initial light discolouration will occur within 7 days of wounding (Sucoff *et al.*, 1967). Bauch *et al.* (1980) felt that the discolouration is caused by accessory compounds that

develop in the strand and ray parenchyma. Sucoff *et al.* (1967) felt that the early discolouration is probably due to the oxidation of phenolic compounds produced in the xylem parenchyma from stored lipids. Therefore, air entering the tree through a wound may cause the oxidation of phenols, which is the early discolouration. It was also noted that the pigments, or their precursors, don't appear to be translocated via the phloem, and that microbial factors were not involved in the early discolouration.

The microbial origin of discoloured wood as purported by Boddy and Rayner (1983) is not commonly supported in the modern literature. Boddy and Rayner felt that fungi were present (as bud cells, mycelial fragments, or oidia) throughout the tree at all times. It is then the increase in oxygen and the reduction of the moisture content that accompanies a wound that allows the microorganisms, which are already present, to grow. Sucoff *et al.*, (1967) felt that four lines of evidence suggested that microorganisms were not essential in inducing early discolouration; 1) the inability of biocides to reduce discolouration, 2) the orderly sequence of metabolic changes with time that accompanied discolouration, 3) the absence of fungi from microscopic sections, and 4) the spread of the discolouration almost solely with the grain. Shigo and Sharon (1968) found that microorganisms were seldom associated with the distal margins of the discolouration, which would seem to imply that the microorganisms are secondary to the early discolouration. Also, the severity of the wound was more important in determining the extent of discolouration than was the introduced fungus.

The initial, "early", discolouration appears to be replaced by a deeper coloured discolouration by the end of the first year after wounding (Sucoff *et al.*, 1967).

There appears to be a chemical difference between normal heartwood and discoloured associated with wounding (Hillis, 1968). Shigo and Hillis (1973) felt that heartwood and wound associated discolouration differed in method of formation and in the types of extractives and an increase in inorganic elements in wound associated discoloured wood. Shortle and Ostrofsky (1983) indicated that discoloured wood has a higher free water content and higher potassium ion concentration than does heartwood. They also indicated that heartwood had a higher water soluble phenol content than does wound associated discoloured wood.

The colour of wound associated discoloured wood is caused by deposits and extractives. Good *et al.* (1955) found that the discoloured wood of *Acer saccharum* was composed of dark material principally in the parenchyma cells, with vessels and fibres sometimes showing brown inclusions. Good *et al.* (1955) believed that the stain was caused only by fungi interacting with the wood. Scheffer (1939) in his work with hard maples, felt that the wound associated discolouration (which he called "mineral stain") was mainly confined to the ray cells and vessels. These ultimately contained dark globular masses of material that were directly responsible for the colour. Hillis (1968) found that the resinous polyphenolics and other extractives in heartwood are almost entirely located in the ray parenchyma. He also felt that there was much

evidence that indicated that heartwood extractives arose *in situ* from translocated or stored carbohydrates.

Bauch *et al.* (1980) believed that the longitudinal discolouration is caused by accessory compounds that develop in the strand and ray parenchyma.

The new wood that is laid down by the tree after wounding is distinct from normal wood. Bauch *et al.* (1980) indicated that the new wood had an increased number of parenchyma cells, decreased number and diameter of vessels, decreased fibre length and decreased cell wall thickness. This tissue started to return to normal at the end of the first season, but it may take several years before it is completely normal.

CHAPTER II: DESCRIPTION OF RED HEART IN PAPER BIRCH

Red heart of paper birch has been, and still is, somewhat misunderstood. It was thought that red heart was the normal heartwood of paper birch, (Dana, 1909), until Fritz (1931) recognized that paper birch did not have a normal heartwood. Campbell and Davidson (1941) noticed a correlation between the number of branch stubs and wounds and the extent of red heart, and Shigo and Sharon (1968) considered it to be wound altered tissue. The discolouration has been attributed to fungi (Fritz, 1931), enzymic oxidation (Siegle, 1967), and to normal wound altered tissue (Shigo and Sharon, 1968) without the presence of microorganisms.

The intent of this chapter is to describe the red heart found in the sample material used in the subsequent studies. An attempt is made to locate deposits, at a cellular level, that may influence the readings of the Shigometer. The presence of microorganisms is also examined in relation to the red heart and their possible influence on Shigometer readings.

MATERIALS AND METHODS

Wood samples were taken from the clear wood, discoloured wood and from the transitional boundary between clear and discoloured wood of living paper birch trees. These samples were either taken from trees that had been felled or from increment cores removed from standing trees.

Discoloured and clear wood samples were sectioned by hand or with a sliding microtome. Some of the sections were left unstained to avoid dissolving any soluble deposits that may be present and other sections were stained with picro aniline blue (Wilcox, 1964) to differentiate any microorganism that might be present from the wood. The sections were examined with a Zeiss photomicroscope.

Other microtomed wood samples (90 um thick) were prepared for observation on an Hitachi S-570 scanning electron microscope (SEM). A few drops of water were used to lubricate the block surface and the knife. The samples were then attached to a mounting stub and allowed to air dry before being sputtercoated and viewed under the SEM.

Wood samples were also hand sectioned and examined under the dissecting microscope.

Attempts were made to isolate fungi from 20 living paper birch trees. The isolations were taken with an increment borer that was cleaned with 1% sodium hypochlorite. The cores were then divided between clear or discoloured wood and placed into petri dishes containing malt agar (2.5% malt extract). There was a total of 20 clear wood and 15 discoloured wood samples taken from the 20 trees. The culture plates were left on the bench top and when fungal growth was noticed, hyphae were transferred into a fresh culture plate. Identifications were made of fungi that sporulated.

Finally, four trees with red heart, as determined by increment borer, were felled. The stems were cut longitudinally in order to establish the pattern of red heart discolouration throughout the stem.

RESULTS

The light microscope and scanning electron microscope examinations showed that in the red heart there were dark and sometimes granular deposits in the ray parenchyma (Figure 2.1). Generally the vessels did not have occlusions plugging the entire vesssel, but rather deposits on the sieve plates which tended to block them. Fewer longitudinal parenchyma and vessels contained deposits as you moved further into the discoloured wood. Ray parenchyma contained deposits in the red heart even when they were no longer seen in the longitudinal parenchyma.

The longitudinal parenchyma and vessels in the clear/discoloured wood transition zone, as well as the ray parenchyma in this region, also had dark and sometimes granular deposits in the cell lumens (Figure 2.1). In the transition zone some vessels were completely plugged.

There were no deposits in the longitudinal parenchyma, radial parenchyma or vessels of the clear wood (Figure 2.1).

No evidence of fungal hyphae nor bacteria were seen in any of the light microscope or SEM sections.

Although the light microscope and SEM sections showed a reasonably distinct barrier zone of occluded cells, the dissecting microscope examinations showed that the edge of the discoloured zone did not appear as a distinct line, but rather a fading of the clear wood into the discoloured wood. The colour change tended to be gradual rather than abrupt. Vessels were occluded at the boundary

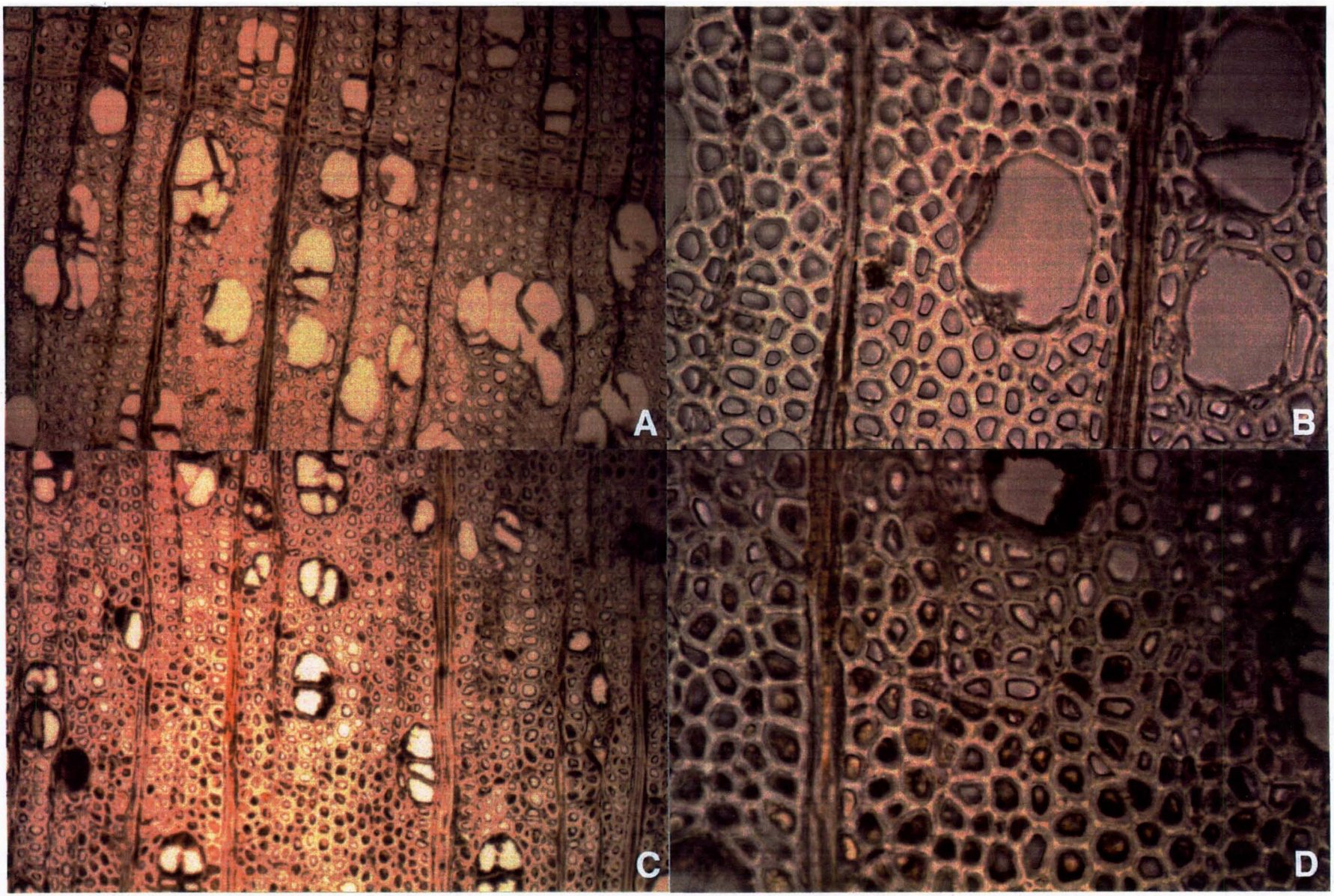

Figure 2.1. Photomicrographs of thin sections of clear (A & B) and discoloured (C & D) paper birch xylem. (1100 & 2200 X)

but no blocked vessels were observed in the clear wood or deeper in the discoloured wood.

