

MODIFICATION OF WOOD COLOR VIA ELECTROHEATING TECHNOLOGY

A Thesis
Presented in Partial Fulfillment of the Requirements for the
Degree of Masters of Science
with a
Major in Forest Products
in the
College of Natural Resources
University of Idaho

by
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ABSTRACT

It is well established that the properties of wood can be modified by thermal treatments, which can result in enhanced durability and dimensional stability; however, strength loss and embrittlement often result after conventional thermal treatment. Current commercialized thermal treatment technologies are also known to change wood color during treatment, although color change is not the primary objective of these thermal treatments. Nevertheless, wood color is a property that can add significant value and increase perceived quality of wood. In order to meet consumer preferences, industrial finishing of wood, such as staining and coating, is often used to enhance wood color. Use of these finishing technologies, however, results in the emission of volatile organic compounds (VOCs). No particular thermal treatment technology has been commercially implemented to effect and control the change in wood color. This study evaluates the use of electroheating technology to thermally treat wood, while at the same time controlling the degree of color change in the wood. The specific objective of this study is to investigate the effect of different electroheating technology treatment conditions on wood color. Electroheating is achieved by passing an electrical current through a wood specimen utilizing two electrodes that are in direct contact with the wood. Color measurements were carried out before and after treatment in order to evaluate net color change; this was performed by using a spectrometer. Results indicate that the color of wood was affected by the electroheating technology regardless of treatment condition. It was found that grand fir (*Abies grandis*) and ponderosa pine (*Pinus ponderosa*) exhibited average color changes (ΔE^*_{ab}) of 42 and 34, respectively. Furthermore, the results show that electroheating technology can affect wood color through the thickness of the material with as little as 900 seconds of treatment exposure.

ACKNOWLEDGMENTS

I would like to express my gratitude and appreciation to my major professor Dr. Steven Shook for his support and advice during the course of this research project. I would also like to thank Dr. Armando McDonald and Jill Dacey for their advice and input on this research project as members of my thesis committee.

I would also like to thank the staff, faculty and graduate students in the Department of Forest Products for their support and friendship.

I would especially like to thank Giancarlo and my parents for their love and support throughout the time that it took me to complete my degree.

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INTRODUCTION

Over the past 30 years, considerable investment has been made in developing technologies that produce more environmentally benign wood-based products. Many of these technologies add value through the modification and/or enhancement of various wood properties. Durability¹ and hardness of wood are two properties of wood that have been enhanced for centuries through the use of heat treatment (Rowell et al. 2002). Recent advancements in heat treatment technologies for wood have been shown to be both technologically and commercially viable processes to improve dimensional stability and enhance biological resistance without adding harmful additives to the wood (e.g., Bekhta and Niemz 2003, Hon and Minemura 1991, Jämsä and Viitaniemi 2001, Mayes and Oksanen 2002, Syrjänen 2001). Furthermore, these heat treatment technologies are known to change wood color during treatment, although color change is not a primary function in the implementation of these technologies since there is rather limited control over the degree of color change (cf. Militz 2002).

Wood color, however, is one property that can add significant value and increase the perceived quality of wood. Value added wood-based products, such as architectural millwork, cabinets, flooring, and furniture, for instance, compete in a market where quality and aesthetic appeal often dictate market success or failure (Bennington 1996). For this reason, manufacturers of wood-based products emphasize not only product design, but also aesthetic features of the wood itself when developing products for end use market (Fell 2002 and Janin 2001).

Recent research has clearly shown that wood color has a significant influence on consumer preferences for cabinet and flooring woods (Fell 2002). The significance of wood color is also evident in the volume of wood-based products that are industrially stained and finished prior to end use. Currently, there are approximately

¹ Durability in this document refers to the inherent resistance of wood against wood destroying organisms.

38,000 companies in the United States in the architectural woodwork, cabinetry, flooring, and furniture industries that are engaged in industrial wood finishing (AWFI 2002). Much industrial finishing of wood includes the process of staining and coating, whereby the color of the wood material is altered to meet consumer preferences. The US market for wood coating is in excess of \$14 billion in annual sales revenue (Bankowsky 2003, Huang 1996).

The consumption of wood coatings in the United States is estimated to be more than 238 million liters (63 million gallons) per year (Huang 1996, Maty 2001). Given that the average volatile organic compound (VOC) content of wood coatings is approximately 0.6 kilograms per liter (five pounds/gallon), more than 142.9 million kilograms (315 million pounds) of VOCs are emitted each year into the air from contemporary solventborne and waterborne systems for coating wood surfaces, much of which is not appropriately recovered by pollution control technology (Huang 1996). Substantial research is currently being conducted to reduce emissions of VOC through the development of low-VOC wood coatings (Bankowsky 2003, Huang 1996, Kubillus and Venkataraman 2004, Maty 2001). One estimate indicates that the increased regulation of VOC emissions by the US Environmental Protection Agency is expected to cost industrial users of wood coatings more than \$210 million to switch to low-VOC coatings, which are typically waterborne systems (US Environmental Protection Agency 1998). Despite a push toward the use of low-VOC waterborne coatings, solventborne systems still account for more than 78 percent of wood coatings used in the United States on a volume basis (Bankowsky 2003, Kubillus and Venkataraman 2004).

Notwithstanding a relatively long history of research and development in color science and technology to control and change wood color, no particular technology has been widely commercialized to both effect and control change in wood color (Table 1). A basic premise of this study is to explore an alternative system to reduce industry reliance on chemical-based wood coatings and the resulting VOC

emissions. A technology that shows significant promise in serving as a substitute for wood coatings, and in particular wood staining, is electroheating. Electroheating, briefly defined here, is a technology whereby a controlled high voltage alternating current is passed through a biomaterial medium (e.g., wood) in order to rapidly heat the material, which results in the modification of specific characteristics of the biomaterial.

Table 1. Summary of technical studies examining the science and technology of wood color.^a

Study Objective	Citation
General measurement methods to assess wood color	Beckwith 1974; Janin et al. 2001; Loos and Coppock 1964; Moon 1948; Moslemi 1967; Nakamura and Takackio 1960; Onodera 1959; Sullivan 1967; Tolvaj and Faix 1995
Kiln drying (i.e., convective heat treatment) and its effect on wood color	Bekhta and Niemz 2003; Charrier et al. 1992, 1995; Hon and Minemura 1991; Jämsä and Viitaniemi 2001; Mayes and Oksanen 2002; McGinnes and Rosen 1984; Militz 2002; Mononen et al. 2002; Rappold and Smith 2004; Smith et al. 2003; Smith and Herdman 1998; Smith and Montoney 1998; Sundqvist 2002a,b; Sundqvist and Morén 2002; Syrjänen 2001; Terziev and Boutelje 1998; Yeo and Smith 2004
Oil heat treatment and its effect on wood color	Rapp and Sailer 2001
Color analysis of wood for color matching	Phelps et al. 1994
Effect of visible, irradiated, and/or ultra-violet light on wood color change	Burtin et al. 1998; Dawson and Torr 1992; Hon and Minemura 1991; Kawamura et al. 1996, 1998; Mitsui et al. 2001, 2004; Ota et al. 1997; Saudermann and Schlumbom 1962; Tolvaj and Faix 1995; Wiberg 1996
Effect of preservatives on wood color	Shibamoto et al. 1960
Effect of steaming on wood	Brauner and Conway 1964; Brauner and Loos 1967; Burtin et al. 2000; Chen and Workman 1980; Morita and Yamazumi 1987
Effect of smoke on wood color	Ishiguri et al. 2003
Effect of growth site factors on wood color	Nelson et al. 1969; Phelps et al. 1983
Effect of chemical constituents on wood color	Bourgois et al. 1991; Dellus et al. 1997; Hon and Minemura 1991; Kondo and Imamura 1985; Sundqvist et al. 2003
Stabilization of wood color by chemical modification(s)	Grelier et al. 1997; Hon 1995; Kai et al. 1985

^a This summary does not include studies examining the color and photodegradation of pulp and paper and their derivative products, nor does it include discoloration of wood caused by fungi (e.g., brown stain and blue stain) and sap.

LITERATURE REVIEW

Overview of Existing Wood Heat Treatment Technologies

It is well established that several intrinsic properties of wood can be changed by thermal treatment at elevated temperatures ranging from 150° to 250° C (e.g., Hietala et al. 2002, Kolin and Danon 1998, Kotilainen et al. 2000, Stamm 1956). The main positive effects of heat treated wood are improved durability and the reduction of wood hygroscopicity, which results in improved dimensional stability (Hillis 1984, Tjeerdsma et al. 1998). Yet, undesirable effects, such as strength loss and increased brittleness, have hindered the widespread commercialization of thermally modified wood for various applications. Permanent strength loss can occur at temperature above 65° C in wood if it is exposed for an extended period of time. For example, thermal treatment of wood at 180° to 200° C can result in up to a 50 percent reduction in modulus of rupture (MOR) and compression resistance (Giebelier 1983). The permanent intrinsic property change in wood due to extended high temperature treatment is a result of degradation of one or more chemical constituents of the cell wall: namely, cellulose, hemicellulose, and lignin (Alén et al. 2002, Fengel and Wegener 1984, LeVan 1989). However, due to a transitory change in the internal energy level of wood, the strength property will essentially return to its original value if the temperature change is rapid (Green and Evans 2001). This return to original strength after rapid heat treatment of wood is also referred to as the “reversible effect” or “immediate effect.”

