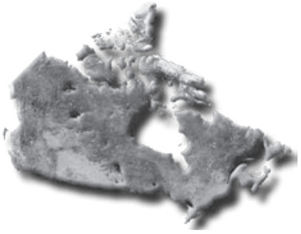


# Optimizing Drying of Mountain Pine Beetle Wood

**Luiz Oliveira, John Wallace, Liping Cai**

**Mountain Pine Beetle Initiative**
**Working Paper 2005–12**

**Natural Resources Canada, Canadian Forest Service,**
**Pacific Forestry Centre 506 West Burnside Road, Victoria, BC V8Z 1M5**
**(250) 363-0600 • www.pfc.cfs.nrcan.gc.ca**

Natural Resources Canada
Ressources naturelles Canada

Canada

Canada

Mountain Pine Beetle Initiative
Canadian Forest Service

# Optimizing Drying of Mountain Pine Beetle Wood

Luiz Oliveira, John Wallace, Liping Cai

Mountain Pine Beetle Initiative
Working Paper 2005-12

Forintek Canada Corp.
2665 East Mall
Vancouver, British Columbia, Canada
V6T 1W5

Natural Resources Canada
Canadian Forest Service
Pacific Forestry Centre
506 West Burnside Road
Victoria, British Columbia V8Z 1M5
Canada

Mountain Pine Beetle Initiative PO #3.24

2005

# Abstract

This report presents the methods and results for the industrial and laboratory tests carried out for the project "Optimizing Drying of Mountain Pine Beetle Wood". The results can be used by sawmills to assist them in choosing cost effective drying strategies to recover value from post-mountain pine beetle (MPB) wood.

Meetings with industry representatives in the early stages of the project surveyed the impact that MPB is having on the manufacturing of lumber products. These meetings were used to fine tune the research deliverables and obtain feedback and commitment for the field activities.

The main problems identified by industry representatives that they attributed to the MPB were:

(a) increased variation of the initial moisture content, not only among pieces of lumber, but also within the piece, along the length
(b) increased difficulty in estimating the correct kiln shutdown time
(c) over-drying as a consequence of incorrect kiln shutdown
(d) lower grade recovery
(e) non-uniform final moisture content.

Post-MPB (bluestained) sapwood demonstrated substantial increases in permeability and diffusion coefficients (at 50°C, 70°C and 90°C). The increase in tangential permeability was 8 to 25 times and the radial permeability was 6 to 23 times when compared to non-stained wood. The increase in the diffusion coefficients ranged from 34% to 76%. These increases will allow post-MPB sapwood to dry faster than non-infested sapwood but after drying, the post-MPB sapwood will equalize faster than non-infested sapwood, ultimately producing a piece of lumber with uniform moisture content.

Air-drying of post-MPB-infected wood during the summer months significantly lowered the average initial moisture content and standard deviation in two locations: Quesnel and Vancouver. The best results for lumber with initial moisture content below 20% were found when employing typical industrial schedules and processing (planing) 24 hours after drying. For lumber with initial moisture content ranging from 20% to 30%, the best results were found when the lumber was air-dried for one week, followed by typical heat-treatment schedules and planing one week after drying. The best results for lumber with initial moisture content greater than 30%, were obtained for lumber dried according to typical industrial schedules and planed one week after drying. These results will allow sawmills to target different strategies for moisture sorted post-MPB wood.

# Résumé

Ce rapport présente les résultats et les méthodes utilisés pour les tests effectués en laboratoire et sur le terrain dans le cadre du projet d'optimisation du séchage du bois atteint par le Dendroctone du pin ponderosa (DPP). Les gestionnaires des scieries peuvent utiliser ces résultats pour choisir une stratégie de séchage économique permettant de récupérer une certaine valeur du bois dégradé par le passage de dendroctones du pin.

Des réunions avec des représentant de l'industrie au début du projet ont permis de faire le survol de l'impact du DPP sur la fabrication des produits en bois. Ces réunions ont également permis de préciser quels devaient être les produits livrables à visés pour les activités de recherche et d'obtenir des commentaires et des engagements pour les activités sur le terrain.