The trees that were felled and dissected showed a column of red heart that tapered out in both longitudinal directions similar to a wound compartment under the CODIT model (Shigo and Marx, 1977). The discoloured wood compartment ended just above the root collar and tapered out some distance up the tree, most often in apparent association with old branch stubs. The red heart resembled a wound compartment much more than it did heartwood, since it was not always centrally located in the stem through the entire length of the compartment. Campbell and Davidson's (1941) findings of the amount of red heart being proportional to the condition and age of the tree were also upheld in these examinations.

The identified fungi from the 20 increment cores (15 containing red heart) of clear wood and the discoloured wood were non-hymenomycetes. There were no distinct difference in species isolated or number of isolates between the clear wood and the discoloured wood (Table 2.1).

Table 2.1. Microorganisms isolated from living paper birch xylem.

Microorganism	Clear Wood	Red Heart	Total
Alternaria sp.	1	0	1
Aureobasidium sp.	2	3	5
Cephalosporium sp.	0	2	2
Cladosporium sp.	2	1	3
Geotrichum sp.	1	0	1
Nigrospora sp.	1	0	1
Penicillium sp.	8	4	12
Rhinocladiella sp.	0	2	2
Trichocladium sp.	0	5	5
Trichoderma sp.	1	1	2
Tritirachium sp.	1	1	2
Dissophora sp.	5	3	8
Bacteria	5	4	9
Clean (no isolates)	1	0	1
Total	28	27	55
Wood Samples	20	15	35

DISCUSSION

The pattern of the red heart as observed with the dissecting microscope, light microscope and SEM, indicate that it is a wound compartment with a distinct barrier zone and is in agreement with Shigo and Marx's (1977) CODIT model. The observable colour change in the wood (with the naked eye or the dissecting scope) is more gradual than the distinct barrier zone of occluded cells that can be seen at the microscopic level. Although the barrier zone is a relatively abrupt change in the wood, there are some changes occurring, more gradually in front of and behind the barrier zone. The pattern of the red heart columns in the dissections of the trees also supports the wound compartment conclusion.

The lack of hymenomycetes in the isolations would seem to indicate that the red heart is not the result of decay. *Trichocladium canadense* was not a predominate isolate. It was recovered from only one third of the red heart samples and made up less than one fifth of all the isolates from the red heart. Shigo and Sharon (1968) also found that *T. canadense* could not be isolated consistently from red heart samples.

The existance of fungi in the clear wood of both trees with and without redheart, would indicate that fungi are a normal component of the clear wood and are not necessarily deliterious to the tree. These non-hymenomycetes may play a primary role in the succession of microorganisms that are found in a tree after wounding.

Since there is no abrupt change in the presence of fungi from the clear wood to the red heart, it appears that the Shigometer is not responding to an effect created solely by the presence of fungi.

The lack of evidence of fungi in the microscopic sections might indicate that the discolouration is not caused by microorganisms. It could be argued that no visual evidence (i.e. hyphae) was seen in the sections examined but may have been present in other sections which were not examined. This might be possible, however, if the fungi are only sparsely distributed through the wood (such that by chance none were present in the sections examined), it would be unlikely that the fungi could cause the amount of discolouration that is present. Therefore, it would seem more likely that the discolouration is caused by the tree itself, either as an active process or a passive chemical oxidation of compounds that are already present in the tissues.

CHAPTER III: EVALUATION OF THE SHIGOMETER FOR DETECTING RED HEART IN PAPER BIRCH

The Shigometer was developed based on an instrument that used a pulsed current to measure the electrical resistance inside a tree, in order to describe its internal condition (Skutt *et al.*, 1972).

The Shigometer is a pulsed current resistance meter. It is an ohmeter that uses an output signal that has short pulses rather than a constant signal of direct current. The pulsed signal is 0.5 uA for 0.5 ms at 10 ms intervals. The Shigometer can measure resistances on two different scales, 0-500 k ohms and 0-50 k ohms.

The Shigometer is used to detect stain and decay in wood in service (i.e. utility poles) and in living trees (Shigo and Shigo, 1974). This is accomplished by drilling a small hole into the tree or wood and inserting a small twisted wire probe with a pair of contact points at its end. As the probe is inserted into the tree, the readings on the meter are monitored, a sharp drop in resistance readings would normally indicate the presence of stain or decay at that depth. The Shigometer can also be used to determine the vigour of living trees by measuring the resistance of the cambium with a pair of needle probes inserted through the bark (Shigo and Shortle, 1985).

It works on the theory that stained and/or decayed wood will have a greater quantity of mobile ions, particularly K, Ca, Mg, and Mn than will sound wood (Shigo and Shortle, 1985).

The origin of these mobile ions is a matter of dispute. One theory suggests that the mobile ions are present in the wood as

bound ions before the wood is altered by the staining or decay, or are brought in by the microorganisms (Shortle and Smith, 1973; and Tattar *et al.*, 1972). The process of staining or decay then releases the ions from their bound form to a mobile form. With the increase in mobile cations, there will be a decrease in the resistance measured by the Shigometer.

A second theory suggests that the increase in the mobile ions is a response by the tree. This response would be part of the process that occurs in the creation of phenolic compounds during the formation of wound compartments (Shortle and Smith, 1987). However, this theory, in itself, would not account for an increase in ions during staining and decay of wood in service or soil block decay studies, since the tissues are no longer active.

Other theories imply that an increased moisture content of the wood during staining and decay causes the decreased resistance readings. Although the Shigometer only functions correctly on wood that is above the fibre saturation point, the amount of moisture present above the fibre saturation point does not determine the amount of resistance measured. Shigo and Shortle (1985) measured tap water with the Shigometer and found that the water content alone did not give low enough resistance readings to adequately explain the resistance readings that could be found in wood.

The degeneration of the cell structure during decay might allow for a lessening of physical barriers to the conduction of an applied current (Wilkes and Heather, 1982a).

This study attempts to determine to what degree of accuracy the Shigometer is capable of detecting the "red heart" discolouration commonly found in paper birch.

MATERIALS AND METHODS

The Shigometer was tested on 56 living paper birch trees and on the cut faces of 50 recently cut logs gathered at a landing at Lakehead University's Jack Haggerty Forest near Thunder Bay. The stands from which the trees and logs were obtained were mixedwood stands (Bw Pj Po, Sb Bw Po Bf, or Sb Bw Bf Pj) site class 2 with stockings from 0.5 to 0.7.

The 56 standing trees had an average DBH of 19.5 cm and ranged in diameter from 10 to 35 cm. These trees were randomly choosen from within birch stands in the woodlot. A 2.4 mm diameter hole was drilled into the trees at breast height (1.3 m). The twisted wire probe, being kept with the contact points in the horizontal plane, then was used to determine the resistance readings every 1 cm along the length of a single radius. The resistance readings from the meter were used to predict the actual condition based on 70% and 75% decreases from the maximum reading. Stain was said to be present when the readings were above the percent decrease critical values. These determinations were done in the field by estimating the critical values from field scales. The field scales were developed for the appropriate percent decreases from maximum resistance rules (Figure 3.1).

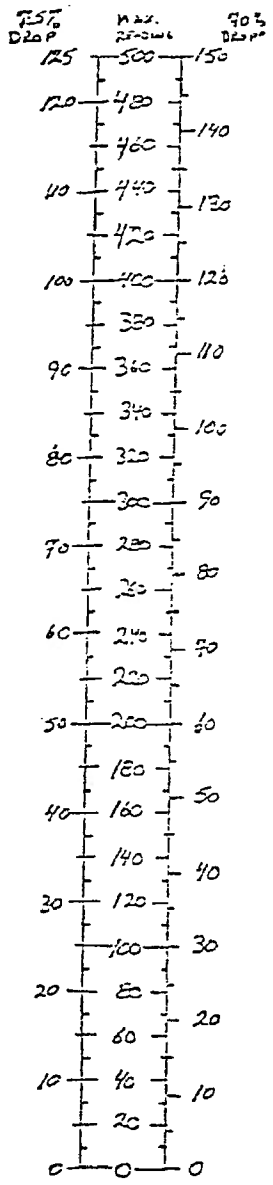

Figure 3.1. Field scale used for the determination of critical points for the 70% and 75% decrease from maximum resistance rules.

Figure 3.2. Typical examples of "red heart" discolouration and clear wood in paper birch.

Predictions based on 15% to 85% decreases from the maximum reading rules were calculated afterwards. An increment core was then taken, and the actual condition of the radius was determined by visual examination of the core.

The cut faces of the 50 logs, which had been felled within a few weeks of the time of measurement, were examined with the needle probes. The logs averaged 22 cm in diameter and ranged in diameter from 14 to 36 cm. Stain was present to some degree on all but four of the cut faces of all the logs choosen. Figure 3.2 shows the typical discolouration. A reading was taken every 2 cm on two radii from each log (92 radii with stain and eight radii without stain). The predicted conditions were compared with the actual conditions. These comparisons were made after the readings had been taken and the visual conditions of the faces of the logs had been determined.