Considerable research on the thermal heat treatment of wood has been conducted, especially over the past two decades in Europe (Militz 2002). Except for some differences in the process conditions, such as oxygen or nitrogen steaming and wet or dry processing environments, the European heat treatment methods are relatively comparable technologies for heating sawn wood at an elevated temperature (160° to 260° C). In short, these processes involve conventional convective heating techniques set at varying time regimens (four to eight hours). The PLATO®

(Netherlands), retification (France), Bois (France), oil heat treatment (Germany), and ThermoWood® (Finland) processes are examples of some wood heat treatment processes currently in commercial use (e.g., Dirol and Guyonnet 1993, Mayes and Oksanen 2002, Rapp and Sailer 2001, Syrjänen 2001, Tjeerdsma et al. 1998).

Each of the current heat treatment processes mentioned above results in some particular negative impact on wood properties (Table 2). For instance, the PLATO® process, which is considered one of the more benign high heat treatments with respect to effects on wood properties, is a three phase process consisting of a hydrothermolysis reaction (170° to 190° C under high pressure) followed by thermolytic and dry curing steps that take place over a four to six day period (Militz and Tjeerdsma 2001). This process results in some depolymerization of hemicellulose during the hydrothermolysis reaction, consequently lowering wood strength by up to 15 percent (Tjeerdsma et al. 1998). The ThermoWood® technology, also a three phase process, is intended for improving durability and dimensional stability, as well as increasing color darkness; however, it also significantly reduces bending strength by up to 30 percent (Jämsä and Viitaniemi 2001, Mayes and Oksanen 2002, Rapp 2001, Syrjänen 2001).

Table 2. Summary of wood heat treatment effects on selected properties.

Commercial Heat Treatment Process	Treatment Effect on Wood Property ^{a,b,c}				
	Dimensional Stability	Hygroscopicity	Mechanical	Paintability	Color Change
Bois Process	+	+	-	-	darker
Oil Heat Treatment	+	+	No Change	+	darker ^d
PLATO® Process	+	+	-	?	darker
Retification (RETITECH®)	+	+	-	-	darker
ThermoWood® ^e	+	+	-	?	darker

^a The "+" and "-" symbols indicate positive and negative effects, respectively.

^b Most heat treatment studies have concentrated on various commercial softwood species, aspen, and birch.

^c Some processes are have documented effects on biological durability, heat conductance, post-treatment rosin surface spotting, surface finishing, and weatherability.

^d Oil heat treatment results in darker wood color when treatment consists of high temperature. Low temperature treatment has a very minimal effect on wood color.

^e Wood heat treated using the ThermoWood® process is sold under the trade names of Stellac®Wood, Lunawood®, and Tekmawood®.

Retification (also known as RetiBois[®], Retifie[®], and RetiTech[®]), a derivative of the torrefaction process, involves the thermal treatment of previously dried wood at 200° to 260° C for a short period of time in an inert atmosphere (Dirol and Guyonnet 1993, Vernois 2001). During processing, the close control of temperature, pressure, and treatment time facilitates thermo-condensation reactions of wood structure with little to no degradation of cellulose and lignin. The Bois process is similar to retification, but the process begins with green sawn wood heated to 230° C under steam atmosphere (Vernois 2001). The retification and Bois heat treatment processes result in the dimensional stabilization of the treated wood through what is believed to be the creation of furfural derived polymers, which are less hygroscopic (Dirol and Guyonnet 1993). While both processes result in darker wood that is less prone to surface checking, they are also known to significantly reduce the mechanical properties of wood. Both processes also severely affect the paintability of the wood surface (with conventional paint formulations) due to changes in the wood's surface tension (Pétrissans et al. 2003, Vernois 2001).

Fundamental Electrical Properties of Wood

Like all materials, wood exhibits certain properties that are unique. One such property is the electrical nature of wood. The electrical properties of wood, however, go beyond that of being a good insulator material.

Wood has three primary electrical properties: namely, conductivity (σ) or its reciprocal resistivity (ρ), the dielectric constant (ϵ'), and the dielectric loss factor (ϵ''). All three properties are important and dependent on the nature of the voltage that is applied to the material. The dielectric constant (ϵ') is defined as the measurements of electric polarization that take place in an insulating material when it is placed in an electric field (Yavorsky 1951). In addition, the dielectric constant of wood is a function of the relative mass and volume of wood substrate, water, and air in its structure. Variation in the dielectric constant can occur depending on the wood's frequency, temperature, density, and grain direction (Darveniza 1980).

The dielectric loss factor (ϵ'') is a measure of the energy dissipated or absorbed in the dielectric material per unit volume per cycle (Yavorsky 1951). The dielectric loss factor is highly dependent on the current frequency (Darveniza 1980).

In this study, we focus on the conductivity (σ) of wood, or its reciprocal, resistivity (ρ). Wood conductivity is increased when moisture content is elevated; this mechanism (electrical conduction) depends upon the presence of ions in the wood (Kollman and Côté 1968). The conductivity is a measure of the flow of electrical energy through the substance, and it can be affected by the pressure applied to the electrodes, dimensions of the sample, grain direction, wood density, and wood temperature (Yavorsky 1951).

Electroheating Technology

Electroheating is a modern technology developed by Raztek Corporation (www.raztek.com) that is commercially employed within food and drug industries to heat treat fluids for the purpose of sterilization and Pasteurization (Reznik 1985, 1996a, 1996b, 1997, 1998, 1999). Electroheating (similar in concept to Ohmic heating, resistance heating, and/or Joule heating technologies) is based on passing a high voltage alternating current (AC) through a biomaterial medium utilizing two electrodes. The fluid in the medium offers an electrical resistance to the current and is rapidly heated in proportion to the square of the magnitude of the applied AC. The specific resistance of the specimen is the electrical resistance offered by 1 cm^3 unit of the respective biomaterial. This specific resistance decreases with temperature by a factor of two to three over a 120° C temperature rise (Reznik 1999).

Electrical power is the product of voltage and the square of AC passing through the biomaterial, which is subsequently converted to energy at a rate of 860 K cal/KW/hr on the University of Idaho electroheating system. The AC current density at time of

treatment is another critical parameter in the application of an electroheating system. Current density is calculated as the applied current divided by the area of the electrode. Every biomaterial has a specific current density limit. Once the current density limit is known and current flowing through the material is accurately measured, minimum area of electrode can be dictated for the system (Reznik 1997, 1999). The biomaterial substrate has to be held at the peak temperature for a certain period of time during treatment to ensure the desired level of product performance. Electrolysis of the electrode will occur at low frequency AC, which could contaminate the treated product. Pure carbon electrodes are therefore used to avoid the dissolution of metal during processing of wood.

Electroheating technology has potential applications to thermally treat wood in the green state with very minimal degradation of wood properties (Mangalam 2005). The extremely rapid and very uniform heating of wood are two important differentiating attributes of electroheating technology relative to all other currently utilized wood heat treatment technologies. Unlike conventional convective heat treating processes, electroheating develops no temperature gradient in the biomaterial being treated (e.g., wood), assuming a relatively uniform density of the biomaterial, since the current flow through the bulk of the biomaterial is uniform. Another positive characteristic of electroheating is related to temperature accuracy. The electroheating system can be configured with a thermocouple-based feedback mechanism that is interfaced to a silicon controlled rectifier (SCR) to regulate the applied energy (i.e., voltage). The thermocouple-SCR system allows setting temperatures to high accuracy and resolution. In sum, electroheating is a highly controllable technology that allows the biomaterial under treatment to be heated uniformly and instantaneously at a very set temperature in order to meet specific user requirements (e.g., degree of color darkening).

Electroheating of Wood

Preliminary electroheating experimentation at the University of Idaho's Forest Products Laboratory, using modified equipment donated by Raztek Corporation, clearly demonstrates that the process results in extremely short treatment times (e.g., approximately 900 seconds for most species of wood) relative to alternative convective heat treatment processes and technologies used to modify specific properties of wood (Mangalam 2005). Moreover, pressurizing the electroheating treatment chamber results in higher temperature regimes being attained more rapidly (Lide 2004), thereby decreasing the required treatment time. The extremely short treatment time is an advantage in lowering overall energy usage (and consequent energy costs), as well as inventory carrying costs (i.e., produce heat treated product at the time the market demands it).