Les représentants de l'industrie ont identifié les problèmes suivants comme étant directement imputables au DPP :

(a) augmentation de la variation du taux d'humidité initial, non seulement d'une grume à l'autre mais aussi à l'intérieur des grumes elles-mêmes, dans le sens de la longueur
(b) difficulté accrue pour l'estimation du temps de résidence du bois dans le séchoir
(c) séchage excessif résultant d'un temps de séchage incorrect
(d) obtention d'un bois de qualité inférieure
(e) taux d'humidité final du bois non uniforme.

Les coefficients de perméabilité et de diffusion (à 50 °C, 70 °C et 90 °C) de l'aubier bleui après une infestation de DPP se sont avérés largement supérieurs à ceux du bois normal. La perméabilité tangentielle augmente d'un facteur 8 à 25 tandis que la perméabilité radiale est multipliée par 6 à 23 par rapport au bois non bleui. L'augmentation des coefficients de diffusion allait de 34 à 76 %. Ces augmentations permettront à l'aubier bleui après une infestation par le DPP de sécher plus vite que l'aubier des arbres non infestés mais après séchage, l'aubier bleui s'égalisera plus vite que l'aubier non bleui, produisant à la fin un morceau de bois dont le taux d'humidité est uniforme.

Le séchage à l'air, durant la période estivale, du bois provenant d'arbres infestés par le DDP a permis d'abaisser de manière importante les taux initiaux moyens d'humidité et les déviations standard connexes en deux endroits : Quesnel et Vancouver. Les meilleurs résultats pour le bois dont le taux d'humidité initial était inférieur à 20 % ont été obtenus avec la méthode et le traitement industriel typique 24 heures après séchage. Pour le bois dont le taux d'humidité initial allait de 20 % à 30 %, les meilleurs résultats ont été obtenus lorsque le bois était séché à l'air pendant une semaine puis traité thermiquement et planed de façon habituelle une semaine après le séchage. Les meilleurs résultats pour le bois dont le taux initial d'humidité dépassait 30 % ont été obtenus lorsque le bois était séché conformément aux méthodes industrielles et planed une semaine après séchage. Ces résultats permettront aux These results will allow sawmills to target different strategies for moisture sorted post-MPB wood.

# Table of Contents

# List of Tables

## List of Figures

# 1 Introduction

The mountain pine beetle (MPB) infestation has reached epidemic proportions in most of the western and central regions of British Columbia. The affected area now covers 8.0 million hectares with an estimated timber value of $3.2 billion (NRCan, 2005). Although mills will be producing more lumber due to the short-term increase in annual allowable cut of infested lodgepole pine inventory, benefits can only be realized if the increase in production is coupled with new processing strategies and if new markets suitable to the timber quality are developed (Ferguson, 2003).

Although there is a limited amount of current literature on the physical properties of post-MPB wood, Woo et al. (2004) suggests that changes in the physical characteristics of post-MPB lodgepole pine lumber, such as reduced moisture content for sapwood and heartwood, decrease in the specific gravity and lower concentrations of hemicellulose, lignin and extractives, may have an impact on manufacturing and kiln drying. However, the impact of these changes has not been evaluated. To extract the most value from the increased available infested resource, it is necessary to:

a) determine whether potential large variations of moisture content in MPB lumber will increase the amount of over-drying and/or under-drying and therefore contribute to increased degrade;
b) take advantage of the inherently low initial moisture content for MPB lumber on drying times and therefore increase kiln drying productivity;
c) evaluate the opportunity to develop new drying schedules that can reduce drying times and improve grade recovery; and
d) develop strategies to improve uniformity of final moisture content.

This study was designed to provide the necessary information so that mills can devise the best strategy to process MPB lumber. A survey of mills processing MPB lumber was conducted to find out how they were dealing with MPB lumber to reduce the impact on grade recovery. Physical properties of MPB lumber (permeability and diffusion) were measured and compared to non-stained wood so that the information generated can be used to develop new and innovative drying strategies.

