Microwave Surface Modification of *Pinus radiata* Peeler Cores: Technical and Cost Analyses

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Abstract

Radiata pine (*Pinus radiata*) peeler cores are classified as a by-product of plywood manufacture and have the potential for development as value-added solid wood products. This article outlines technical and cost analyses of microwave surface modification of radiata pine peeler cores along with the methodology, including measurements of temperature distribution and of preservative uptake and distribution following microwave heating. After microwave treatment, the highest temperatures are observed on the surfaces of the peeler cores. A gradual decrease in temperature is noted with depth within the timber. Chromated copper arsenate uptake after pressure impregnation ranges between 94 and 314 liters/m^3. This uptake is three to nine times higher than that of control timber (no microwave treatment). Cost analyses focus on the microwave treatment of peeler cores and indicate that microwave modification costs range from US$0.95 to US$1.23 for one peeler core (i.e., US$29 to US$37 per m^3), depending upon electricity charges and the number of working shifts employed.

A peeler core is a log residue derived from veneer peeling in plywood manufacturing (Appleby 1988). Peeler cores of radiata pine (*Pinus radiata*) are abundantly available in Australia. The cores generally are used for fuel, chips, and pulp or are sawn for use as low-quality timber. Despite the low quality of this wood, products can potentially be developed from the core given the uniform diameters. Possible value-adding timber products from radiata pine peeler cores include retaining walls, pergolas, landscaping, motorway barriers, and post and rail fencing.

According to Australian Standard 1604.1 (Standards Australia 2002), radiata pine heartwood is classified as having little natural durability (Class 3), and untreated timber of this type is readily attacked by organisms. It will decay very quickly when in contact with the ground or in moist conditions. Radiata pine timber must therefore be preservative treated before use in such applications.

To use radiata pine in an outdoor environment with direct ground or water contact (retaining walls, piling, housing supports, and building poles [Hazard Class H5]), preservative must penetrate not less than 20 mm from the surface of the timber. Hazard Class H4 (fence posts, greenhouses components, and in-ground pergolas and landscaping timbers) requires preservative to penetrate at least 10 mm into the peeler core. In timber exposed to Hazard Class H3 situations (weatherboard, fascia, above-ground pergolas, framing, and decking), the preservative must penetrate at least 8 mm from the surface (Standards Australia 2002).

The peeler core represents the center of the log; therefore, the timber consists almost exclusively of heartwood, which is less permeable than sapwood. The cells of heartwood are darker in color because of their enrichment with various extraneous chemicals known collectively as extractives (Butterfield 1993). Extractives permeate both the cell wall and lumen, and as a result, liquid penetration in heartwood is slower than in sapwood. Aspirated pits in heartwood also block the flow of liquid along the tracheids, which makes heartwood less permeable (Booker 1977).

Methods to increase wood permeability include steaming, biological treatments, and incising. Steaming timber

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alone at 127°C or using vacuum to accelerate moisture loss after steaming has been reported extensively (McQuire 1962, Bergervoet 1983). Once the timber has been cooled (usually 24 h after steaming), it can be treated using the Alternating Pressure Method (Vinden and McQuire 1978). Alternatively, the wood can be left for 7 to 21 days to allow further moisture loss and redistribution and then treated using the Bethell or ''full cell'' process (McQuire 1974). Steaming improves timber permeability and treatability but also reduces timber strength. Usually, a 25 percent loss in modulus of rupture and an 18 percent loss in modulus of elasticity as well as timber discoloration occur (Bellmann 1968). Biological treatments using specific bacteria have improved wood permeability before treatment (Archer 1983). Biological methods have not been used commercially, however, because of the lack of uniformity in results, poor improvement in heartwood permeability, and difficulty in optimizing the bacterial combinations used. Incising, boring holes, piercing, and slitting have also been used since the mid-1800s (Bellmann 1968). Timber permeability has been enhanced on the wood surfaces by inserting small holes (0.7 mm in diameter and 10 mm in depth) in a regular pattern at approximately 14,000 incisions per m^2 (Ruddick 1991). A problem associated with incising relates to the lack of standards that regulate its use in different species, products, and specific conditions (Morris et al. 1994).