Previous electroheating experimentation at the University of Idaho has specifically focused on the effects of treatment on mechanical properties (bending strength and stiffness) and physical properties (dimensional stability) of grand fir (*Abies grandis*) and ponderosa pine (*Pinus ponderosa*), as well as assessing the chemical changes that occur in the wood during processing (Mangalam 2005). The differences in modulus of rupture (MOR) and modulus of elasticity (MOE) between electroheated and matched control grand fir samples, evaluated according to ASTM Standard D143-94 (ASTM 2004a), have been found to be statistically insignificant when treatment times were less than 900 seconds and statistically significant when treatment times exceed 900 seconds. Maximum reduction in MOR and MOE of grand fir samples electroheated more than 900 seconds (up to 1,800 seconds), however, was found to be no greater than 15 percent. Similar evaluation of ponderosa pine showed no statistically significant loss in MOR or MOE between electroheated and matched control samples regardless of treatment time (up to 1,800 seconds). It is also important to note that no significant end, internal, or surface checking result from electroheating of wood, which may partially explain the minimal decline in bending properties of treated wood.

It is also well recognized that heat treatment of wood generally improves wood dimensional stability and resistance to fungal attack, especially brown rot fungi (Mayes and Oksanen 2002, Militz 2002, Tjeerdsma et al. 1998). In order to assess the effects of electroheating wood on dimensional stability, preliminary experiments in a hydrothermal environment were carried out in a temperature range of between 100° and 200° C (Mangalam 2005). Results from these studies have established that the dimensional stability of electroheated grand fir and ponderosa pine, evaluated using ASTM Standard D143-94, was significantly improved relative to control samples, which is consistent with numerous results published using various convection heat treatments for wood (e.g., Rapp 2001, Tjeerdsma et al. 1998). At the 100° and 200° C temperature range, lignocellulosic material undergoes hydrolysis. Acetyl groups (ester linkage) are easily cleaved from the hemicellulosic fraction of wood during hydrothermolysis liberating acetic acid. As the treatment progresses, the presence of acetic acid lowers pH and catalyzes the reaction, resulting in bond cleavage and increased solubility of water soluble oligomers (Fengel and Wegener 1984).

For a number of wood processes, correlations between chemical changes and macroscopic properties have also been reported (Hsu et al. 1988, McDonald and Singh 1996). Recently, Winandy and Lebow (2001) have correlated wood molecular features (chemical composition) to wood macroscopic performance (strength). Depending on the operational conditions of the electroheating treatment, the above mentioned reactions are likely to take place resulting in the depolymerization of a portion of the hemicellulose present to oligomers and monomers. These sugars are water-soluble and are easily extracted with water from the wood. Unlike hemicellulose, significant cellulose degradation does not occur below 230° C, especially in the case of wood (Gardner et al. 1993). An in-depth chemical and physical characterization of wood constituents before and after

treatment would provide a further understanding of what chemical features govern polymer behavior within wood during the electroheating process.

Simple quantification of solubilized carbohydrates from electroheated wood was performed in our preliminary experimental investigations in order to provide some insight as to the changes that occur to the wood chemistry at temperatures between 100° to 200° C (Mangalam 2005). Our analyses found that the yield of monosaccharides produced by the depolymerization (i.e., hydrolysis) of hemicellulose and other water soluble components, evaluated by hot water extraction followed by gas chromatography-mass spectrometry (GC-MS) analyses as their alditol acetate derivatives, was significantly higher in samples electroheated at higher temperature-pressure regimes. These experimental results provide some confirmation of the important linkage between dimensional stabilization and the hydrolysis of wood carbohydrates due to thermal treatment.

As alluded to earlier, heat treatment of wood using convection heat technology is well known to greatly improve outdoor durability relative to untreated wood (e.g., Jämsä and Viitaniemi 2001, Militz 2002, Stamm 1956). Specifically, several technical assessment methods have shown that heat treatment of wood improves resistance to fungal attack (e.g., Dirol and Guyonnet 1993, Feist and Sell 1987). The resistance to mold and rot is related to degradation of the wood material. For instance, when using superheated steam as the wood heat treatment method, a weight loss of three percent is recommended for a noticeable effect (Viitaniemi et al. 1994).

There have been a variety of hypotheses suggested to explain the enhanced durability of heat treated wood. Kamdem et al. (2000) found that toxic chemicals (for wood destroying organisms) are created when wood is exposed to heat treatment. In addition, the decrease in hygroscopicity of wood that has been heat treated results in lower moisture content relative to untreated wood, which deprives

the access to water that is vital to a wide variety of mold and rot causing fungi (e.g., Kolin and Danon 1998, Militz 2002). Our own preliminary research has revealed that hydrothermal treatment of wood via electroheating results in a leeching of converted polysaccharides and extractives, which may deprive a threshold nutrient base for molds and rots (Alén et al. 2002).

Finally, preliminary experimentation with electroheating at the University of Idaho has also shown that wood color can be changed from nearly bright white to dark reddish brown. However, unlike convective wood heating technologies, we have found that the degree of color change in electroheated wood appears to be highly controllable and typically takes place in between 900 to 1,200 seconds; in comparison, heat treatment usually takes four to five days with convective heat treating technologies. Given the controllability of the wood heating technology, it has the possibility of being a viable commercial substitute to wood staining, resulting in no emission of VOCs.

Research Objectives

The principal objective of this research is to evaluate the effects that the application of electroheating technology has on wood color given different treatment conditions. The species of focus in this study are ponderosa pine and grand fir.

Outcomes of this research will result in a greater understanding of the effects of electroheating on color characteristics of solid wood. Fundamental knowledge gained, combined with our preliminary experimental studies, has the potential to broaden a laboratory scale process to an industrial scale. From an environmental perspective, the reduction of the staining of solid wood material in various applications would also result in fewer VOC emissions through technology substitution. From an end product perspective, the technology could reduce the financial losses incurred by the architectural millwork, cabinets, and flooring industries caused by dye lot variation through more consistent coloration of the

material. The technology could also be of considerable value to consumers and users of wood flooring by reducing the frequency of refinishing since preliminary experiments indicate that electroheated wood is colored uniformly through the thickness of the material. Finally, the technology has the potential to improve the marketability of species of lesser value through color modification and improved durability. For example, laboratory experimentation has shown that certain species of electroheated wood can simulate the coloration of black walnut.

METHODS

Below, we discuss the electroheating system used in this study, followed by an outline of the electroheating process as it applies to wood. We then discuss the experimental design and analytical methodology used in this study.

Electroheating System

The electroheating unit used in this study includes a treatment vessel connected to a Type-GP power transformer that operates using a normal alternating current with a frequency of 50/60 Hz, 220 volt (input), and a maximum current of 5 amps (Figure 1). The transformer increases the voltage from 220 volts input to 1,000 volts output. The voltage and current were regulated by modulating the AC current to the desired output needed for electroheating treatment, which is approximately 1,000 volts for wood. The treatment vessel has a pressure limit of 1,380 kPa (200 psi) at 230° C. Pressure developed inside the chamber was visually monitored by an integrated real-time pressure gauge. During the electroheating process, the current, voltage, temperature, and pressure inside the chamber were recorded at two minute intervals. Specifically, the current was measured using a Fluke-33 true RMS clamp ammeter, voltage was measured using a Fluke-99B Scopemeter for true RMS voltage, and temperature of the wood specimen was measured using an Omega-HH509R thermometer with a J-type thermocouple.

Experimental Design

All wood used in this study was obtained from commercial sawmills located within Idaho that agreed to collaborate in this study. Two species of wood were evaluated: namely, grand fir and ponderosa pine. Eight specimen boards of 137.2 x 15.2 x 5.1 cm (54 x 6 x 2-inch) minimum dimension and composed of clear heartwood were collected for each species. All specimen boards were obtained immediately after sawmill processing and were in fresh green condition upon arrival to the laboratory facility; upon arrival, each 137.2 x 15.2 x 5.1 cm specimen board was sawn and

planed to a 127 x 10.2 x 4.4 cm (50 x 4 x 1.75-inch) dimension to ensure more uniform moisture content and to remove any possible surface contaminants acquired during manufacture and shipment.

Each 127 x 10.2 x 4.4 cm specimen board was then sawn into five 22.9 cm (9-inch) lengths, each 22.9 cm length being randomly assigned into one of 12 treatment conditions, labeled appropriately with a removable tag system (so as not to contaminate the specimen with ink or dyes), and then submerged in a distilled H₂O tank for storage until being processed by electroheating in order to preserve their green state. Therefore, 60 samples of 22.9 cm in length were produced for each species, yielding a total of 120 samples for the study and eight samples per treatment condition.

For certain treatment conditions, sodium chloride (NaCl) was added to increase the solution conductivity. Increasing the conductivity allows more energy to be passed through the wood, thereby shortening treatment time. Solution conductivity was measured by utilizing a conductivity meter manufactured by VWR International. Since water not only dissolves the salt but also dissociates the salt molecules, the conductivity meter allowed for observation to ensure that solution conductivity was increased effectively.

Variables in the electroheating process for this study included the treatment solution (distilled H₂O; 0.25 g/L NaCl solution), pressure (0 kPa; 550 kPa), and time (600, 900, and 1,200 seconds). NaCl was added to increase the electrical conductivity of the wood substrate. The 12 treatment conditions for this study are exhibited in Figure 1.