The accuracy of the meter was evaluated as the difference (in cm) of the predicted radius of stain from the actual radius of stain, such that a negative result indicated an underestimate of the amount of stain and a positive result an overestimate. Also, it was noted when stain was not detected by the meter, when the meter falsely detected stain when it was not present, and when the meter correctly detected the absence of stain.

RESULTS

Of the 56 standing trees analysed, 19 trees did not have any stain and 37 showed the presence of stain. The discoloured wood could be detected on average with a decrease in resistance of approximately 50% from the maximum reading (Figure 3.3). Using a 50% decrease from maximum reading rule allowed for 23 of the 37 trees that had stained wood to have the location correctly predicted within 2 cm. At the same time in six of the 37 trees with stain, the stained wood was not detected and only three of the 19 trees without stain were incorrectly assessed (Table 3.1). In 84% of the standing trees the presence of stained wood was correctly assessed within 3 to 4 cm.

Using a 75% decrease from the maximum rule led to only half of the trees with stain to be correctly assessed (Table 3.1). However, it allowed for no false detections when stained wood was not present.

The condition of the cut faces of the logs could be assessed by using a prediction rule of approximately a 50% decrease in resistance from the maximum reading (Figure 3.4). Using a 50% decrease rule allowed for 82 of 92 radii with stained wood to have it located within 2 cm. At the same time 9 radii that had stained wood were not detected and 4 radii of the 8 without stained wood were incorrectly assessed (Table 3.2). In 87% of all attempts, the presence of stained wood was correctly detected within 2 to 4 cm.

The 75% decrease rule allowed for the location of stained wood in 62 of the 92 radii within 2 cm, while missing 27 radii that had

stained wood. However, no radii were falsely predicted to have stained wood when it was stain free.

The complete results for the 15% decrease to the 85% decrease from the maximum readings (in 5% intervals) are found in Appendix I.

The meter appears to be able to slightly better predict the presence and location of stained wood in the cut faces of logs compared to the standing trees.

The Shigometer readings tended to show a decrease in resistance prior to the barrier zone.

Table 3.1. Shigometer performance in predicting location of discoloured and clear wood in individual trees.

Predicted - actual radius of discolouration	Decrease from maximum reading when stain is predicted		
	50 %	65 %	75 %
No Stain Present (19 trees):			
Correct Detection	16	17	19
False Detection	3	2	0
Stain Present (37 trees):			
+ 4 cm[1]	2	1	0
+ 3 cm	1	1	1
+ 2 cm	3	0	0
+ 1 cm	8	4	1
0 cm[2]	13	9	10
- 1 cm[3]	2	5	3
- 2 cm	1	2	1
- 3 cm	1	2	2
Not detected	6	13	19

[1](+) Overestimate of the extent of discolouration.
[2](0) Predicted extent equals actual extent of discolouration.
[3](-) Underestimate of the extent of discolouration.

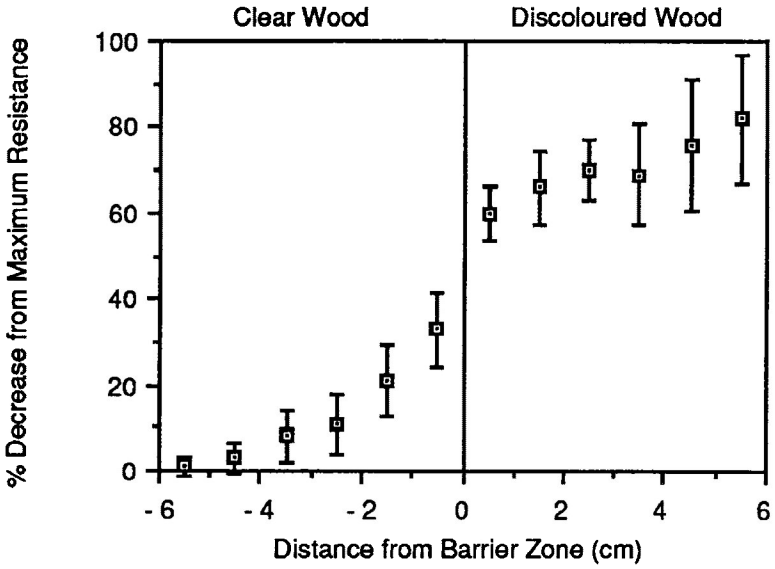

Figure 3.3. Average percent decrease from maximum resistance reading for living paper birch trees with discoloured wood (95% Confidence Interval shown).

Table 3.2. Shigometer performance in predicting location of discoloured and clear wood in individual logs.

Predicted - actual radius of discolouration	Decrease from maximum reading when stain is predicted		
	50 %	65 %	75 %
No Stain Present (8 radii):			
Correct Detection	4	7	8
False Detection	4	1	0
Stain Present (92 radii):			
+ 4 cm[1]	1	0	0
+ 2 cm	14	6	2
0 cm[2]	59	53	44
- 2 cm[3]	9	14	16
- 4 cm	0	2	2
- 6 cm	0	1	1
Not detected	9	16	27

[1](+) Overestimate of the extent of discolouration.
[2](0) Predicted extent equals actual extent of discolouration.
[3](-) Underestimate of the extent of discolouration.

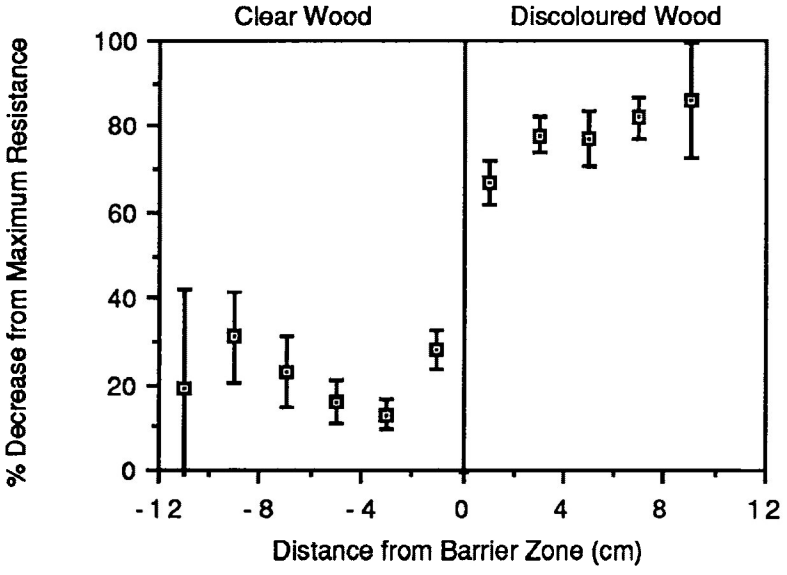

Figure 3.4. Average percent decrease from maximum resistance reading for paper birch logs with discoloured wood (95% Confidence Interval shown).

DISCUSSION

The meter was able to detect the presence of red heart in most cases, but as with most techniques, it is not a perfect method. On average a detection rule of a 50% decrease from the maximum reading was sufficient to predict the presence and approximate location of stained wood in white birch. Using a 50% decrease from the maximum reading will allow some false detections to occur but few trees with discoloured wood will not be detected. Using the 75% decrease from the maximum reading will give more "missed" detections but no false detections will occur. The choice of the percent decrease from the maximum reading that will be used to determine the presence of discoloured wood is dependent on which side a conservative prediction is desired.

It should be kept in mind that stain or decay columns do not occur as an abrupt change, there is a short transition from clear to discoloured wood (as noted in the previous chapter). There was a tendency for the position of the red heart to be predicted earlier than the "actual" visible red heart position. This may be the result of the Shigometer detecting the begining of the transition of the clear to discoloured wood (Shigo and Shortle, 1985).

Wilson *et al.* (1982), working with red beech (*Nothofagus fusca* (Hook. f.) Oerst.), also found a decrease in resistance readings with discolouration. However they were not able to state that statistically the patterns of resistance readings could be placed into one of the four catagories of wood condition that were actually present in the

sampled trees (clear wood, heart wood, discoloured heartwood, and decayed heartwood).

Wilson *et al.* (1982) noted that the duration of the drilling of the probe hole can have an effect on the resistance readings. Drill holes were made from the bark to the pith and from the pith to the bark, and the far ends of the drill holes had higher resistance readings than the near end for the same position in the wood. Therefore, drilling must be consistent, which is not always possible throughout the hole. The twisted wire probe also has problems with maintaining contact with the wood. They correctly noted that the Shigometer really measures the resistance of the wood surrounding the drill hole and not the resistance of the wood in its natural condition.

The results for the logs being slightly better than for the living trees may be due to the difference in the probes being used. The needle probes give a solid contact between the probe and the wood. The twisted wire probe can not keep enough pressure between the probe and the wood to maintain a consistent and solid contact. The successful application of the Shigometer requires that the operator understand the basic patterns of decay and the obvious external signs of a trees internal problems (Shortle, 1979) as well as the limits of his instruments.

The needle probe gave lower resistance readings than the twisted wire probe. This is mostly due to the quality of the contact between the probe and the wood. The needle probe is pushed into the wood so that there is tight, consistant contact between the probe and the wood. The twisted wire probe has poorer physical contact

and is susceptible to false readings due to contact disruption by loose pieces of wood fibre.

The tendency to have a decrease in resistance prior to the barrier zone is consistent with Shortle (1982) and supports the idea that the barrier zone is a more gradual than abrupt transition from clear to discoloured wood.

The instrument could be improved for detecting internal discolouration if a method of ensuring a solid contact between the wood and the probe (such as with the needle probes) could be developed.

CHAPTER IV: ION ACCUMULATION IN THE RED HEART OF PAPER BIRCH

The Shigometer works on the theoretical basis that there is an increase in soluble ions in stained and decayed wood over that found in the clear wood (Shigo and Shigo, 1974). Unfortunately, most of the earlier studies measured the total ion concentrations as total ash or total concentration of individual ions (Wilson *et al.*, 1982). Since the Shigometer theoretically operates on the basis of soluble ions, it would make sense to measure only the soluble ion concentrations.