# 2 Materials and Methods

## 2.1 Industry Survey on Issues Related to Post-MPB Wood

In order to assess preliminary information regarding the impact of MPB on processing results, the following mills were visited:

a) Riverside – Williams Lake Division
b) Lignum (Williams Lake)
c) Tolko – Quest Wood Division
d) Riverside – Soda Creek Division.

Each of the mills was, at the time of the visit, processing both infested and non-infested wood. Meetings with production personnel were designed to obtain either evidence or perceptions related to the potential impact of post-MPB wood on several processing phases. Whenever possible, an attempt was made to assess the impact on results (grade recovery, drying times and variation of final moisture content) amongst the different stages of infestation (green, red and gray stages). The areas discussed in all meetings were as follows:

a) moisture content variation for the different stages of infestation
b) increase in over-drying and under-drying
c) increase in final moisture content variation
d) increase in drying defects
e) increase in drying degrade
f) differences in drying times for different lumber sizes.

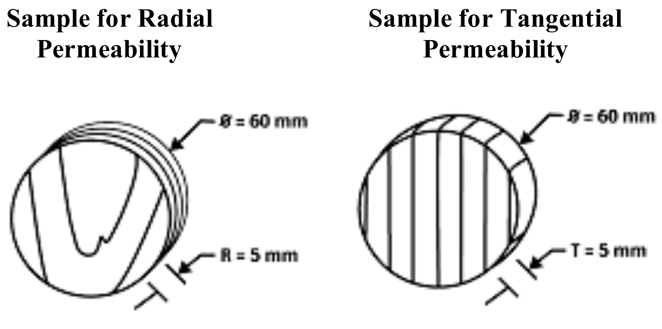
## 2.2 Determination of Permeability and Diffusion Coefficients

### *2.2.1 Determination of Permeability*

In this study, sapwood permeability in both radial ($K_R$) and tangential ($K_T$) directions was determined. Sapwood was chosen because of its inherent vulnerability to bluestain and determinations of transverse permeability (radial and tangential) were carried out because of their importance to drying and chemical treatment.

Ten 50 mm x 100 mm x 5 m (2 in. x 4 in. x 16 ft.) kiln dried lodgepole pine specimens that exhibited bluestained and non-stained sapwood regions were chosen from Tolko's Quest Wood Division sawmill production. Based on grain direction, six specimens were selected for determining $K_R$ and four were selected for determining $K_T$.

Sample discs 60-mm in diameter and 5-mm thick were prepared as shown in Figure 1. One sample was cut from the region exhibiting bluestain and matched with another one extracted from a region without bluestain. The samples were slowly dried in an oven at 60°C for one week until they reached 0% moisture content.


**Sample for Radial Permeability**

**Sample for Tangential Permeability**

**Figure 1: Samples for determining permeability**

Ten to thirty samples (discs) for both radial and tangential directions from either bluestain or non-stained regions were prepared from each specimen.

Gas permeability determinations (Siau 1984, 1995) were carried out with an apparatus (Figure 2) that includes:

1) two mercury manometers ($R_1$ – $R_4$) to determine the pressure difference between both sides of the sample;
2) a flow meter to indicate the airflow rate.