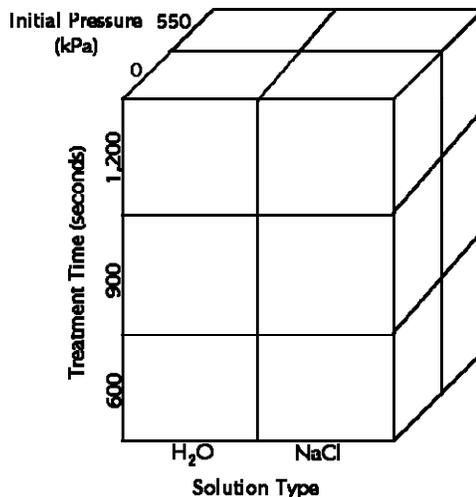


Figure 1. Matrix of treatment conditions used in this study.

Electroheating Process

The general electroheating process that was utilized in treating a sample of wood in this study is outlined next; a schematic of the electroheating system is provided in Figure 2. First, samples were vacuum infused with H₂O and NaCl (0.25 g/L) to remove the remaining air from the wood lumens. The chamber was then put under a 140 kPa vacuum for approximately 30 minutes, after which the sample was removed from the vacuum chamber and a 0.32 cm (0.125-inch) diameter hole was made with a hand drill approximately 0.64 cm (0.25-inch) in depth in the center of the top of the flat-wise positioned sample to allow for the insertion of a needle-type thermometer.

All electrical power to the electroheating system was initially turned off and locked-out. The sample was then placed into a ceramic box containing carbon electrodes at each end. The ceramic box was filled with a sufficient amount of solution, approximately 300 ml (i.e., 0.25 g/L NaCl or distilled H₂O) to fully submerge the sample, then placed into the electroheating vessel, the needle-type thermometer inserted into the drilled hole, and electrical connections made to the carbon electrodes to complete the circuit to the transformer (Tech-Tran KVA Type-GP power transformer). The Fluke-99B Scopemeter was then connected to the system.

Electrodes were connected to the transformer after completing all other electrical connections to the electroheating vessel.

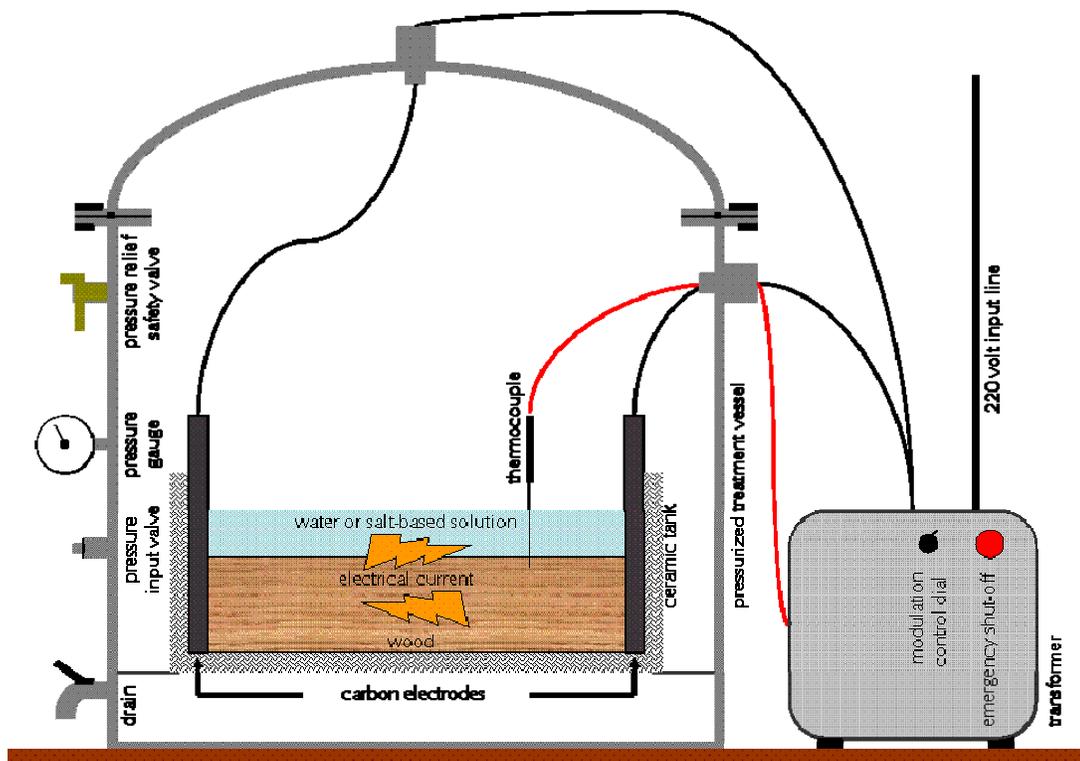


Figure 2. Cut-away view of electroheating vessel and associated system components used in heat treating wood.

The lid of the electroheating vessel was then secured and sealed with a bolted flange connection containing a lubricated O-ring seal. If the sample was to be treated at atmospheric pressure, then the pressure release valve was left in the open position on the electroheating vessel. For pressurized runs, compressed air (at 550 kPa) was applied to the sealed electroheating vessel.

The digital thermometer (Omega-HH509R thermometer with J-type thermocouple) was turned to the on position in order to record the treatment temperature. In addition, a clamp meter was placed around the wiring between the transformer and the electroheating chamber to measure current in ampere. The Fluke-99B Scopemeter was turned to the on position, the transformer to the electroheating

vessel was connected to the power grid, the power switch toggled to the on position, and the transformer was turned to the on position. The transformer current calibrator was then adjusted until about 600 to 700 V, as displayed by the scopemeter, were passing through the wood sample in the electroheating vessel.

Measurements of vessel pressure (if applicable), sample temperature, and current were recorded every minute according to each treatment time (600, 900, and 1,200 seconds). The power box was then turned off and locked-out and the transformer power cord was disconnected from the power grid. For samples under pressure, the electroheating vessel was allowed to cool for approximately 5 to 10 minutes before opening the pressure relief valve. Wiring was unconnected in reverse order from that previously described, the ceramic box was removed from the electroheating vessel, and the sample was removed from the ceramic box for inspection and further analysis.

Analytical Methodology

Color analysis of each specimen was measured by employing a diffuse reflectance module for a StellarNet EPP2000 fiber optic tristimulus UV-VIS (200-850 nm) spectrometer containing a 12 V DC krypton light source (SLI, Stellar Net), which conforms to the internationally approved Commission Internationale de l'Eclairage (CIE) 1986 system for color measurement, TAPPI Official Test Method T452, and ASTM Standard D985-97 (ASTM 2004b, CIE 1986, TAPPI 2004). This system transforms spectrophotometric color data into tristimulus data, which represents the amounts of the three primary colors required in combination to match the color being analyzed. The procedure employed in this study has been widely used to analyze wood color (e.g., Bekhta and Niemz 2003, Janin et al. 2001, Mitsui et al. 2001, Phelps et al. 1994, Rappold and Smith 2004, Smith and Herdman 1998, Sundqvist 2002a and 2002b, Sundqvist and Morén 2002).

The spectrometer calculates three-dimensional color coordinates (L^* , a^* , b^*) based on the integrated spectral response of the colors blue, green, and red. The value L^* describes psychometric lightness (0 = black to 100 = white). The value a^* describes the amount of redness (positive) or greenness (negative) present in the specimen, while the value b^* describes the amount of yellowness (positive) or blueness (negative) present in the specimen. Combined, the values a^* and b^* define the hue (chroma) and intensity (saturation) of the color (Moslemi 1967). Color metric difference ($\Delta E_{a^*b^*}$), or the difference between original and treated color, is calculated using the following formula (Equation 1):

$$\Delta E^*_{ab} = \sqrt{(L_2 - L_1)^2 + (a_2 - a_1)^2 + (b_2 - b_1)^2} \quad [1]$$

Where L^*_1 , a^*_1 , b^*_1 represent the color coordinates of the pre-electroheated specimen (i.e., control) and L^*_2 , a^*_2 , b^*_2 represent the color coordinates of the electroheated specimen.

The color metric distance, ΔE^*_{ab} , represents the Euclidean distance between two colors, and it is proportional to color differences perceived by humans. Terziev and Boutelje (1998) determined that color metric distance differences of two and greater in wood are visually perceivable by humans, although research by Mononen et al. (2002) indicates that perceived color differences may differ between wood species.

Color and brightness data was obtained from a 4.286 cm (1.688 inch) diameter spherical viewing region. The spectrometer averaged the L^* , a^* , and b^* color parameters by the use of a microprocessor unit employing an aberration corrected concave grating (i.e., no mirrors) with the reflectance probe set at $45/0^\circ$ illumination geometry. Processing of color data was automated using SpectraWiz[®] software.