This study attempts to measure the amount of soluble and insoluble ions in order to determine if there is a relationship between these ionic concentrations and the meter readings from the Shigometer. Also, an attempt is made to locate where the ion concentrations occur at the cellular level.

MATERIALS AND METHODS

Twenty four paper birch trees were randomly selected in August and September 1988, before leaf fall, from stands at Lakehead University's Jack Haggerty Forest. The stands were predominately 60-yr-old birch site class 2 with an 80% stocking. The average DBH of the trees was 18 cm and they ranged from 11 to 30 cm in diameter. On each of these trees a Shigometer measurement was made with a twisted wire probe. Four increment cores were

then taken around the Shigometer probe hole. The Shigometer readings were taken at centimetre intervals from the outside bark. The four increment cores were divided into 3 cm lengths such that the samples were either discoloured wood or clear wood, with as many samples as possible being removed from each core. The parallel 3 cm segments from each core from the same tree were placed in screw cap test tubes and then brought back to the lab.

The soluble ions were extracted according to a procedure similar to that used by Shortle and Smith (1987). The main difference being that whole cores were used rather than ground wood samples. The cores were placed in standard 20 x 150 mm test tubes with 15 ml of deionized water. The test tubes then were placed under a water siphon vacuum. The vacuum was created by plugging the test tube with a stopper that had a glass tube running through it, which was connected by a rubber tube to a water siphon. The vacuum was maintained for 2 min. at a low enough pressure to just keep the air bubbles rising to the surface without allowing the sample to boil up the vacuum tube. The test tubes were then placed in a hot water bath that was maintained at 90° C. The test tubes were "swirled" after 15 and 30 min. and removed from the hot water bath after 1 hr. The extract solutions were then filtered through Whatman No. 1 filter papers. The "extracted" cores then were placed in a drying oven set at 100° C for 24 hrs. Their oven dry weights were recorded. The extracted samples were placed back into the screw cap test tubes for later acid digestion. The extract solution was then analysed for ions by Inductively Coupled Plasma Atomic Emmission (ICP-AE) spectrometry. The ions analysed were K, Ca, Mg,

Na, Mn, and Fe. These ions were selected on the basis of their expected occurrence and concentration as shown by earlier tests of the ion concentrations in extract solutions and their theoretical conductivities. The possiblity of conduction by organic compounds was not considered because of their low conductance values due to their relatively large molecular size.

Once the extract solutions were returned from ICP-AE spectrometric analysis, the pH of the solutions was measured, and a Shigometer reading of each extract solution was taken. Care was taken not to touch the sides of the test tube with the probe.

Deionized water control tubes were handled just as were the extract solutions. The result of the ICP-AE spectrometry of the controls were averaged and used as a correcting factor for background ionic concentrations. The correction was applied to the conversion of the extract solution concentrations to ion concentrations in the wood (Blanchard *et al.*, (1978) as follows:

$$\text{Wood (ppm)} = \frac{(\text{Extract Solution(ppm)} - \text{Control(ppm)}) * \text{Dilution Volume(ml)}}{\text{Oven Dry Weight of wood sample (g)}}$$

Dilution Volume = **15 ml.**

These extract solutions (converted to ppm in the wood) were considered to be the "soluble" ions.

Once the water extractions were completed, and the ODW of the wood samples determined, the wood cores were stored (oven dry) in screw cap test tubes for complete acid digestion.

These cores were placed in 50 ml beakers and digested with the sulfuric acid-hydrogen peroxide method according to Lindner (1944). Each digestion of 1.0 g (ODW) of wood was made by adding 4 ml of concentrated sulfuric acid (H_2SO_4) 2 ml at a time. One ml of 30% hydrogen peroxide (H_2O_2) was then added 0.5 ml at a time. The beakers were then placed on the hot plate, set on high, for no more than 1-2 min (when the acid began to bubble). They then were removed from the heat and allowed to cool. Then another 1 ml (0.5 ml at at time) of H_2O_2 was added and the beaker returned to the hot plate. Digestion proceeded until white fumes were observed. At this time, the beakers were again removed from the heat, allowed to cool, and another 0.5 ml of H_2O_2 was added. This last step of adding H_2O_2 was repeated until the liquid was completely clear (the final additions of H_2O_2 was normally less than 0.5 ml so as not to unnecessarily add an excess of H_2O_2 to the digestion). Approximately 8 ml of H_2O_2 was used for each digestion of 1.0 g of OD wood.

Once the digestions were complete, the samples were diluted to 30 ml with deionized water and then two 10.0 ml samples were analyzed by ICP-AE spectrometry for K, Ca, Mg, Na, Mn, and Fe.

Controls were established by boiling 4 ml of H_2SO_4 and 8 ml of H_2O_2 down to approximately 3 ml and then diluting to 30 ml with deionized water. Three controls were prepared and one sample from each control was analysed by ICP-AE spectrometry with the other samples.

A previous test demonstrated that the digestion procedure was adequate and the error between replicate digestions was always within 5% of the mean and usually within 2% of the mean.

The data from the ICP-AE spectrometry was converted to ppm in the wood after subtracting the controls as follows:

$$\text{Wood (ppm)} = \frac{(\text{Extract Solution(ppm)} - \text{Control(ppm)}) * \text{Dilution Volume(ml)}}{\text{Oven Dry Weight of wood sample (g)}}$$

Dilution Volume = **30 ml.**

The ion concentrations from the digestions (converted to ppm in the wood) were considered to be the "insoluble" ion concentrations. The sum of the "soluble" and the "insoluble" ion concentrations was considered to be the "total" ion concentration.

Conductance Factors (CF) were calculated for each of the ions for the soluble, insoluble and total concentrations. The Conductance Factor is equal to the sum of the ion concentrations (ppm) in the wood multiplied by their respective ionic conductances (10^6 $ohms^{-1}$ cm^{-1}). The Conductance Factors do not equal the actual conductances, but rather reflect the theoretical ability of the concentrations and types of ions present to contribute to a total conductance. The ionic conductances for the six ions under consideration are presented in Table 4.1.

Table 4.1. Ionic conductances.

Ion	Conductance (10^6 $ohms^{-1}$ cm^{-1})
Potassium (K)	0.139
Calcium (Ca)	0.298
Magnesium (Mg)	0.226
Sodium (Na)	0.210
Manganese (Mn)	0.007
Iron (Fe)	0.093

Source: Sargent-Welch (1980).

A scanning electron microscope (Hitachi S-570) was used with supplementary detectors to determine the emission counts and maps for elements at specific locations within the samples. Wood samples of clear, discoloured and transitional tissues were taken from living paper birch trees with an increment borer. The wood samples were sectioned (90 um) on the microtome and then affixed to an SEM stub. They were then allowed to air dry before being carbon coated and examined.

Natural logarithm transformations were required for some of the data in order to make their variances homogeneous.

RESULTS

The analysis indicates that there are differences in concentrations for most ions between the clear and discoloured wood. The discoloured wood generally has higher concentrations of ions. The increased ion concentrations in the discoloured wood were generally correlated to a decrease in the resistance.

The t-tests for the soluble, insoluble, and total ion concentrations for Na and Fe had no significant differences ($P \leq 0.01$) between the clear and discoloured wood (Table 4.2). Calcium, Mg, and Mn showed highly significant increases in concentration in the discoloured wood compared to the clear wood. The discoloured wood had higher concentrations of these ions in the soluble and insoluble fractions. Potassium was significantly higher as a soluble ion in the discoloured wood, but there was no significant difference in the insoluble ion concentration (Table 4.2). The electrical resistance of the wood was significantly lower in the discoloured wood than in the clear wood.

The extract solution ion concentrations were all significantly greater for the discoloured wood than for the clear wood, except for Na and Fe. The conductance factor (CF) was significantly greater in the discoloured wood than the clear wood (Table 4.3).

The extract solution resistance (SR), as measured by the Shigometer, was significantly lower for the discoloured wood than the clear wood. There were no significant differences between the pH values for the clear wood and discoloured wood. A test of the

deionized water samples showed an average resistance of 58 K ohms with a standard error of 5.3.

A multiple regression and Pearson correlations were run for wood resistance with soluble, insoluble, and total ion concentrations and for wood resistance with the conductance factors. Due to the maximum interpretable reading of the Shigometer being 500 K ohms and that clear paper birch wood, as measured with the twisted wire probe, was frequently 500+ K ohms, the regressions have an artificial upper boundary at that point. This causes the regression, although mostly significant, to have relatively low correlation coefficients for both the ions and the conductance factors (Table 4.4). A negative relationship exists between the resistance of the wood and most of the soluble, insoluble and total ion concentrations and with the conductance factors, but no strong statistical significance can be placed on these relationships.

Table 4.2. Unpaired t-tests of ion concentrations (ppm) between clear wood and red heart ($P \leq 0.01$).

Ion	Clear Wood Mean	(SE)	Red Heart Mean	(SE)	2-tailed Prob.
Soluble ion concentrations:					
K	**243**		**504**		**.000**
Ca	**52**		**120**		**.000**
Mg	**16**		**57**		**.000**
Na	54	(8)	61	(11)	.606
Mn	**3**		**7**		**.000**
Fe	2		3		.907
CF[1]	**65**		**132**		**.000**
Insoluble ion concentrations:					
K	71		98		.042
Ca	**229**		**632**		**.000**
Mg	**72**		**145**		**.000**
Na	0	(1)	2	(1)	.472
Mn	**23**		**55**		**.000**
Fe	32	(3)	31	(5)	.911
CF[1]	**98**		**238**		**.000**
Total ion concentrations:					
K	**313**		**602**		**.000**
Ca	**282**		**753**		**.000**
Mg	**88**		**202**		**.000**
Na	54	(7)	63	(12)	.551
Mn	**25**		**62**		**.000**
Fe	34	(3)	34	(5)	.965
CF[1]	**162**		**370**		**.000**
WR[2]	**491**		**310**		**.000**

Standard errors of the means are not provided for transformed data.