Microwave technology has been developed for improving wood permeability (Torgovnikov and Vinden 2009). Wood exposed to intense microwave energy generates steam pressure within the wood cells. Under high internal pressure, the weak ray cells in radiata pine are ruptured to form pathways for easy transportation of liquids and vapors in the radial direction (Vinden et al. 2004). An increase in the intensity of microwave energy applied to wood increases the internal pressure, forming narrow voids in the radial and longitudinal planes. A several thousand-fold increase in wood permeability in the radial and longitudinal directions can be achieved in wood species previously considered to be impermeable (Vinden and Torgovnikov 2000). A disadvantage of this system, however, arises when microwave heating is higher at depth in the wood compared with at the surface.

A key aim of the present research was to examine the effect of microwave treatment using the PC-1 applicator to meet preservative treatment standards. The PC-1 applicator is a specifically designed waveguide (hollow metallic tube of uniform cross section) that operates at a frequency of 2.45 GHz to modify timber surfaces only. This article discusses the technical and cost aspects of using the PC-1 applicator to enhance preservative treatability of peeler cores. The research objectives include studying temperature and preservative distribution and uptake after microwave modification as well as analyzing costs relating to the microwave treatment process.

Materials and Methods

Radiata pine peeler cores were obtained from the Carter Holt Harvey plywood mill located at Myrtleford, Victoria, Australia. Peeler core dimensions varied between 126 and 130 mm in diameter and 2,560 and 2,600 mm in length. The moisture content of the cores ranged from 26 to 35 percent and the ovendry density between 372 and 435 kg/m^3.

Temperature distribution measurements

PC-1 microwave applicators with a frequency of 2.45 GHz and tunnel cross section of 155 by 155 mm were fitted into a 60-kW microwave facility (Fig. 1). The peeler core was fed through the tunnel using electric rollers with various microwave powers and feed speeds. The microwave modification process parameters are outlined in Table 1. To obtain even surface modification, the peeler cores were fed through the applicator twice.

Temperature distribution in timber was measured to estimate the energy distribution during microwave modification. The energy distribution pattern following microwave irradiation provides a prediction of the microwave-modified area in the core. Temperature was measured after modification using thermocouples in a static position in holes that had been drilled to five different depths (10, 20, 30, 65, and 110 mm) before modification. Temperature distribution was measured for three conditions: one-sided, two-sided, and four-sided treatments.

Preservative distribution

Following microwave processing, the peeler cores were pressure impregnated with chromated copper arsenate (CCA). The following preservative treatment schedule was used: 25 minutes of initial vacuum (−85 kPa, gauge), and then flooding with preservative and immediate pressure impregnation (1,400 kPa, gauge) for 45 minutes. After emptying the treatment chamber, a final 25 minutes of vacuum (−85 kPa, gauge) was applied. After treatment, the preservative distribution was determined by copper spot test reagent Chrome Azurol-S (American Wood-Preservers' Association 2006). The presence of copper was identified as a black or blue coloration on cross sections of the peeler cores.

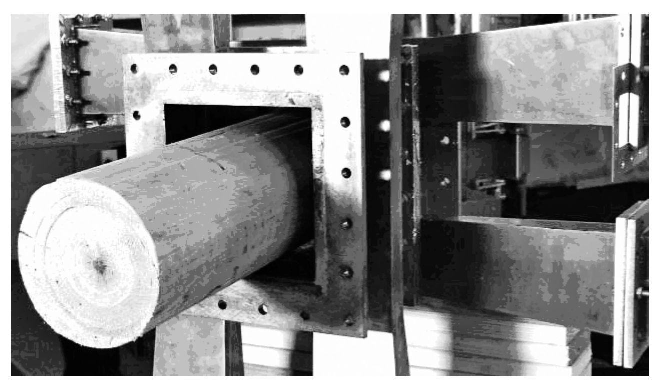

Figure 1.—Peeler core position on the PC-1 applicators.

Table 1.—Microwave parameters for peeler core surface treatments.