After spectrometer calibration, a total of three spectrometer readings were taken from clear areas on the top surface for each unsanded/unplaned specimen prior to treatment; clear areas were marked for post-treatment color analysis. The top surface generally represented the tangential or tangential-longitudinal surface of each specimen depending on the original sawmill cut. Care was taken to ensure that obvious discolorations were not included in the color analysis. The three spectrometer readings for each specimen were then averaged to provide mean L^* , a^* , and b^* colorimetry base values for the specimen surface. A total of three spectrometer readings were again taken from clear areas on the top surface for each unsanded/unplaned specimen after electroheating treatment and averaged to provide mean L^* , a^* , and b^* colorimetry treatment values for the surface. Colorimetric difference, ΔE^*_{ab} , was calculated using pre and post treatment L^* , a^* , and b^* values. Samples were then conditioned at 21° C (70° F) and 65 percent relative humidity.

Also of interest in this study was the effect of electroheating on wood color change through the thickness of the specimen. Color change through the thickness was assessed by cutting obliquely through the tangential surface of each electroheated specimen after equilibrium moisture content (EMC) had been achieved. The oblique cut, rather than a cut perpendicular to the flat-wise surface, was necessary to allow for sufficient surface area to operate the spectrometer; the spectrometer requires some support area that is not achieved with a perpendicular cut. A total of four spectrometer readings were taken on both sides of the sample through the thickness of the specimen (two readings in each side). The four spectrometer readings for each specimen at each location through the thickness were averaged to provide mean L^* , a^* , and b^* colorimetry values. Colorimetry data from each location through the thickness of each electroheated specimen was assessed to determine consistency of color through the specimen, as well as with the surface of the specimen.

Data Collection and Analysis

All work associated with this study was recorded in laboratory notebooks. A centralized database was used to archive all data collected in this study. Each of the analyses outlined above employed standard univariate (e.g., mean, variance, regression, pair-wise comparisons) and multivariate statistical techniques that are consistent with data analysis techniques within those areas. The data analyses were used to identify statistically significant variables and to detect significant trends. Data was also analyzed across the different analyses to uncover factors that were correlated with one another.

RESULTS AND DISCUSSION

General Response to Electroheating

Table 3 and Table 4 provide the results of the surface color response of ponderosa pine and grand fir, respectively, to different electroheating treatment conditions. As mentioned previously, treatment variables consisted of three different times (600, 900, and 1,200 seconds), two types of solutions (H₂O and 0.25 g/L NaCl), and two initial pressures (0 and 550 kPa). Each of the 12 treatments consisted of five replicates. The results reported in the following tables were obtained after performing a paired t-test (by treatment block) and obtaining the mean pre and post treatment color spectrometer readings.

Samples of ponderosa pine treated at the 600, 900, and 1,200 seconds with the solution of NaCl and at 550 kPa, exhibited statistically significant differences between the pre and post treatment on the three colors coordinates L*, a*, and b* (Table 3). These three treatment conditions also resulted in the greatest color difference, $\Delta E_{a^*b^*}$. Results in Table 3 also indicate that longer treatment times with ponderosa pine treated in a NaCl and 550 kPa environment produce greater color differences. Another treatment block that presented statistically significant differences between pre and post electroheating treatment was the H₂O and 0 kPa environment treated for 600 seconds. Finally, samples treated at 600 seconds within the H₂O and 550 kPa environment also resulted in a statistically significant difference between pre and post electroheating treatment in the L* coordinate value.

Samples of grand fir treated for 900 and 1,200 seconds with H₂O and at 0 kPa were found to exhibit statistically significance differences between pre and post treatment on each of the three colors coordinates (Table 4). These two treatment conditions also presented the highest color difference, ΔE^*_{ab} , in grand fir. The 600 seconds, H₂O and 550 kPa treatment environment also resulted in a statistically significant

difference between pre and post treatments in the color measures of L^* and b^* . In addition to these treatments, grand fir samples treated for 900 s in the H_2O and 550 kPa environment also presented statistically significant difference in the L^* coordinate. The same response was also found when grand fir samples were treated for 600 seconds with the NaCl and 550 kPa environment.

Grand fir samples treated for 1,200 seconds in the H_2O and 550 kPa environment show statistically significant differences only in the a^* (red to green) and b^* (yellow to blue) coordinates. This result was also found when samples were treated for 900 seconds in the NaCl and 550 kPa environment. The last treatment that resulted in a statistically significant difference consisted of grand fir samples that were treated for 1,200 seconds in the NaCl solution and the 550 kPa environment, affecting only the b^* coordinate. The grand fir results suggest that the NaCl solution and an initial treatment pressure of 550 kPa have a substantial influence on color change.

Table 3. Change in surface color of ponderosa pine by treatment block in response to electroheating system.^a

Treatment Conditions			Mean Lightness		Mean Red to Green		Mean Yellow to Blue		Mean ΔE^*_{ab}
Time (seconds)	Solution ^b	Pressure (kPa)	L* _{pre}	L* _{post}	a* _{pre}	a* _{post}	b* _{pre}	b* _{post}	
600	H ₂ O	0	54.62* (3.08)	62.09* (2.28)	7.87** (1.88)	12.14** (5.14)	28.84* (3.09)	54.96* (15.23)	29.17
900	H ₂ O	0	61.62 (2.72)	65.98 (5.40)	13.40 (1.85)	5.33 (9.55)	44.05** (2.29)	58.84** (13.95)	22.37
1,200	H ₂ O	0	62.84 (2.01)	61.33 (8.19)	12.52 (0.93)	17.51 (8.39)	41.00 (2.80)	39.07 (11.60)	18.88
600	H ₂ O	550	63.78* (6.08)	58.74* (6.00)	7.49 (4.70)	7.08 (3.84)	49.58 (13.70)	50.71 (35.78)	30.01
900	H ₂ O	550	61.71 (2.25)	59.36 (3.12)	6.79 (3.06)	8.23 (2.32)	64.40 (11.59)	68.09 (13.32)	16.43
1,200	H ₂ O	550	60.29 (3.33)	54.86 (6.98)	9.94 (3.45)	11.02 (5.03)	59.40 (10.26)	41.95 (38.32)	35.00
600	NaCl	0	62.78 (7.65)	62.51 (8.11)	6.72 (4.81)	11.72 (10.85)	59.38 (9.69)	60.62 (8.67)	17.08
900	NaCl	0	57.25 (4.17)	57.52 (12.60)	9.97 (3.38)	11.46 (10.97)	59.40 (5.62)	40.89 (26.61)	26.65
1,200	NaCl	0	62.49 (4.75)	60.89 (6.95)	7.73 (3.40)	7.66 (5.22)	63.43 (11.59)	53.52 (17.31)	26.35
600	NaCl	550	51.12* (1.11)	99.18* (0.12)	3.54* (0.74)	-17.68* (0.76)	28.48* (1.20)	49.86* (4.13)	57.01
900	NaCl	550	49.93* (2.30)	98.88* (0.56)	3.98* (1.49)	-17.75* (1.43)	30.00* (1.18)	54.64* (7.43)	59.41
1,200	NaCl	550	50.19* (1.99)	97.73* (0.90)	4.75* (2.31)	-17.06* (2.41)	28.34* (2.72)	71.03* (5.31)	68.12

^a Sample size for each treatment block equals five.

^b 0.25 g/L NaCl solution concentration.

^c number in parentheses represents the standard deviation of treatment block.

* indicates that a statistically significant difference exists between the pre and post treatment response variable (repeated measure t-test; 0.05 α -level; $p \leq 0.05$).

** indicates that a statistically significant difference exists between the pre and post treatment response variable (repeated measure t-test; 0.05 α -level; $p \leq 0.10$).

Table 4. Change in surface color of grand fir by treatment block in response to electroheating system.^a

Treatment Conditions			Mean Lightness		Mean Red to Green		Mean Yellow to Blue		Mean ΔE^*_{ab}
Time (seconds)	Solution ^b	Pressure (kPa)	L* _{pre}	L* _{post}	a* _{pre}	a* _{post}	b* _{pre}	b* _{post}	
600	H ₂ O	0	53.91 (9.33)	47.48 (4.82)	25.79 (12.69)	28.23 (4.33)	14.76 (36.24)	28.24 (7.84)	33.33
900	H ₂ O	0	50.97* (2.00)	58.49* (6.43)	54.86* (9.35)	20.93* (22.18)	-30.45** (7.16)	18.56** (49.64)	70.18
1,200	H ₂ O	0	47.72** (3.13)	55.59** (6.99)	52.04* (6.08)	12.32* (4.38)	-27.10* (7.76)	38.33* (28.76)	78.70
600	H ₂ O	550	44.07* (8.69)	49.24* (7.07)	27.58 (21.70)	19.69 (9.12)	.98* (24.13)	12.51* (26.71)	19.27
900	H ₂ O	550	48.20** (7.22)	60.22** (17.33)	12.92 (2.83)	7.09 (14.77)	43.62 (34.18)	48.26 (42.05)	24.53
1,200	H ₂ O	550	63.98 (4.19)	68.78 (3.55)	17.30* (0.41)	-0.89* (2.46)	47.27** (3.84)	66.41** (7.09)	27.43
600	NaCl	0	55.96 (5.78)	52.35 (2.66)	18.76 (4.19)	16.86 (2.66)	31.33 (29.12)	8.15 (2.84)	33.96
900	NaCl	0	56.23 (4.68)	49.70 (9.82)	15.72 (2.47)	17.73 (8.79)	47.65 (13.98)	42.61 (23.21)	33.71
1,200	NaCl	0	52.45** (16.00)	43.49** (9.57)	15.45* (14.38)	29.99** (12.74)	31.83 (38.34)	23.96 (17.62)	29.06
600	NaCl	550	39.18* (7.78)	54.01* (7.23)	26.48 (7.27)	17.13 (9.05)	-8.55** (17.77)	28.31** (31.64)	43.11
900	NaCl	550	43.95 (1.65)	35.11 (13.94)	20.15** (5.50)	32.39** (14.75)	7.55 (20.91)	-3.63 (32.99)	43.37
1,200	NaCl	550	44.55 (9.15)	33.42 (22.56)	19.68 (7.17)	28.53 (11.52)	33.90* (33.03)	-23.43* (28.51)	67.35

Sample size for each treatment block equals five.