[1] CF = Conductance Factor (sum of the ion (ppm) * 10^6 ohm^{-1} cm^{-1})

[2] WR = Wood Resistance (K ohms).

Table 4.3. Unpaired t-tests of ion concentrations (ppm) in the extract solutions between the clear wood and red heart ($P \leq 0.01$).

Ion	Clear Wood Mean	(SE)	Red Heart Mean	(SE)	2-tailed Prob.
SR[1]	**30.0**	**(0.7)**	**26.3**	**(0.8)**	**.002**
pH	6.1	(0.0)	6.2	(0.1)	.549
K	**19.6**		**37.4**		**.000**
Ca	**5.5**		**10.2**		**.000**
Mg	**1.4**		**4.2**		**.000**
Na	10.3	(0.5)	10.5	(0.7)	.754
Mn	**0.2**		**0.5**		**.001**
Fe	0.2		0.2		.908
CF[2]	**6.9**		**11.4**		**.000**

Standard errors of the mean are not provided for transformed data.
1 SR = Solution Resistance (K ohms).
2 CF = Conductance Factor (sum of the ions (ppm) * 10^6 ohm^{-1} cm^{-1})

Table 4.4. Regression summary of the resistance of the wood with soluble, insoluble, and total ion concentrations and conductance factors ($P \leq 0.01$).

	Ions	Cond. Fact.
Multiple R	0.70	0.53
R Square	0.50	0.29
Adj. R Square	0.46	0.27
S.E.	83.31	96.20
Signif. F	0.000	0.000

The Pearson correlations of the resistance of the wood with the soluble, insoluble and total ion concentrations are relatively low but most are significant ($P \leq 0.01$) and negative (Table 4.5). The correlations with Na and Fe were not significant for the soluble,

insoluble or total ion concentrations. The correlations with insoluble Ca and Mn concentrations were not significant.

Table 4.5. Pearson Correlations of Wood Resistance with ions ($P \leq 0.01$).

	Soluble		Insoluble		Total	
Ion	Corr.	Prob.	Corr.	Prob.	Corr.	Prob.
K	**-.61**	**.000**	**-.35**	**.002**	**-.59**	**.000**
Ca	**-.42**	**.000**	-.27	.015	-.30	**.009**
Mg	**-.58**	**.000**	**-.47**	**.000**	**-.52**	**.000**
Na	+.07	.301	-.13	.148	+.05	.340
Mn	**-.43**	**.000**	-.27	.016	**-.30**	**.009**
Fe	-.21	.046	-.04	.366	-.06	.321
CF[1]	**-.53**	**.000**	**-.30**	**.008**	**-.39**	**.001**

[1] CF = Conductance Factor.

The SEM emissions counts showed that cells without deposits, whether in the stained wood or clear wood, showed the presence of Ca (Figure 4.1). The emission counts of cells with deposits showed the clear presence of high amounts of Ca and some Mn and possibly some K. The ion maps clearly showed the Ca and Mn were the main constituents of the deposits, with Fe, Mg, and Na being present in small amounts throughout the cells and in the occlusions. Potassium was only visible in small quantities in the occlusions and not present at all in the empty cells (Figures 4.3).

The ion mapping and the spectral analyses both indicate that Ca and Mn are definitely present in the occlusions and Na may be present to a limited extent (Figure 4.2). These three ions do not

show up in the non-occluded cells. The K does not seem to show up in either the ion mapping or the spectral analyses of occluded, non-occluded cells or in discoloured or clear wood cells.

Calcium is the only ion which shows up as being distinct in the non-occluded cells or in the clear wood cells (Figures 4.2).

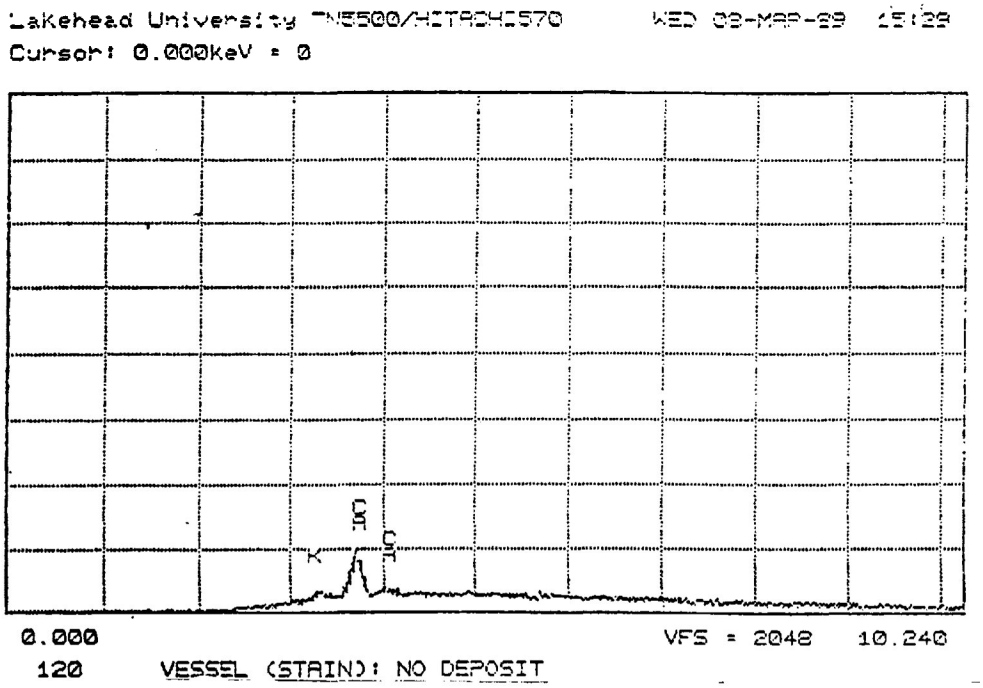

Figure 4.1. Spectral analysisof a non-occluded vessel in the discoloured wood.

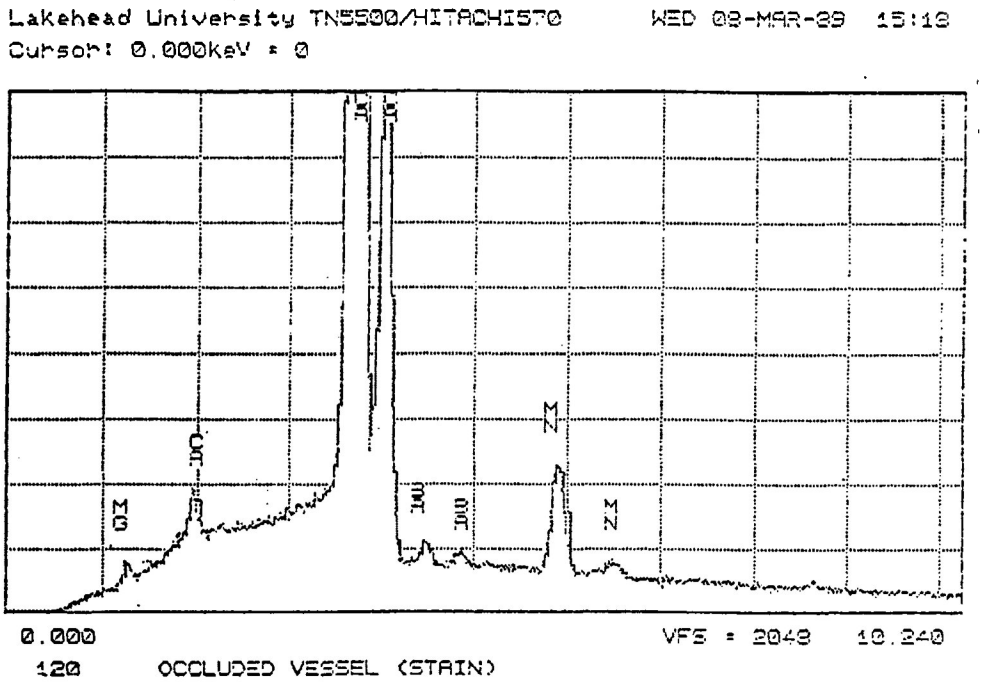

Figure 4.2 Spectral analysis ot an occluded vessel on the transitional zone between the clear and discoloured wood.