Frequency	2.45 GHz
Microwave power	22–36 kW
Applied microwave energy	55–90 kWh/m^3
Mode of energy application to wood	Continuous
Electric field strength vector ''E''	
Orientation relative to wood grain	Parallel
Conveyor speed of timber through applicator	10–24 mm/s[a]

[a] Higher feed speeds are possible; speeds in the current experiment reflect equipment limitations.

Preservative uptake

Preservative uptakes were calculated based upon weight differences before and after CCA impregnation per cubic meter of timber. Regression models between CCA uptake and microwave energy and maximum possible preservative saturations were calculated based on core density and the moisture content of the samples using the following equation (McQuire 1974):

$$F = 1,000 - \frac{d(g + 66.7)}{100} \tag{1}$$

where F is the maximum possible uptake (liters/m^3), d is the basic density (kg/m^3), and g is the wood moisture content (%).

Production capacity assumptions

One plywood plant, with two working shifts, annually produces an average of about 350,000 peeler cores. With three working shifts, the production is around 525,000 peeler cores per year. Peeler core dimensions vary between 126 and 130 mm in diameter and 2,560 and 2,600 mm in length. Based on these conditions, this cost analysis is divided into two models: The first model is based upon two working shifts, producing 11,600 m^3 of peeler cores annually, and the second model is based upon three working shifts, producing 17,400 m^3 of peeler cores annually.

Microwave facility assumptions

To treat the peeler core output of a two- or three-shift operation, 210 kW of microwave power with the frequency of 2.45 GHz is required. These microwaving facilities (plant) cost approximately US$727,000 and have a 6-year economic life (depreciation rate of 17% per annum). Estimations regarding the microwave generator used for the plant are based on the average microwave energy needed to treat the core (60 kWh/m^3).

The microwave magnetron needs to be replaced every 6,000 hours. With the first model, in which two working shifts are employed, the magnetron would operate 5,840 h/y; therefore, one magnetron per generator would be required per annum. In comparison, the magnetron in the second model, in which three working shifts are employed, would operate 8,760 h/y, thus requiring 1.5 magnetrons per generator per annum. Because the plant requires seven microwave generators, the first model requires seven magnetron replacements per annum, and the second model requires 10.5 per annum. The microwave plant would occupy an area of about 200 m^2. This includes a provision for a feeding-in and -out system.

Cost assumptions

All costs are quoted in US dollars. Total peeler core cost ideally includes costs for microwave treatment, preservative treatment, packaging, transportation, and handling. For this assessment, however, cost estimates are limited to microwave treatment. The cost of microwave treatment for peeler cores is estimated based on the various costs shown in Table 2.

Table 2.—Various costs of microwave treatment for peeler cores.

Cost of microwave plant (US$)	727,000
Depreciation rate (%)	17
Variable costs	
Electricity cost (US$/kWh)	
Variation 1	0.07
Variation 2	0.09
Variation 3	0.11
Labor (US$/y)	45,000
Model 1 (no. of working shifts)	2
Model 2 (no. of working shifts)	3
Fixed costs (US$/y)	
Capital recovery (17% × US$727,000)	123,590
Maintenance (2% × US$727,000)	14,540
Magnetron replacement	
Model 1 (7 magnetrons × US$8,000)	56,000
Model 2 (10.5 magnetrons × US$8,000)	84,000
Plant site rent (200 m^2 × US$200)	40,000

Results and Discussion

Temperature distribution

After one-sided treatment (Fig. 2A), the highest temperatures recorded were on the surfaces of the peeler cores. A gradual decrease in temperature with peeler core depth was then observed. The outer sample zone recorded the highest temperature (>80°C) to a depth of 10 to 30 mm. Temperature then gradually dissipated with depth in the peeler core. Because the PC-1 applicator was designed to heat predominantly timber surfaces, a consistent temperature distribution was observed along the core.

Similarly, after two-sided treatment (top and bottom), the highest temperatures were recorded on the top and bottom surfaces of the peeler core. A gradual decrease in temperature with depth in the peeler core was then observed (Fig. 2B). The outer zone achieved the highest temperature (>80°C) up to a depth of 10 to 35 mm. The bottom side of the core attained temperatures of 60°C to 80°C to a depth of 10 to 25 mm. Outside this zone, the temperature gradually dissipated with timber depth.