^b 0.25 g/L NaCl solution concentration.

^c number in parentheses represents the standard deviation of treatment block.

* indicates that a statistically significant difference exists between the pre and post treatment response variable (repeated measure t-test; 0.05 α -level; $p \leq 0.05$).

** indicates that a statistically significant difference exists between the pre and post treatment response variable (repeated measure t-test; 0.05 α -level; $p \leq 0.10$).

Upon spectrometric measurement of the three colors coordinate values, the color difference, ΔE^*_{ab} , was calculated via Equation 1. The mean of the color difference for each treatment for ponderosa pine and grand fir is displayed, respectively, in Table 3 and Table 4. A full factorial analysis of variance (ANOVA) was then performed on the ΔE^*_{ab} , L^* , a^* , and b^* values to determine individual factors and interactions that were significant in influencing color change in ponderosa pine and grand fir.

In the case of ponderosa pine, the main effects of solution type and initial pressure were each found (statistically) to be highly significant on ΔE^*_{ab} , while treatment time was found to be marginally significant. Similarly, the main effects of solution type and initial pressure were each found to be highly significant on the response variable ΔL^* and Δa^* . Note, however, that the main effect of solution type on ΔE^*_{ab} , ΔL^* , and Δa^* was found to be modified (i.e. qualified) by initial pressure. In addition, the main effect of initial pressure on Δa^* was found to be modified by treatment time, although this effect was only marginally significant (p-value = 0.090). For Δb^* , the main effect of initial pressure was established as being marginally significant (p-value = 0.053), and it was found to be modified by solution type. Finally, the interaction between treatment time and solution type was found to have a significant effect on the response variable Δb^* (p-value = 0.037).

ANOVA results for grand fir differed from those of ponderosa pine. Treatment time was the only main effect having a statistically significant impact on the response variable ΔE^*_{ab} , albeit marginal (p-value = 0.055). The two-way interaction of solution type and initial pressure (p-value = 0.000) and the full factorial three-way interaction (p-value = 0.047) were found to be significant with regard to their effect on ΔE^*_{ab} . Solution type was the only main effect variable found to be have a statistically significant effect on ΔL^* , although the response of solution type was found to be modified by treatment time (p-value = 0.001). The interaction between treatment time and initial pressure on ΔL^* was also found to be statistically significant (p-value = 0.018). ANOVA results for Δa^* and Δb^* were similar, whereby the main effects of solution type and initial pressure were found to be significant,

as were each of the three two-way interaction effects. The full factorial three-way interaction for Δa^* was also found to be marginally significant (p -value = 0.055).

Some issues require mention with regard to the full factorial ANOVA results. First, ANOVA results for ΔE^*_{ab} are partially correlated with ANOVA results from ΔL^* , Δa^* , and Δb^* since the calculation of ΔE^*_{ab} is linearly related to ΔL^* , Δa^* , and Δb^* . Second, the large inherent color variation present in the study within each treatment block may be masking both main and interaction effects. Calculation of power of test reveals low values, which is in large measure due to the considerable color variance. This information suggests that a greater number of samples per treatment block should be used in future studies evaluating the effect of electroheating technology on the color of wood.

Table 5. Full factorial ANOVA significance results on ΔE^*_{ab} , ΔL^* , Δa^* , and Δb^* for electroheated ponderosa pine.

Full Factorial ANOVA	p-value			
	ΔE^*_{ab}	ΔL^*	Δa^*	Δb^*
Treatment Time	0.095	0.150	0.136	0.378
Solution Type	0.000	0.000	0.000	0.284
Initial Pressure	0.000	0.000	0.000	0.053
Treatment Time x Solution Type	0.284	0.521	0.166	0.037
Treatment Time x Initial Pressure	0.117	0.381	0.090	0.235
Solution Type x Initial Pressure	0.000	0.000	0.000	0.000
Treatment Time x Solution Type x Initial Pressure	0.692	0.508	0.124	0.685
Adjusted R ²	0.586	0.940	0.748	0.362

Table 6. Full factorial ANOVA significance results on ΔE^*_{ab} , ΔL^* , Δa^* , and Δb^* for electroheated grand fir.

Full Factorial ANOVA	p-value			
	ΔE^*_{ab}	ΔL^*	Δa^*	Δb^*
Treatment Time	0.055	0.326	0.729	0.751
Solution Type	0.722	0.002	0.000	0.000
Initial Pressure	0.207	0.120	0.023	0.049
Treatment Time x Solution Type	0.230	0.001	0.000	0.004
Treatment Time x Initial Pressure	0.294	0.018	0.002	0.000
Solution Type x Initial Pressure	0.000	0.870	0.010	0.032
Treatment Time x Solution Type x Initial Pressure	0.047	0.576	0.055	0.290
Adjusted R ²	0.361	0.331	0.617	0.469

Table 7 and Table 8 were constructed to more easily interpret the $L^*a^*b^*$ spectrometric data displayed in Table 3 and Table 4, respectively. In Table 7 and Table 8, the treatment conditions (time, solution, and pressure) are displayed in the first three columns; as can be observed from the data, the treatment condition had differential effects on ponderosa pine and grand fir color change.

Electroheating treatments performed on ponderosa pine resulted in different color responses. The last column in Table 7 shows the interpretation of the color response by treatment. Generally, results for ponderosa pine indicate that electroheating decreased the L^* value, while the values of a^* increased and b^* decreased. This result suggests that a^* (red to green) had a better dispersion on the point of measurement. There were exceptions, however, such as samples treated for 900 seconds with H_2O and an initial pressure of 550 kPa and samples treated for 1,200 seconds in the NaCl solution and an initial pressure of 0 kPa. In these cases, although the value of L^* decreased, the values of a^* and b^* increased and decreased, respectively, resulting in visually darker wood. Other exceptions were samples treated for 600 seconds with H_2O and an initial pressure of 550 kPa, which decreased the value of L^* and a^* and increased the value of b^* .

Table 7 also shows that the value of L^* in ponderosa pine decreased when treatment time was longer (1,200 seconds), the initial pressure was 550 kPa, and the solution was NaCl or the combination of two conditions such as time plus pressure, and time plus solution of NaCl. When exposed to the three extreme variables (i.e., 1,200 seconds, mix of H_2O with NaCl solution, 550 kPa), samples of ponderosa pine became brighter, decreasing a^* , turning into green (negative value observed in Table 3) and increasing b^* , producing a yellowing effect. The same reaction was obtained when the samples were treated at 600 and 900 seconds without changing the other variables. Ponderosa pine turned into a brighter wood when the value of a^* decreased or presented a negative value (green), as observed in Table 3, and the value of b^* increased. In one exception where the ponderosa pine samples were treated for 600 seconds in H_2O and an initial pressure of 0 kPa, the samples became brighter and the values of a^* and b^* increased. In this particular case, the

treatment samples may have had better reflection and dispersion of L^* and b^* , and as a consequence, the spectrometer took the most dominant color coordinate reading (in this case b^*).

Table 8 displays that the color response of grand fir to electroheating by treatment condition. In general, the color change in grand fir due to the electroheating process and treatment condition was similar to that of ponderosa pine. This is observed when examining the values of L^* and b^* for grand fir, which decreased (less bright), while the value of a^* increased. However, there were exceptions to this general response behavior. For instance, grand fir samples treated for 900 and 1,200 seconds in NaCl solution and an initial pressure of 550 kPa became less bright, increasing the amount of a^* and turning from $+b^*$ to $-b^*$ (negative value observed in Table 4). Also, grand fir samples treated for 600 seconds in H₂O and an initial pressure of 0 kPa and samples treated for 600 seconds in NaCl solution and an initial pressure of 0 kPa became less bright and the values of a^* and b^* increased and decreased, respectively. In these cases, the spectrometer acquired the dominant color coordinate (in this case a^*) and L^* had greater absorbance, consequently resulting in a^* having a greater reflection and distribution.