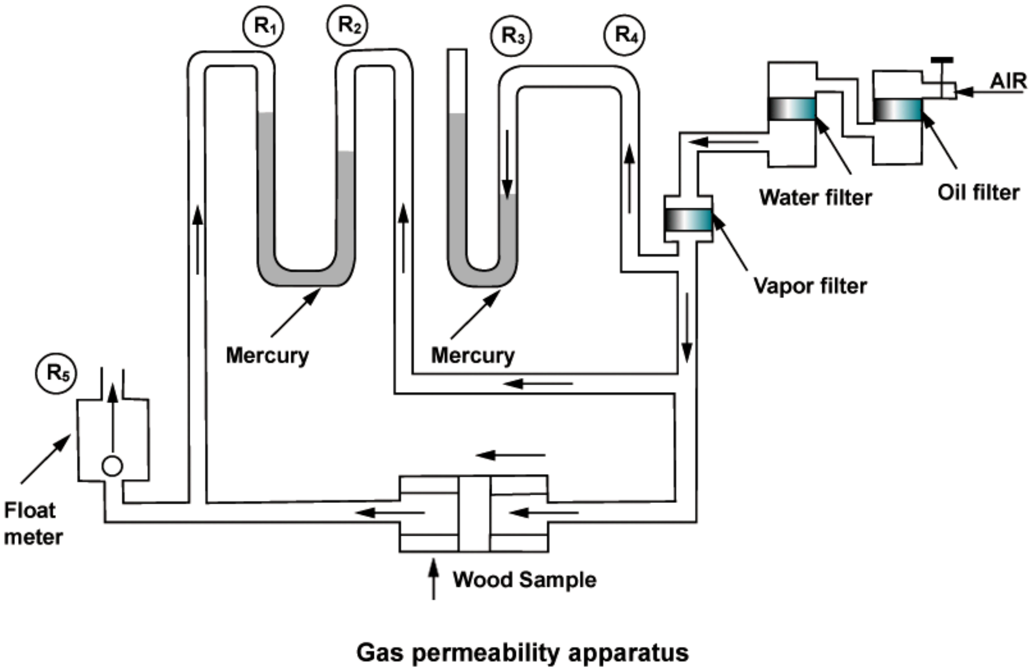


**Figure 2: Permeability apparatus**

The permeability (K) was calculated using the following equation:

$$K = \frac{\mu \cdot L \cdot Q \cdot P_2}{A \cdot \Delta P \cdot \overline{P}} \qquad (1)$$

where K is the intrinsic permeability, $m^3/m$ ; $\Delta P = (P_1 - P_2)$; $\overline{P} = (P_1+P_2)/2$; $P_1$ and $P_2$ are the pressures at the air entrance and exit side of the sample, mmHg; Q is the flow rate of volume of air, $m^3/s$; L is the thickness of sample, m; A is the cross-section area of sample, $m^2$; μ is the dynamic viscosity of air, $N \cdot s/m^2$.

### *2.2.2 Determination of Diffusion Coefficients*

From the same source material used for the permeability tests, the samples used for transverse diffusion coefficients were cut to 50 mm (width) × 10 mm (thickness) × 100 mm (length). Matched samples were obtained from bluestained and non-stained regions. Fifteen replicates were used for each sample type and at each temperature level. All samples were free from any visual defects. They were edge-coated with two layers of epoxy to restrict moisture movement in the longitudinal and transverse directions.

A conditioning chamber was used in the study. Temperature and relative humidity were maintained constant throughout the experiment within ±1°C and ±2% respectively. To minimize the effect of surface resistance on the diffusion coefficient (D), a high air velocity, about 5 m/s, was employed.

Before the tests of de-sorption (drying), the samples were equilibrated at 20°C and 95% relative humidity (23% Equilibrium Moisture Content [EMC]) for eight weeks. Upon reaching equilibrium, the samples for both bluestained and non-stained wood were placed in the chamber. De-sorption experiments were carried out at three temperatures: 50°, 70° and 90°C. During de-sorption, the weight of each sample was monitored with a digital balance sensitive to 0.0001g. To obtain their oven-dry weight, the samples were oven-dried at 103 ± 2°C and reweighed.

Assuming that the diffusion coefficient is independent of moisture content, the following equation (Siau, 1984) can be used:

$$\boldsymbol{D = \frac{705.88 \times (\overline{E})^2 L^2}{t}} \tag{2}$$

where, D is the diffusion coefficient, $mm^2/h$; L is half the thickness in the moisture diffusion direction, mm; t is the time, hrs.

$\boldsymbol{\overline{E}}$ is the fractional change in average moisture content at time t and can be described as follows:

$$\boldsymbol{\overline{E} = \frac{\overline{C} - C_e}{C_0 - C_e}}$$

where, $\boldsymbol{\overline{C}}$ is the moisture concentration at time t, $kg/m^3$; $C_e$ is the moisture concentration in equilibrium with the water vapor pressure in the surrounding air, $kg/m^3$; $C_0$ is the initial moisture concentration, $kg/m^3$.