During four-sided treatment (Fig. 2C), microwave energy heated the total cross section of the timber. The top and right-hand sides, which were heated directly by the microwave generator, achieved the highest temperature (>80°C). Temperature in the bottom and left-hand sides, which were only heated by leftover microwave energy, reached 60°C to 80°C. In contrast to one- and two-sided treatments, in which the center part of the core was not heated, the temperature in the center of the core reached approximately 58°C with four-sided treatment. This observation indicates that temperature increases in the center of the core were induced by four-sided energy application.

After microwave modification, the highest temperature recorded was on the surface of the peeler cores up to the depth of 10 to 35 mm, demonstrating that the PC-1 applicator effectively distributes microwave energy onto the surface of the wood. Temperature distribution on the surfaces of the peeler core was consistently similar to those found by Sugiyanto et al. (2008) in sawn timber.

Preservative distribution

Several authors have reviewed the flow of liquid and gases in softwoods (Bamber and Burley 1983, Siau 1983, Booker 1990, Booker and Evans 1994). Tracheids provide the main pathways for penetration in the longitudinal direction. Tracheids interconnect with each other through pits, which are located on the radial face of the tracheids (Stamm 1967). Penetration of liquid in the radial direction is

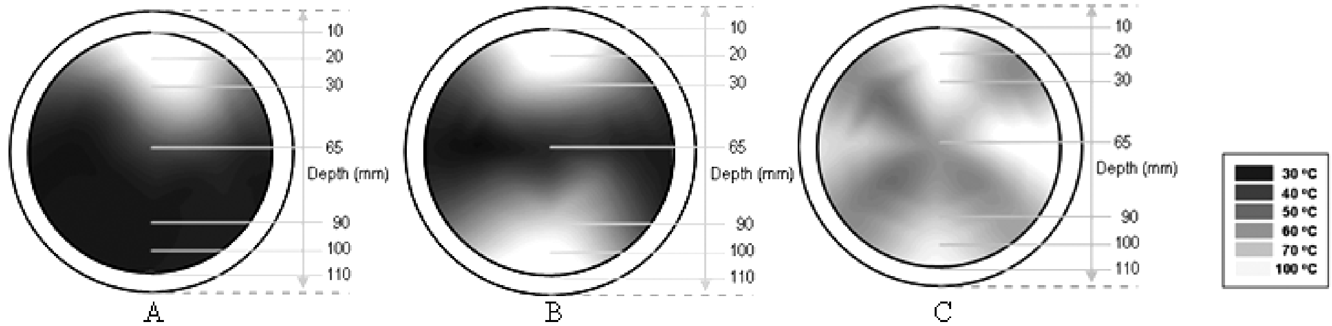

Figure 2.—Temperature distribution of one-sided (A), two-sided (B), and four-sided (C) microwave-treated peeler cores.

mainly through rays (Nicholas and Siau 1973). Ray tracheids, ray parenchyma, and resin ducts are the main cell types responsible for conducting fluid in softwood (Siau 1983).

Preservative flows through radial resin canals without interruption from changes that occur during the transition from early to late wood or from sapwood to heartwood. However, the epithelial and parenchymal cells in heartwood resin canals are lignified. As a result, the creation of interstitial spaces in radiata pine heartwood is limited, which reduces the speed of the diffusion process. Preservative solutions must pass through the intact and lignified epithelial and parenchymal cells and then move through aspirated pits, which are often clogged with resins (Booker 1990).

Vinden and Torgovnikov (2000) reported the impact of microwave treatment on increasing permeability in the radial and tangential directions in wood. When intense levels of microwave energy are applied, steam is generated within the wood cells. Under high internal steam pressure, the pit membranes in cell walls, tyloses in vessels in hardwoods, and weak ray cells rupture to form pathways for easy transportation of preservative.