Table 8 also indicates that grand fir, in general, developed into a less bright wood when the treatment time was longer (1,200 seconds), the initial pressure was 550 kPa, and the solution used was NaCl. In contrast with ponderosa pine results, when exposed to the three extreme conditions (i.e., 1,200 seconds, NaCl solution, initial pressure of 550 kPa), grand fir responded becoming less bright (decreasing L^*) and increasing a^* and turning from $+b^*$ to $-b^*$ (negative value observed in Table 4). This result strongly suggests that grand fir responded in a different manner to electroheating at these particular conditions.

Table 7. Interpretation of the change in color of ponderosa pine by treatment in response to electroheating system

Treatment Conditions ^a			Color Coordinates ^c	Color Response
Time (seconds)	Solution ^b	Pressure (kPa)		
600	H ₂ O	0	L* a* b*	brighter more red more yellow
900	H ₂ O	0	L* a* b*	brighter less red more yellow
1,200	H ₂ O	0	L* a* b*	darker more red less yellow
600	H ₂ O	550	L* a* b*	darker less red more yellow
900	H ₂ O	550	L* a* b*	darker more red more yellow
1,200	H ₂ O	550	L* a* b*	darker more red less yellow
600	NaCl	0	L* a* b*	darker more red more yellow
900	NaCl	0	L* a* b*	darker more red less yellow
1,200	NaCl	0	L* a* b*	darker less red less yellow
600	NaCl	550	L* a* b*	brighter green more yellow
900	NaCl	550	L* a* b*	brighter green more yellow
1,200	NaCl	550	L* a* b*	brighter green more yellow

^a Sample size for each treatment block equals five

^b 0.25 g/L NaCl solution concentration

^c L* = lightness, a* = red to green, and b* = yellow to blue

Table 8. Interpretation of change in color of grand fir by treatment in response to electroheating system.

Treatment Conditions ^a			Color Coordinates ^c	Color Response
Time (seconds)	Solution ^b	Pressure (kPa)		
600	H ₂ O	0	L* a* b*	darker more red more yellow
900	H ₂ O	0	L* a* b*	brighter less red more yellow
1,200	H ₂ O	0	L* a* b*	brighter less red more yellow
600	H ₂ O	550	L* a* b*	brighter less red more yellow
900	H ₂ O	550	L* a* b*	brighter less red more yellow
1,200	H ₂ O	550	L* a* b*	brighter less red more yellow
600	NaCl	0	L* a* b*	darker less red less yellow
900	NaCl	0	L* a* b*	darker more red less yellow
1,200	NaCl	0	L* a* b*	darker more red less yellow
600	NaCl	550	L* a* b*	brighter less red more yellow
900	NaCl	550	L* a* b*	darker more red Blue
1,200	NaCl	550	L* a* b*	darker more red Blue

^a Sample size for each treatment block equals five

^b 0.25 g/L NaCl solution concentration

^c L* = lightness, a* = red to green, and b* = yellow to blue

Uniformity of Color Change

Each specimen within each treatment was cut obliquely through the approximate center of the specimen in order to examine color change consistency through the thickness. In other words, we set out to determine whether the post electroheating treatment surface color of each treated specimen was consistent with the post electroheating treatment internal color of the same specimen. A paired sample t-test was performed for each treatment block with the aim to compare the surface color response to electroheating treatment with the internal color response to the treatment.

As observed from Table 9, there were some statistically significant differences between surface and internal specimen color within various ponderosa pine post electroheating treatment conditions. For instance, the treatment block consisting of 900 seconds, with H₂O as solution, and an initial pressure of 0 kPa resulted in a statistically significant difference in the b* (yellow to blue) coordinate. Another treatment block that presented statistically significant differences between surface and internal wood color, but only in the color measure of L*, was the 1,200 second, H₂O solution, and 550 kPa treatment. The 900 and 1,200 second, NaCl solution, 0 kPa initial pressure treatment blocks also resulted in a statistically significant differences between surface and internal wood color along the measure of b*. Finally, treatment blocks where samples were subjected to 600, 900, and 1,200 seconds within the NaCl solution and 550 kPa environment resulted in statistically significant differences between surface and internal color measures along all three color coordinates, with the only exception of samples treated at 600 seconds that only presented statistically significance differences along the L* (lightness) and a* (red to green) color coordinate values.

With respect to differences in post electroheating treatment differences in surface and internal color for grand fir (Table 10), samples treated for 600 seconds in the H₂O and 550 kPa environment showed statistically significant differences only in the a* (red to green) coordinate. Another treatment block that presented a statistically significant difference between surface and internal color only in the color measure of b* (yellow to blue)

coordinate, was the H₂O and 550 kPa environment treated for 900 seconds. A statistically significant difference in treatment response was also obtained when samples were treated for 1,200 seconds in the H₂O and 550 kPa environment along all three measured color coordinates (L*a*b*).

In addition to the previously described treatments, grand fir presented statistically significant differences between surface and internal color response to the electroheating process in the b* color coordinate when treated for 600 seconds in the NaCl solution and initial pressure of 0 kPa. The 1,200 second treatment in the NaCl solution and 0 kPa treatment environment also resulted in a statistically significant difference between surface and internal color measures of L* and a*. Finally, samples treated for 600 seconds within the NaCl solution and 550 kPa environment also resulted in a statistically significant difference for all three color coordinates (L*a*b*).

Note that similar to the data presented in Table 3 and Table 4, the large variance that was observed for the pre and post treatment measurements was also present in the post electroheating treatment comparison between surface and internal color uniformity.

In sum, the color of both species was affected by the electroheating system regardless of treatment condition. Although no statistically significant difference was found between treatments with regard to color changes, it was found that grand fir and ponderosa pine exhibited average color changes (ΔE^*_{ab}) of 42 and 34, respectively. Results suggest that the most influential treatment conditions that yield color change in ponderosa pine and grand fir were the interactions between pressure and NaCl solution and between time and NaCl solution. Results were consistent in showing that samples treated with in NaCl solution produced a greater color change than samples treated in distilled water. This is very likely attributable to the fact that NaCl solution is more electrically conductive, which allows for a better conduction of the electrical current through the material.

Table 9. Comparison of surface and internal color of ponderosa pine by treatment block in response to electroheating system.^a

Treatment Conditions			Mean Lightness		Mean Red to Green		Mean Yellow to Blue	
Time (seconds)	Solution ^b	Pressure (kPa)	L* _{surface}	L* _{internal}	a* _{surface}	a* _{internal}	b* _{surface}	b* _{internal}
600	H ₂ O	0	62.09 (2.28)	61.88 (3.58)	12.14 (5.14)	7.78 (3.46)	54.96 (15.23)	41.49 (3.89)
900	H ₂ O	0	65.98 (5.40)	60.52 (5.75)	5.33 (9.55)	10.28 (6.73)	58.84** (13.95)	35.86** (16.18)
1,200	H ₂ O	0	61.33 (8.19)	58.62 (3.62)	17.51 (8.39)	10.80 (4.31)	39.07 (11.60)	43.50 (20.43)
600	H ₂ O	550	58.74 (6.00)	65.52 (3.18)	7.08 (3.84)	6.74 (2.56)	50.71 (35.78)	73.00 (4.56)
900	H ₂ O	550	59.36 (3.12)	63.73 (4.70)	8.23 (2.32)	6.48 (5.07)	68.09 (13.32)	70.91 (3.73)
1,200	H ₂ O	550	54.86** (6.98)	43.22** (9.64)	11.02 (5.03)	17.24 (4.96)	41.95 (38.32)	17.88 (44.96)
600	NaCl	0	62.51 (8.11)	62.31 (2.13)	11.72 (10.85)	6.71 (2.81)	60.62* (8.67)	74.20* (2.78)
900	NaCl	0	57.52 (12.60)	55.81 (5.22)	11.46 (10.97)	8.68 (3.38)	40.89** (26.61)	71.80** (3.97)
1,200	NaCl	0	60.89 (6.95)	57.93 (5.78)	7.66 (5.22)	5.89 (4.31)	53.52** (17.31)	69.16** (5.30)
600	NaCl	550	99.18* (0.12)	58.50* (5.27)	-17.68* (0.76)	10.88* (6.18)	49.86 (4.13)	40.50 (25.13)
900	NaCl	550	98.88* (0.56)	49.11* (5.87)	-17.75* (1.43)	9.08* (5.26)	54.64** (7.43)	29.78** (22.34)
1,200	NaCl	550	97.73* (0.90)	38.43* (9.34)	-17.06* (2.41)	13.05* (8.23)	71.03* (5.31)	12.34* (30.12)

^a Sample size for each treatment block equals five.

^b 0.25 g/L NaCl solution concentration.

^c number in parentheses represents the standard deviation of treatment block.

* indicates that a statistically significant difference exists between the pre and post treatment response variable (repeated measure t-test; 0.05 α -level; $p \leq 0.05$).

** indicates that a statistically significant difference exists between the pre and post treatment response variable (repeated measure t-test; 0.05 α -level; $p \leq 0.10$).