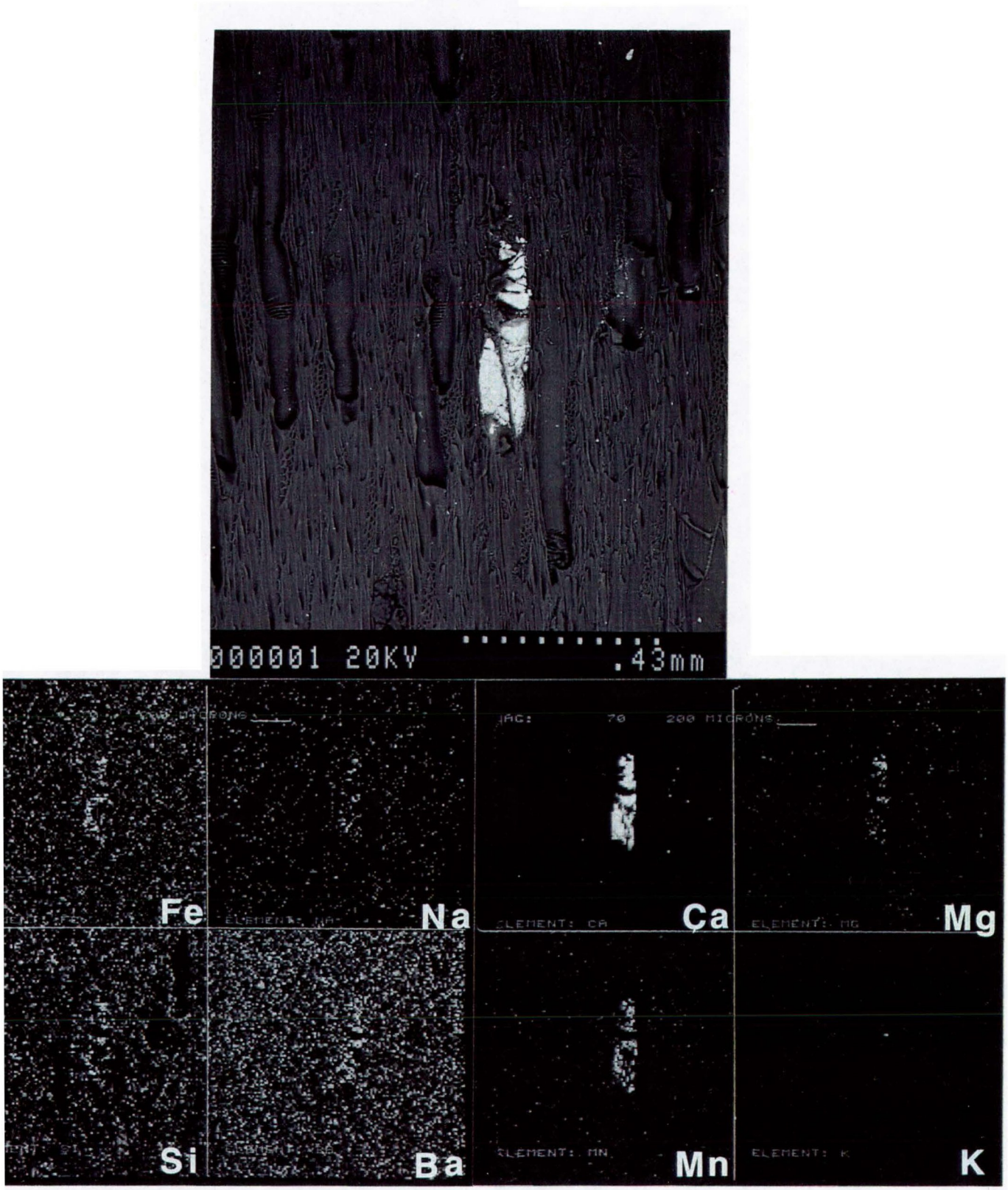

Figure 4.3. Ion maps of transitional zone with occluded vessel between the clear and discoloured wood.

DISCUSSION

The Na and Fe for the soluble, insoluble and total concentrations are not altered between the clear and discoloured wood. Also no Na or Fe showed up in the SEM analysis for elements. This would seem to indicate that these two ions are contaminants, the Fe possibly from the increment borer and the Na from the glassware. Tattar *et al.* (1972) also found that the Na concentration did not vary between clear and discoloured wood.

Except for the Na and Fe, all the ions for each of the insoluble, soluble and total concentrations were significantly greater in the discoloured wood as previously discovered by (Good *et al.*, 1955; Hart, 1968; Tattar *et al.*, 1972; Malia and Tattar, 1978; and Shortle and Ostrofsky, 1983). It is interesting to note that both the soluble and insoluble concentrations increase with discoloration. This also is reflected in the conductance factors.

Apparently the increase in ion concentration that accompanies the discolouration of the wood is mostly concentrated in the occlusions of the vessels in the clear wood/discoloured wood boundary and the deposits in the ray parenchyma in the discoloured wood. Deposits at the clear wood/discoloured wood boundary were also noted by Hillis (1968). He found that these deposits were greatest at the transition boundary and almost entirely located in the ray parenchyma. He also felt that the extractives were produced on the site of the altered wood from carbohydrates that were transloctaed to the site. Hillis noted that the extractives did not

always fill the lumens of the cells but coated the cell walls or simply plugged the pit aperatures. Scheffer (1939) found that wound-altered wood of maple had globular masses that were mainly in the ray cells and vessels.

The results of this study agree with Shevenell and Shortle (1986) in their studies of red maple (*Acer rubrum* L.). They found that K was the predominate water soluble cation and that Ca was mostly insoluble and that H^+ was equivalent in clear wood and discoloured wood.

The K concentration from the wood analysis are not reflected in the SEM spectral analyses nor the ion mapping. The K concentration are by far the largest portion of the soluble ions but a much smaller portion of the insoluble ions.

If the K was highly soluble (easily soluble) then it is possible that the small amount of water used to lubricate the microtome knife during sectioning may have removed the soluble K and therefore it would not show up in the SEM spectral analyses or ion maps.

The Pearson correlations demonstrate that there is a link between the resistance measured in the wood and the ion concentrations, most notably with the soluble ion concentrations.

CHAPTER V: ION ACCUMULATION ASSOCIATED WITH WOUNDING IN PAPER BIRCH

The presence of an increased concentration of ions after wounding has been noted in many studies (Hart, 1968; Safford *et al.*, 1974; and Shortle and Shigo, 1973). The cause of this accumulation of ions in wound associated discoloured wood has been debated. A commonly supported theory is that the initial discolouration following wounding is a response by the tree, either active or passive. In the active response, the tree manufactures materials at the site of the wounding (either from constituents present at the site or from those transported to the site), or will manufacture the materials elsewhere and then transport them to the wound site. This all goes on without the necessity of fungi being present.

The purpose of this study is to determine if there is an early response (within a few months) to wounding, in the form of increased ion concentrations. If these ions are transported to the wound site, then there may be a differential accumulation of ions above or below the wound.

MATERIALS AND METHODS

Fourteen white birch trees were randomly selected in August from a birch stand at Lakehead University's Jack Haggerty Forest. The selected trees had an average DBH of 20 cm and ranged in size

from 16 to 23 cm in diameter. The average height was 15 m and ranged from 13 to 18 m. The stand was a 60-yr-old Bw_9 Pj_1 site class 2 with 0.8 stocking. Each of these trees was selected for a similar appearance of good health and to be predominately of clear wood, in at least the outer 6 cm (a few trees had a small central core of discoloured wood). Seven of the trees were randomly selected as wound treatments, the other seven as controls.

The wounded trees were measured at breast height with the Shigometer. Four increment cores, in a horizontal row (with the Shigometer hole in the middle), then were removed. The increment cores were divided into the two outer 3 cm sections (1-3 cm and 4-6 cm). The outer 3 cm from each of the four cores from the same tree were pooled and the same for the inner 3 cm sections. The pooled increment cores were placed in a screw cap test tube and taken to the lab.

The "soluble", "insoluble" and "total" ion concentrations were determined in the same manner as in Chapter IV (Ion Accumulation in the "Red Heart" of Paper Birch).

The trees from which the samples were taken from were then wounded at breast height on top of the location of the Shigometer readings and increment core sampling. The wounds were 5.0 cm high, 15.0 cm wide and 1.25 cm into the xylem. The wounds were made by making two horizontal cuts with a swede saw and then removing the wood and squaring the wound with a square chisel.

Three months after wounding, after leaf fall (November), the seven wounded trees and the seven control trees were remeasured with the Shigometer and new wood samples were taken, as

previously described, but the samples were taken both above and below the wound (Figure 5.1). These samples were digested and analysed in the same manner as the prewound samples.

RESULTS

Soluble, insoluble and total K concentrations are greater in the wounded trees than in the non-wounded trees, both above and below the wound and at both depths (Table 5.1). The conductance factors (CF) for soluble ions is significantly greater (2-tailed Prob. $\leq$ 0.01), in the wounded trees than in the nonwounded trees, both above and below the wound and at both depths.

The insoluble and total calcium concentrations, at the first depth only, were significantly smaller in the wounded trees for both above and below the wound in the wounded trees and in the nonwounded trees (Table 5.2).

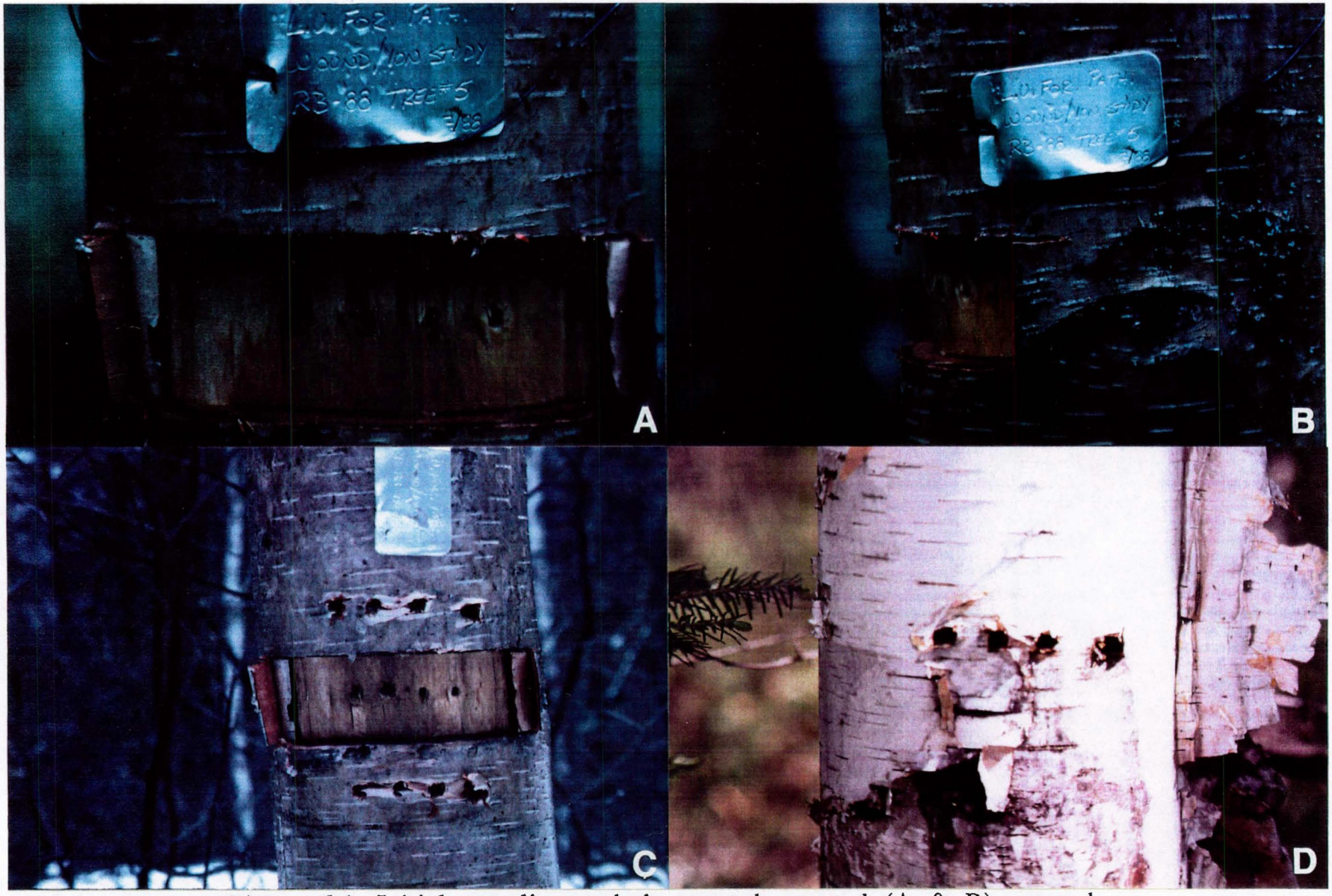

Figure 5.1. Initial sampling and the wounds created (A & B), second sampling (C), and control tree sampling (D).