Figure 3 depicts the preservative penetration in control and microwave-treated samples. The preservative penetration of control samples (Fig. 3A) was relatively poor, with very little copper penetration (used to represent preservative penetration) evident in the core. In microwave-conditioned samples (Figs. 3B, 3C, and 3D), preservative penetration was achieved through microvoids that formed during microwave modification. Microvoids formed during microwave modification as defined by Vinden and Torgovnikov (2000) created characteristic streaking of preservative from the surface through to the core.

One-sided treatment (Fig. 3B) gave rise to modification of the ray tissue only on the top side of the cores, and copper penetration was obvious only throughout the area that had been heated using microwave energy. Two-sided microwave modification created microvoids not only on the top and bottom sides of the cores but also, to a lesser extent, on the left- and right-hand areas, which were not directly heated (Fig. 3C). The loss of moisture during microwave modification at the top and bottom portions may have generated tension in the adjacent areas, causing them to collapse.

After four-sided treatment (Fig. 3D), microvoids were apparent throughout all areas directly modified by microwave energy. The presence of copper occurred throughout the radial and longitudinal planes in direct association with ray tissue. With increasing levels of microwave energy, pit membranes between the ruptured ray tissue and tracheids also ruptured, leading to improved lateral penetration of the preservative from the ray tissue and providing almost complete preservative penetration (Fig. 3D).

Four-sided microwave processing of the peeler cores increased the permeability of the core surfaces, allowing uniform CCA distribution. To achieve four-sided microwave treatment of peeler cores, it was necessary to move the core through the applicator twice using different speeds. The first run used 12, 14, and 16 mm/s, and the second run used 18, 21, and 24 mm/s. Microwave power applied to the logs ranged from 21.7 to 36.3 kW.

Preservative uptake

Table 3 shows preservative uptake was significantly increased with microwave modification. Preservative uptake in microwave-modified peeler cores ranged between 94 and 314 liters/m^3, depending on the microwave energy applied. The uptake of control peeler cores (no microwave treatment) was approximately 35 liters/m^3, indicating

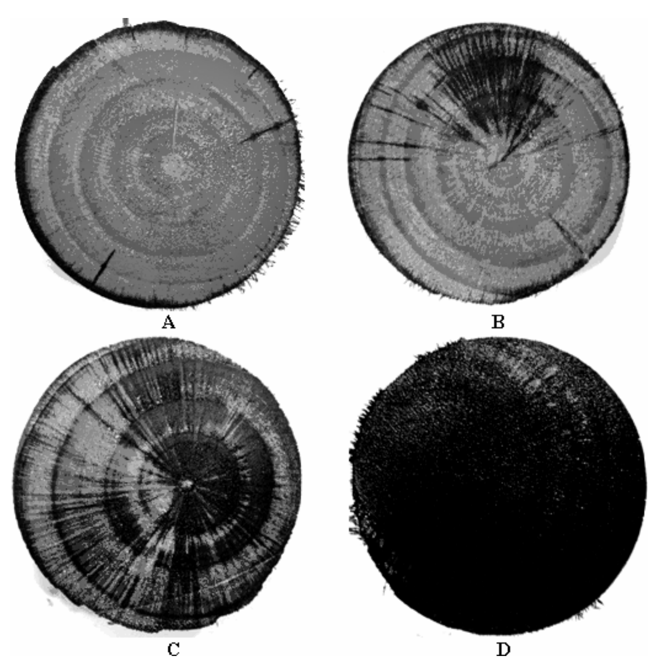

Figure 3.—Comparison of copper spot tested control (A) and of one-sided (B), two-sided (C), and four-sided (D) microwave-treated peeler cores.

Table 3.—Average preservative uptake of microwave-treated peeler cores.

Samples[a]	Microwave power (kW)	Speed (mm/s) First run	Speed (mm/s) Second run	Microwave energy (kWh/m^3)	Preservative uptake (liters/m^3)
CR 90–95	25.3	12	18	73.4	224.97
CR 96–100	29.0	12	18	84.0	314.41
CR 101–105	21.7	12	18	62.9	93.83
CR 106–110	25.3	14	21	63.0	146.19
CR 111–115	29.0	14	21	82.0	231.49
CR 116–120	32.6	14	21	81.0	291.50
CR 121–125	36.3	14	21	90.3	308.39
CR 126–130	25.3	16	24	55.0	125.15
CR 131–135	29.0	16	24	63.1	222.60
CR 136–140	32.6	16	24	71.0	270.79
CR 141–145	36.3	16	24	78.7	259.77
CR 146–150 (control)	—	—	—	—	35.22

[a] CR = core radiata.

microwave surface treatment in comparison to no microwave treatment enhances preservative uptake by a factor of three to nine, depending on the microwave schedule used. A sigmoidal nonlinear regression model of preservative uptake (liters/m^3) and microwave energy (kWh) applied is shown in Figure 4.