Table 10. Comparison of surface and internal color of grand fir by treatment block in response to electroheating system.^a

Treatment Conditions			Mean Lightness		Mean Red to Green		Mean Yellow to Blue	
Time (seconds)	Solution ^b	Pressure (kPa)	L* _{surface}	L* _{internal}	a* _{surface}	a* _{internal}	b* _{surface}	b* _{internal}
600	H ₂ O	0	47.49 (4.82)	55.26 (5.24)	28.73* (4.33)	9.12* (2.72)	28.24 (7.84)	35.65 (37.53)
900	H ₂ O	0	58.49 (6.43)	58.27 (3.51)	20.93 (22.18)	6.17 (2.37)	18.56 (49.64)	64.79 (14.45)
1,200	H ₂ O	0	55.59 (6.99)	57.74 (6.54)	12.32 (4.38)	6.70 (8.24)	38.33 (28.76)	52.79 (31.28)
600	H ₂ O	550	49.24** (7.07)	54.96** (8.68)	19.69 (9.12)	13.96 (7.91)	12.51* (26.71)	50.85* (32.00)
900	H ₂ O	550	60.22* (17.33)	48.11* (18.03)	7.09** (14.77)	13.31** (9.12)	48.26 (42.05)	24.96 (50.54)
1,200	H ₂ O	550	68.78* (3.55)	54.60* (2.95)	-0.89* (2.46)	11.54* (3.54)	66.41** (7.09)	32.98** (31.47)
600	NaCl	0	52.35 (2.66)	54.63 (5.77)	16.86 (2.66)	14.64 (3.89)	8.15* (2.84)	39.94* (18.07)
900	NaCl	0	49.70 (9.82)	53.24 (7.92)	17.73 (8.79)	9.20 (6.34)	42.61 (23.21)	47.74 (31.18)
1,200	NaCl	0	43.49* (9.57)	53.12* (5.10)	29.99* (12.74)	9.41* (4.39)	23.96 (17.62)	40.46 (42.62)
600	NaCl	550	54.01* (7.23)	42.74* (5.56)	17.13** (9.05)	23.13** (5.69)	28.31** (31.64)	-2.43** (12.13)
900	NaCl	550	35.11 (13.94)	30.81 (9.03)	32.39 (14.75)	25.81 (8.20)	-3.63 (32.99)	-24.61 (13.68)
1,200	NaCl	550	33.42 (22.56)	26.98 (6.41)	28.53 (11.52)	28.60 (5.01)	-23.43 (28.51)	-30.19 (10.49)

Sample size for each treatment block equals five.

^b 0.25 g/L NaCl solution concentration.

^c number in parentheses represents the standard deviation of treatment block.

* indicates that a statistically significant difference exists between the pre and post treatment response variable (repeated measure t-test; 0.05 α -level; $p \leq 0.05$).

** indicates that a statistically significant difference exists between the pre and post treatment response variable (repeated measure t-test; 0.05 α -level; $p \leq 0.10$).

It is possible that the presence of extractives play a major role in changing wood color through electroheating treatment (Burtin et al. 1998). Since the electroheating process substantially raises temperature up to 175°C in a rather immediate fashion, chemical modification of wood components likely occurs. To investigate this supposition, Fourier Transform Infrared Spectroscopy (FTIR) analysis was performed on electroheated and control samples of ponderosa pine and grand fir. Initial analytical FTIR results revealed deformation and stretching of C-O and C-H families, which are known to be linked to extractives and lignin and/or hemicellulose. The initial FTIR results provide some measure of evidence that the color change of wood via electroheating was caused by the interaction of wood components with the treatment conditions (time, temperature, pressure, solution type). A more detail interpretation of this part of the study is being conducted and it will be reported in a future paper.

CONCLUSIONS AND LIMITATIONS

This study evaluated the effect of various electroheating treatments on color change in ponderosa pine and grand fir. Wood competes in markets where its aesthetic appearance has become increasingly important. In order to meet consumer preferences, a variety of finishing treatments are performed to modify the color of wood. We found in this study that electroheating technology can be utilized to modify the color of ponderosa pine and grand fir. All treatment conditions evaluated resulted in visually identifiable changes in wood color. However, that no statistically significant differences in color change were uncovered between treatments, regardless of species. Grand fir and ponderosa pine showed average color changes of 42.0 and 34 respectively.

Electroheating treatment conditions affected ponderosa pine and grand fir in different ways. Specifically, greater color change resulted for ponderosa pine when the treatment conditions included NaCl solution and an initial starting pressure of 550 kPa. In case of grand fir, longer treatment times and an initial starting pressure of 550 kPa resulted in the greatest magnitude of color change. Results also suggested that samples treated in a NaCl solution had greater color change than samples treated in distilled water. This result is likely the consequence of NaCl being a highly electrically conductive solution, which allowed for more efficient transmission of the electrical current through the wood material.

The one-way ANOVA was performed to evaluate if any of the three main effect variables had statistically significant effects on wood color change. The ANOVA results suggest that for ponderosa pine the solution type and the initial pressure were highly significant on ΔE^*_{ab} , while treatment time was found to be marginally significant. In case of grand fir treatment time was the only main effect having statistically significance impact on ΔE^*_{ab} .

The results comparing the uniformity of post electroheating treatment surface and internal color generally suggest that the color change produced by the electroheating technology occurs rather uniformly through the entire wood sample, though some statistically

significant differences appeared for a few treatment conditions along the various color measures.

Table 11 provides a comparison among heat treatments currently existing in the market, as well as electroheating technology. Comparing electroheating technology among the others heat treatments, it can be observed that it has similar effects on the dimensional stability and hygroscopicity of wood. Previous studies suggest that the change in the mechanical properties of wood is minimal using electroheating technology (Mangalam 2005).

Table 11. Summary of wood heat treatment effects on selected properties including electroheating.

Commercial Heat Treatment Process	Treatment Effect on Wood Property ^{a,b,c}				
	Dimensional Stability	Hygroscopicity	Mechanical	Paintability	Color Change
Bois Process	+	+	-	-	darker
Oil Heat Treatment	+	+	No Change	+	darker ^d
PLATO [®] Process	+	+	-	?	darker
Retification (RETITECH [®])	+	+	-	-	darker
ThermoWood ^{®e}	+	+	-	?	darker
Electroheating H ₂ O ^f	+	+	Minimal ^h	?	darker
Electroheating NaCl ^g	+	+	Minimal ^h	?	darker

^a The "+" and "-" symbols indicate positive and negative effects, respectively.

^b Most heat treatment studies have concentrated on various commercial softwood species, aspen, and birch.

^c Some processes are have documented effects on biological durability, heat conductance, post-treatment rosin surface spotting, surface finishing, and weatherability.

^d Oil heat treatment results in darker wood color when treatment consists of high temperature. Low temperature treatment has a very minimal effect on wood color.

^e Wood heat treated using the ThermoWood[®] process is sold under the trade names of Stellac[®]Wood, Lunawood[®], and Tekmawood[®].

^f Represents electroheating treatment using sodium chloride solution (0.25 g/L).

^g Represents electroheating treatment using distilled water.

^h Less than 15 percent degradation of MOE and MOR properties resulted in grand fir due to electroheating, while ponderosa pine exhibited no loss in MOE or MOR properties due to electroheating.

Several limitations exist in this study and they should be taken into consideration in further research investigating the electroheating of wood. More notably, the variance in wood color change by treatment was quite high. There are two explanations that can likely explain much of this variance. First, the natural variance in wood color (e.g., difference in early wood and late wood color) leads to a high variance within each treatment. Second, some variance in the spectrometer readings exists due to the limited spherical viewing diameter of the instrument. It is recommended that a greater number of samples per

treatments be included in future research to reduce the amount of color change variance. For future research a number of 12 samples per species are recommended. It is speculated that a larger sample in the present study would have likely resulted in difference being detected in color change due to electroheating between treatments.

Another limitation of this study was the electroheating unit. The unit's size only afforded samples measuring 22.9 x 9 x 4.2 cm in dimension. The size of specimen being electroheated may have an effect on color change. It should also be noted that a consistent voltage was not applied to the wood when electroheated, rather voltage was kept within a tightly controlled range.

This study utilized only two softwood species and two types of treatment solutions. The results should not be generalized to represent the effect of electroheating on other wood species. It is also likely that treatment solutions other than NaCl and distilled water may have a greater impact on color change. Future research should investigate whether other treatment solutions, such as sodium hydroxide (NaOH), result in better conductivity. It has been speculated that acetic acid (CH_3COOH) formation occurs in the wood sample during the electroheating process. This suggests that infusing the wood sample in an acetic acid bath prior to treatment may impart greater color change, as well as reduce the treatment time. However, an acetic acid bath may also result in negative effects. These negative effects include strength loss and increased wood brittleness.

An additional limitation for this study which needs to be taken into consideration is the post treatments remain water toxicity. The water needs to be analyzed with the aim to identify any toxic substance as a result of electroheating.

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