The only two other significant results were that the soluble calcium concentration below the wound at depth 2 was greater for the wounded trees than the nonwounded trees (at this position only), and the soluble iron concentration was greater below the wound at depth 1 in the wounded tree than the nonwounded tree (at this position only).

The paired comparisons between the two depths independently for above the wound and below the wound and in the nonwounded trees showed no clear and consistent patterns (Table 5.4 and 5.5). All significant results were greater at depth two than depth one, except for the insoluble iron concentration above the wound which was greater at depth 1 than depth 2.

There were no statistically significant differences between the paired comparisons between the above wound and below wound locations, for soluble, insoluble or total ion concentrations or at either depth (Table 5.3).

Table 5.1. Paired t-tests of ion concentrations (ppm) between sample depths ("outer" 3 cm or "inner" 3 cm) for "Above" and "Below" the wound ($P \leq 0.01$).

Ion	Above Wound Outer Mean(SE)	Above Wound Inner Mean(SE)	2-tailed Prob.	Below Wound Outer Mean(SE)	Below Wound Inner Mean(SE)	2-tailed Prob.
Soluble ion concentrations:						
K	**417 (31)**	**684 (64)**	**.009**	412 (40)	570 (38)	.028
Ca	35 (2)	38 (4)	.453	**39 (2)**	**47 (2)**	**.005**
Mg	11 (1)	18 (2)	.040	**10 (1)**	**16 (1)**	**.002**
Na	7 (3)	4 (2)	.513	7 (2)	6 (2)	.760
Mn	2 (0)	3 (1)	.070	2 (0)	3 (0)	.023
Fe	1 (0)	1 (0)	.368	1 (0)	1 (0)	.065
CF[1]	72 (5)	112 (10)	.013	72 (6)	98 (6)	.016
Insoluble ion concentrations:						
K	301 (27)	458 (62)	.016	298 (38)	351 (41)	.269
Ca	**351 (-)**[2]	**543 (-)**	**.006**	**349 (21)**	**510(54)**	**.006**
Mg	136 (-)	197 (-)	.026	**131 (9)**	**193(19)**	**.008**
Na	57 (-)	21 (-)	.104	34 (16)	18 (6)	.324
Mn	31 (3)	49 (9)	.024	**31 (-)**	**49 (-)**	**.001**
Fe	**33 (3)**	**23 (2)**	**.009**	31 (4)	25 (4)	.165
CF	96 (-)	138 (-)	.011	93 (6)	125 (13)	.014
Total ion concentrations:						
K	**1134(82)**	**1826(175)**	**.008**	1121 (113)	1491(106)	.050
Ca	**422 (-)**	**620 (-)**	**.009**	**427 (22)**	**605(55)**	**.004**
Mg	158 (3)	232 (23)	.019	**152 (9)**	**226(18)**	**.005**
Na	71 (-)	30 (-)	.048	47 (16)	29 (8)	.137
Mn	34 (3)	55 (9)	.025	**34 (-)**	**55 (-)**	**.001**
Fe	36 (3)	25 (2)	.013	33 (4)	27 (4)	.134
CF	**169 (-)**	**250 (-)**	**.006**	165 (9)	224 (16)	.011

[1]CF = Conductance Factor (sum of the ions (ppm) * 10^6 ohm^{-1} cm^{-1})

[2](-) Standard Errors are not shown for data that were transformed for analysis.

Table 5.2. Paired t-tests of ion concentrations (ppm) between sample depths ("outer" 3 cm or "inner" 3 cm) for the non-wounded trees ($P \leq 0.01$).

Ion	No Wound Outer Mean(SE)		Inner Mean(SE)		2-tailed Prob.
Soluble ion concentrations:					
K	**205**	**(14)**	**292**	**(29)**	**.003**
Ca	35	(3)	32	(3)	.262
Mg	10	(1)	12	(2)	.111
Na	3	(2)	6	(2)	.097
Mn	2	(1)	2	(1)	.396
Fe	1	(0)	1	(0)	.365
CF[1]	**42**	**(3)**	**54**	**(5)**	**.003**
Insoluble ion concentrations:					
K	146	(13)	183	(13)	.189
Ca	474	(12)	533	(24)	.032
Mg	**142**	**(9)**	**196**	**(12)**	**.004**
Na	39	(15)	39	(11)	.999
Mn	39	(4)	43	(5)	.094
Fe	36	(5)	24	(3)	.045
CF	103	(5)	120	(5)	.026
Total ion concentrations:					
K	**556**	**(32)**	**767**	**(66)**	**.006**
Ca	545	(15)	596	(26)	.052
Mg	**162**	**(11)**	**220**	**(15)**	**.003**
Na	46	(16)	50	(9)	.759
Mn	44	(5)	46	(5)	.545
Fe	37	(5)	26	(3)	.050
CF	**145**	**(6)**	**174**	**(8)**	**.004**

[1]CF = Conductance Factor (sum of the ions (ppm) * 10^6 ohm^{-1} cm^{-1})

Table 5.3. Paired t-tests of ion concentrations (ppm) between "Above" and "Below" the wound for each sample depth ("outer" 3 cm or "inner" 3 cm) ($P \leq 0.01$).

	Outer			Inner		
	Above	Below	2-tailed	Above	Below	2-tailed
Ion	Mean(SE)	Mean(SE)	Prob.	Mean(SE)	Mean(SE)	Prob.
Soluble ion concentrations:						
K	417 (31)	412 (40)	.881	684 (64)	570 (38)	.053
Ca	35 (2)	39 (2)	.233	38 (4)	47 (2)	.050
Mg	11 (1)	10 (1)	.661	18 (2)	16 (1)	.463
Na	7 (3)	7 (2)	.941	4 (2)	6 (2)	.745
Mn	2 (0)	2 (0)	.446	3 (1)	3 (0)	.403
Fe	1 (0)	1 (0)	.853	1 (0)	1 (0)	.272
CF[1]	72 (5)	72 (6)	.975	112 (10)	98 (6)	.133
Insoluble ion concentrations:						
K	301 (27)	298 (38)	.940	458 62)	351 (41)	.022
Ca	351 (28)	349 (21)	.821	543 (101)	510 (54)	.536
Mg	136 (3)	131 (9)	.588	197 (22)	193 (19)	.592
Na	57 (21)	34 (16)	.383	21 (5)	18 (6)	.694
Mn	31 (3)	31 (2)	.724	49 (9)	49 (8)	.986
Fe	33 (3)	31 (4)	.728	23 (2)	25 (4)	.707
CF	96 (5)	93 (6)	.524	138 (21)	125 (13)	.192
Total ion concentrations:						
K	1134 (82)	1121 (113)	.897	1826 (175)	1491 (106)	.031
Ca	422 (28)	427 (22)	.702	620 (102)	605 (55)	.787
Mg	158 (3)	152 (9)	.528	232 (23)	226 (18)	.404
Na	71 (20)	47 (16)	.374	30 (5)	29 (8)	.921
Mn	34 (3)	34 (2)	.984	55 (9)	55 (8)	.724
Fe	36 (3)	33 (4)	.729	25 (2)	27 (4)	.773
CF	169 (5)	165 (9)	.711	250 (29)	224 (16)	.130

[1]CF = Conductance Factor (sum of the ions (ppm) * 10^6 ohm^{-1} cm^{-1})

Table 5.4. Unpaired t-tests of ion concentrations (ppm) between "Above" the wound and "Non"-wounded trees for each sample depth ("outer" 3 cm or "inner" 3 cm) ($P \leq 0.01$).