From Equation 2, it can be seen that a plot of $\boldsymbol{\overline{E}}^2$ versus t is linear with a slope of $D/705.88L^2$, so D may be calculated from the slope of a linear regression obtained from the experimental data. Therefore, D can be obtained as follows:

$$\mathbf{D = 705.88L^2 \times Slope}$$

where, $\boldsymbol{Slope} = \frac{(\bar{E})^2}{t}$.

## 2.3 Evaluation of Drying

The evaluation of drying treatments was conducted in two phases. The first phase, an air-drying study, was conducted at Tolko Industries, Quest Wood Division, Quesnel, British Columbia. The second phase, a more comprehensive drying study, was conducted at Forintek Canada Corp.'s Western Laboratory in Vancouver, British Columbia.

### *2.3.1 Phase 1: Air-drying at Quesnel*

Green spruce-pine-subalpine fir (SPF) lumber produced by Quest Wood is usually sorted into three groups using Northern Milltech's MC-Pro 1000 green sorter. The dry sort contains lumber with less than 20% moisture content, the mid sort lumber moisture content ranges between 21 and 30% and the wet sort lumber moisture content is greater than 30%.

Figure 3 illustrates the experimental procedure for Phase 1. One hundred specimens were randomly selected from a Quest Wood package containing 450 pieces. Three 25 mm samples were cut from the 5 m long specimens and subsequently oven-dried to determine moisture content along the length. The remaining two 2.4 m (8 ft.) specimens were weighed and re-piled into the load for one week or three weeks of air-drying (Figures 4 and 5).

After one week of air-drying, both groups of 2.4m specimens were weighed. From one group, three samples were cut to assess the moisture content (oven-dry basis) along the length. Two weeks later the same procedure was repeated.

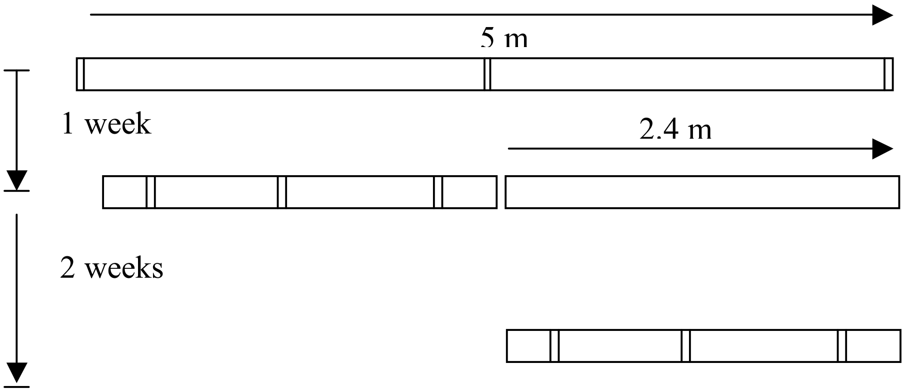


**Figure 3: Experimental procedure for Phase 1 in Quesnel**

**Figure 4:** **Air-drying package with test samples in the middle of package**

**Figure 5:** **Air-drying moisture sorted packages in the lumber yard of Quest Wood (Quesnel)**

### *2.3.2 Phase 2: Drying Trials at Vancouver*

The lumber for the second phase was also supplied by Tolko Industries; Quest Wood Division. To minimize moisture loss during storage, lumber from each moisture sort was only collected upon completion of the tests involving the previous sorting group.

Five hundred 50 mm x 100 mm x 5 m (2 in. x 4 in. x 16 ft.) lodgepole pine specimens from a mill run were selected by Forintek employees and shipped to Forintek. Upon arrival, 192 5 m (16ft.) specimens were cut into two 2.4 m (8 ft.) pieces for one set of experimental groups (one drying charge and one replicate drying charge). Three samples from each piece were collected during the preparation of the 2.4 m specimens and used for oven-dry moisture content and basic density determination.