The equation of the sigmoidal regression model constructed using Sigma Plot version 10.0 software is

$$f(x) = 24.83 + \frac{483.99}{1 + e^{-[(x-79.97)/19.4]}} \qquad (2)$$

where $f(x)$ is CCA uptake (liters/m^3) and x is microwave energy applied (kWh/m^3). The normality and constant variance tests of the sigmoidal model were passed with P values of 0.4144 and 0.7341, respectively.

According to Equation 2, if no microwave power was applied (control samples), the average CCA uptake achieved was 35 liters/m^3. When 55 kWh/m^3 of microwave energy was applied, the uptake increased to 125 liters/m^3. The higher the microwave energy applied to the peeler core, the higher the CCA uptake. Extrapolation of the regression model predicts a maximum possible CCA uptake of approximately 503 liters/m^3 following 165 kWh/m^3 of microwave power.

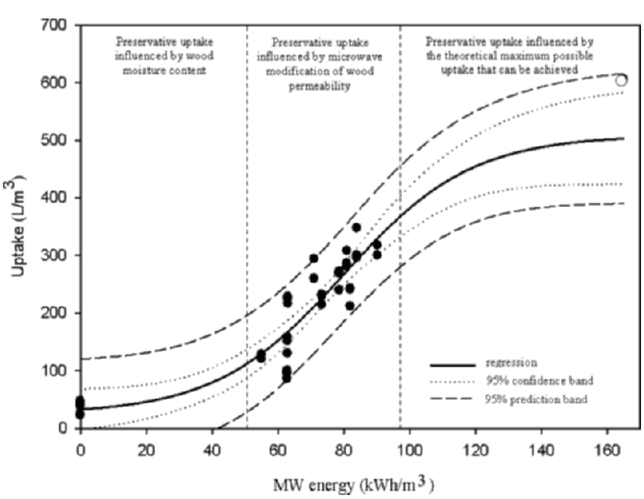

Figure 4.—Sigmoidal regression of preservative uptake and microwave energy.

The Pearson correlation, which is a measure of the linear relationship between CCA uptake and microwave energy, was indicative of a strong correlation (0.93) between these variables. The coefficient of determination (R^2), which is the proportion of variance in one variable explained by a second variable, was 0.86. Thus, 86 percent of CCA uptake is influenced by the microwave energy variable, whereas 14 percent was affected by other factors, such as initial moisture content and density as well as the sapwood and extractive content of the peeler core.

Calculation of the maximum possible uptake from basic density and moisture content of samples before treatment was 606 liters/m^3 (103 liters/m^3 higher than the CCA uptake predicted). However, the calculated value was still within the range of the 95 percent predicted band. The regression equation provided a realistic model to predict uptake as a function of applied microwave energy.

The sigmoidal nonlinear regression model can be divided into three parts: low, medium, and high levels of modification (Torgovnikov and Vinden 2009). Low levels of microwave energy (0 to 55 kWh/m^3) reduce the moisture content of the wood, whereas with increased microwave energy (55 to 95 kWh/m^3), steam builds up within the wood faster than it can dissipate, resulting in rupture of the weaker microstructures. Narrow microvoids created in the radial and longitudinal planes of the core were produced exponentially as more energy was applied. When high levels of microwave energy (95 to 170 kWh/m^3) were applied, the rate of CCA uptake was reduced as the core achieved the theoretical maximum possible absorption of preservative.