	Outer					Inner				
	Above		Non		2-tailed	Above		Non		2-tailed
Ion	Mean	(SE)	Mean	(SE)	Prob.	Mean	(SE)	Mean	(SE)	Prob.
Soluble ion concentrations:										
K	**417**	**(31)**	**205**	**(14)**	**.000**	**684**	**(64)**	**292**	**(29)**	**.000**
Ca	35	(2)	35	(3)	.970	38	(4)	32	(3)	.244
Mg	11	(1)	10	(1)	.480	18	(2)	12	(2)	.107
Na	7	(3)	3	(2)	.285	4	(2)	6	(2)	.668
Mn	2	(-)[2]	2	(-)	.773	3	(1)	2	(0)	.072
Fe	1	(0)	1	(0)	.019	1	(0)	1	(0)	.175
CF[1]	**72**	**(5)**	**42**	**(3)**	**.000**	**112**	**(10)**	**54**	**(5)**	**.001**
Insoluble ion concentrations:										
K	**150**	**(14)**	**73**	**(7)**	**.001**	**229**	**(-)**	**92**	**(-)**	**.000**
Ca	**176**	**(14)**	**237**	**(6)**	**.004**	272	(-)	266	(-)	.751
Mg	68	(1)	71	(5)	.562	98	(11)	98	(6)	.971
Na	28	(10)	19	(7)	.500	11	(2)	19	(6)	.196
Mn	15	(1)	19	(2)	.140	25	(4)	22	(2)	.542
Fe	16	(1)	18	(2)	.650	11	(1)	12	(2)	.784
CF	96	(5)	103	(5)	.365	138	(-)	120	(-)	.476
Total ion concentrations:										
K	**567**	**(41)**	**278**	**(16)**	**.000**	**913**	**(88)**	**384**	**(33)**	**.001**
Ca	**211**	**(14)**	**272**	**(7)**	**.004**	310		298		.906
Mg	79	(2)	81	(6)	.775	116	(12)	110	(8)	.677
Na	35	(10)	23	(8)	.354	15	(3)	25	(5)	.090
Mn	17	(1)	22	(3)	.151	28	(5)	23	(3)	.423
Fe	18	(2)	19	(2)	.810	13	(1)	13	(2)	.921
CF	169	(5)	145	(6)	.016	250	(29)	174	(8)	.039

[1] CF = Conductance Factor (sum of the ions (ppm) * 10^6 ohm^{-1} cm^{-1})

[2] (-) Standard Errors are not shown for data that were transformed for analysis.

Table 5.5. Unpaired t-tests of ion concentrations (ppm) between "Below" the wound and "Non"-wounded trees for each sample depth ("outer" 3 cm or "inner" 3 cm) ($P \leq 0.01$).

	Outer			Inner		
Ion	Below Mean(SE)	Non Mean(SE)	2-tailed Prob.	Below Mean(SE)	Non Mean(SE)	2-tailed Prob.
Soluble ion concentrations:						
K	**412 (40)**	**205 (14)**	**.001**	**570 (38)**	**292 (29)**	**.000**
Ca	39 (2)	35 (3)	.402	**47 (2)**	**32 (3)**	**.003**
Mg	10 (1)	10 (1)	.652	16 (1)	12 (2)	.122
Na	7 (2)	3 (2)	.291	6 (2)	6 (2)	.946
Mn	2 (0)	2 (1)	.414	3 (0)	2 (0)	.045
Fe	**1 (0)**	**1 (0)**	**.002**	1 (0)	1 (0)	.418
CF[1]	**73 (6)**	**42 (3)**	**.001**	**98 (6)**	**54 (5)**	**.000**
Insoluble ion concentrations:						
K	**149 (19)**	**73 (7)**	**.006**	**175 (20)**	**92 (6)**	**.005**
Ca	**175 (10)**	**237 (6)**	**.000**	255 (27)	266 (12)	.720
Mg	66 (4)	71 (5)	.407	97 (9)	98 (6)	.907
Na	17 (8)	19 (7)	.827	9 (3)	19 (6)	.142
Mn	15 (1)	19 (2)	.138	25 (4)	22 (2)	.509
Fe	15 (2)	18 (2)	.433	12 (2)	12 (2)	.920
CF	93 (6)	103 (5)	.220	125 (13)	120 (5)	.676
Total ion concentrations:						
K	**561 (56)**	**278 (16)**	**.002**	**746 (53)**	**384 (33)**	**.000**
Ca	**213 (11)**	**272 (7)**	**.001**	303 (28)	298 (13)	.882
Mg	76 (4)	81 (6)	.514	113 (9)	110 (8)	.829
Na	24 (8)	23 (8)	.940	14 (4)	25 (5)	.109
Mn	17 (1)	22 (3)	.142	27 (4)	23 (3)	.405
Fe	17 (2)	19 (2)	.548	13 (2)	12 (2)	.882
CF	165 (9)	145 (6)	.100	224 (16)	174 (8)	.023

[1]CF = Conductance Factor (sum of the ions (ppm) * 10^6 ohm^{-1} cm^{-1})

DISCUSSION

There appears to be no differential accumulation of ions above or below the wound, within the wounded trees. However, there may be some differences in accumulation between the two depths (i.e. directly above or below the wound as opposed to behind the wound). However, the significant differences show no consistent pattern. Almost all of the significant results were greater concentrations at depth 2.

The ion concentrations appear in similar relationships to the last chapter (Chapter IV: Ion Accumulation in the Red Heart of Paper Birch) except that some of the insoluble concentrations appear to be higher. The most obvious reason for this difference is the difference in season between the two samplings, late summer for the Ion Study and late fall for the Wound Study. It would be expected that the ion concentration might differ between seasons. This is also the reason the prewound samplings were not compared with any of the post wound samplings.

Since the ion accumulation did not differ above or below the wound, it would appear that the ions are not transported longitudinally, or at least not solely longitudinally. There is some evidence for ion transport through the ray parenchyma (Sucoff *et al.*, 1967). Since ion accumulation did appear in the ray parenchyma (Chapter II: Description of Red Heart in Paper Birch) it would appear that the ions may be transported laterally. This may help explain the accumulation of ions behind the wounds and not directly above or below the wounds.

The element that appears to differ between the wounded and non-wounded trees was K, both soluble and insoluble. However, the ion accumulation studies (Chapter IV: Ion Accumulation in the Red Heart of Paper Birch) indicated that K was not strongly concentrated. The inadvertent removal of K during sample preparation is a possible explanation.

CHAPTER VI: CONCLUSIONS

Red heart of white birch appears to be, at least initially, a wound compartment produced by the tree. Although isolates of microorganisms were obtained, no fungal hyphae were seen with either the light microscope or the SEM in the stained wood. No distinct change in microflora occurred between the clear and the stained wood.

The Shigometer appears to be able to detect the presence of red heart using a 50% decrease from the maximum reading rule, however, the determination of the exact extent of discolouration is imprecise. The meter appears to be detecting the stained wood just in advance of the visual signs of the stained wood. In comparisons with other instruments, the Shigometer is certainly no more complex to operate and much simpler than some of the others available. Its reliability is at least as good as any of the other instruments. Understanding how the Shigometer works requires some operator training but again, no more so, and in some cases, considerably less so than would be required for other instruments. The Shigometer adequately provides a determination of the amount of stained or decayed wood such that a more complicated instrument would not be necessary for general surveys of wood quality. A method of improving the probe contact with the wood might improve the meter's accuracy.

Shigometer readings appear to be correlated with the ion concentrations, particularly with soluble K and Mg. There is a definite general accumulation of ions in the red heart of paper birch

in both soluble and insoluble ions. The increased ion concentrations appear to be in the form of deposits in the vessels and ray parenchyma along the clear wood/discoloured wood boundary and in the ray parenchyma of the discoloured wood.

There is no differential accumulation of ions above or below a wound, although there may be a greater accumulation of ions behind the wound rather than directly above or below the wound. This would agree with the idea that the ions are transported horizontally and not vertically.

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APPENDIX

APPENDIX I: SHIGOMETER TEST DATA

Table A. Shigometer performance in predicting location of discoloured and clear wood in individual trees.

Predicted minus actual radius of discolouration	Decrease from maximum reading (%) when stain is predicted														
	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85
No Stain Present (19 trees):															
Correct Detection	12	12	13	13	15	16	16	16	17	17	17	18	19	19	19
False Detection	7	7	6	6	4	3	3	3	2	2	2	1	0	0	0
Stain Present (37 trees):															
+ 5 cm[1]	2	2	2	1	1	1	1	0	0	0	0	0	0	0	0
+ 4 cm	3	3	2	3	2	2	1	2	2	1	1	0	0	0	0
+ 3 cm	4	2	2	2	3	2	3	1	1	1	1	1	1	1	0
+ 2 cm	9	10	9	7	6	4	3	3	2	1	0	1	0	0	0
+ 1 cm	7	6	6	3	4	7	7	8	5	5	4	1	1	0	0
0 cm[2]	12	14	16	19	16	14	15	13	14	12	9	10	10	9	5
- 1 cm[3]	0	0	0	0	1	1	1	2	3	3	5	4	3	1	3
- 2 cm	0	0	0	1	2	2	1	1	1	2	2	0	1	1	0
- 3 cm	0	0	0	0	0	0	1	1	1	1	2	3	2	1	1
- 4 cm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Not detected	0	0	0	1	2	4	4	6	8	11	13	17	19	24	27

[1](+) Overestimate of the amount of discolouration.

[2](0) Predicted extent equals actual extent of discolouration.

[3](-) Underestimate of the amount of discolouration.

Table B. Shigometer performance in predicting location of discoloured and clear wood in individual logs.

Predicted minus Actual radius of discolouration	Decrease from maximum reading (%) when stain is predicted														
	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85
No Stain Present (8 radii):															
Correct Detection	0	0	1	1	1	2	3	4	4	6	7	8	8	8	8
False Detection	8	8	7	7	7	6	5	4	4	2	1	0	0	0	0
Stain Present (92 radii):															
+ 10 cm[1]	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
+ 8 cm	1	2	2	0	0	0	0	0	0	0	0	0	0	0	0
+ 6 cm	4	3	1	1	1	1	0	0	0	0	0	0	0	0	0
+ 4 cm	14	9	8	7	6	5	3	1	0	0	0	0	0	0	0
+ 2 cm	36	39	36	31	29	26	20	14	11	7	6	2	2	1	1
0 cm[2]	32	35	39	45	49	50	54	59	57	56	53	53	44	35	26
- 2 cm[3]	3	3	5	6	7	10	11	9	10	14	14	14	16	12	15
- 4 cm	1	1	1	0	0	0	0	0	0	0	2	2	2	4	3
- 6 cm	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0
- 8 cm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Not detected	0	0	0	0	0	0	4	9	14	14	16	20	27	39	46

[1](+) Overestimate of the amount of discolouration.

[2](0) Predicted extent equals actual extent of discolouration.

[3](-) Underestimate of the amount of discolouration.