Cost estimation for microwave treatment

To achieve the required preservative distribution and uptake in the peeler cores, 60 kWh/m^3 of microwave energy is required. The schedule to apply this amount of energy was used in the calculation of specific costs for the production of preservative-treated peeler cores. A summary of the cost estimates for microwave treatment is presented in Table 4. In the first model (two working shifts, 11,600 m^3 of peeler cores annually), the estimated cost for microwave-treated peeler cores was US\$1.12, US\$1.17, and US\$1.23 each at the electricity supply rate of US\$0.07, US\$0.09, and US\$0.11 per kWh, respectively. In the second model (three working shifts, 17,400 m^3 of peeler cores annually), the

Table 4.—Microwave treatment cost estimation (US$).

Costs	Model 1 (11,600 m^3/y)			Model 2 (17,400 m^3/y)		
	0.07/kWh	0.09/kWh	0.11/kWh	0.07/kWh	0.09/kWh	0.11/kWh
Variable						
Electricity/y	67,200.00	86,400.00	105,600.00	100,800.00	129,600.00	158,400.00
Labor/y	90,000.00	90,000.00	90,000.00	135,000.00	135,000.00	135,000.00
Fixed						
Capital recovery	123,590.00	123,590.00	123,590.00	123,590.00	123,590.00	123,590.00
Maintenance	14,540.00	14,540.00	14,540.00	14,540.00	14,540.00	14,540.00
Magnetron replacement	56,000.00	56,000.00	56,000.00	84,000.00	84,000.00	84,000.00
Plant site rent	40,000.00	40,000.00	40,000.00	40,000.00	40,000.00	40,000.00
Microwave modification						
Cost/y	391,300.00	410,530.00	429,730.00	497,930.00	526,730.00	555,530.00
Cost/m^3	33.74	35.39	37.05	28.62	30.27	31.93
Cost/peeler core	1.12	1.17	1.23	0.95	1.00	1.06

estimated cost was US$0.95, US$1.00, and US$1.06 per peeler core, respectively.

This assessment indicated that microwave treatment of peeler cores before preservative treatment could be achieved at a competitive cost. For a microwave plant with an output of 350,000 to 525,000 peeler cores per year, the estimated microwave treatment cost ranged between US$391,330 and US$555,530 annually, or US$0.95 to US$1.23 per peeler core, depending on electricity rate and number of working shifts employed.

Generally, the mechanical properties of wood are affected by structural changes that result from microwave heating. Torgovnikov and Vinden (2009) reported moderate levels of microwave modification resulted in strength losses of 4 to 26 percent, whereas low levels of modification gave rise to lower strength losses. Similarly, after moderate microwave modification, peeler core strength is also reduced. The average peeler core modulus of elasticity was 6.6 GPa and the modulus of rupture 31.9 MPa, resulting in the cores being rated as Grade F7.

Conclusions

The results of the present study can be summarized as follows.

1. A study of energy distribution in peeler cores following microwave irradiation showed that a specifically designed PC-1 applicator provides surface conditioning of heartwood to a depth of 10 to 35 mm.
2. A significant improvement in wood permeability was achieved. This was verified by preservative impregnation of the microwave-modified samples.
3. Following microwave modification, preservative uptake was increased significantly. Preservative uptake in modified peeler cores ranged from 94 to 314 liters/m^3, whereas the uptake of control peeler cores was around 35 liters/m^3. Microwave surface treatment enhanced preservative uptake by a factor of three to nine compared with that achieved in control samples. An improvement in the distribution of preservative throughout the cross section was noted with increasing total microwave energy applied.
4. Modeling of preservative uptake as a function of microwave energy applied indicated a sigmoidal nonlinear regression model as ''best fit.'' An explanation of the model arises from three influences:
   a. Low levels of microwave energy (0 to 55 kWh/m^3) reduce the moisture content of the wood and increase preservative uptake incrementally.
   b. Medium levels of microwave energy (55 to 95 kWh/m^3) modify the wood structure and facilitate preservative penetration.
   c. High levels of microwave energy (95 to 170 kWh/m^3) cause a reduction in the rate of uptake as the wood samples had been saturated with preservative.
5. Cost assessment indicated that microwave processing of peeler cores before preservative treatment could be performed at competitive cost.

Acknowledgments

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