Figure 7 and Table 1 illustrate the study plan. In Treatment A the lumber was dried according to Schedule 1. For each specimen, final moisture content and grade recovery were assessed 24 hours after drying. In Treatment B the lumber was dried in Schedule 1 and final moisture content and grade recovery were assessed 168 hours after drying. In Treatment C the lumber was air-dried for 168 hours before kiln drying. It was then dried in Schedule 2 and assessed for moisture content and grade recovery 24 hours after drying. In Treatment D the lumber was air-dried for 168 hours before kiln drying according to Schedule 2, but assessed for moisture content and grade recovery 168 hours after drying. In Treatment E the lumber was air-dried for 504 hours prior to kiln drying. It was dried according to Schedule 2, modified and assessed for moisture content and grade recovery 24 hours after drying. In Treatment F the lumber was air-dried for 504 hours prior to kiln drying, dried according to Schedule 2 modified and assessed for moisture content and grade recovery 168 hours after drying.

**Table 1: Study Plan**

| Treatment | Air-drying Time (hrs) | Schedule | Equalizing Time(hrs) |
|---|---|---|---|
| A | 0 | Schedule 1 | 24 |
| B | 0 | Schedule 1 | 168 |
| C | 168 | Schedule 2 | 24 |
| D | 168 | Schedule 2 | 168 |
| E | 504 | Schedule 2 modified | 24 |
| F | 504 | Schedule 2 modified | 168 |

Drying Schedules 1 and 2 were specifically developed for this study. Schedule 1 (Table 2) is ‘conservative’ and was designed to achieve high grade-recovery values. Schedule 2 (Table 3) employed more aggressive conditions and was designed to dry lumber with lower initial moisture content resulting from air-drying. Schedule 2 was modified and employed to dry the wet sort (Table 4).

**Table 2: Schedule 1 for All Three Sorts**

| Step | Ramp (hrs) | Step (hrs) | Dry Bulb Temperature (°C) | Wet Bulb Temperature (°C) | Dry Bulb Temperature (°F) | Wet Bulb Temperature (°F) | EMC (%) |
|---|---|---|---|---|---|---|---|
| Heat-up | 6 | - | 60 | 60 | 140 | 140 | 24.6 |
| D1 | 10 | - | 71 | 68 | 160 | 155 | 15.6 |
| D2 | 8 | - | 82 | 78 | 180 | 172 | 12.4 |
| D3 | - | 12 | 88 | 79 | 190 | 174 | 8.5 |
| D4 | 12 | - | 91 | 76 | 195 | 168 | 6.0 |

**Table 3: Schedule 2 for Dry Sort and Mid Sort**

| Step | Ramp (hrs) | Step (hrs) | Dry Bulb Temperature (°C) | Wet Bulb Temperature (°C) | Dry Bulb Temperature (°F) | Wet Bulb Temperature (°F) | EMC (%) |
|---|---|---|---|---|---|---|---|
| Heat-up | 8 | - | 93 | 77 | 200 | 170 | 5.4 |
| D1 | - | 3 | 93 | 77 | 200 | 170 | 5.4 |

**Figure 6: Dry kiln at Forintek Canada Corp. showing a load of post-MPB lumber**

**Table 4: Schedule 2 Modified for Wet Sort**

| Step | Ramp (hrs) | Step (hrs) | Dry Bulb Temperature (°C) | Wet Bulb Temperature (°C) | Dry Bulb Temperature (°F) | Wet Bulb Temperature (°F) | EMC (%) |
|---|---|---|---|---|---|---|---|
| Heat-up | - | 4 | 71 | 71 | 160 | 160 | 23.5 |
| D1 | 5 | - | 82 | 76 | 180 | 168 | 10.2 |
| D2 | 4 | - | 88 | 72 | 190 | 161 | 5.7 |
| D3 | 12 | - | 88 | 56 | 190 | 133 | 2.9 |
| D4 | 12 | - | 93 | 61 | 200 | 141 | 2.8 |

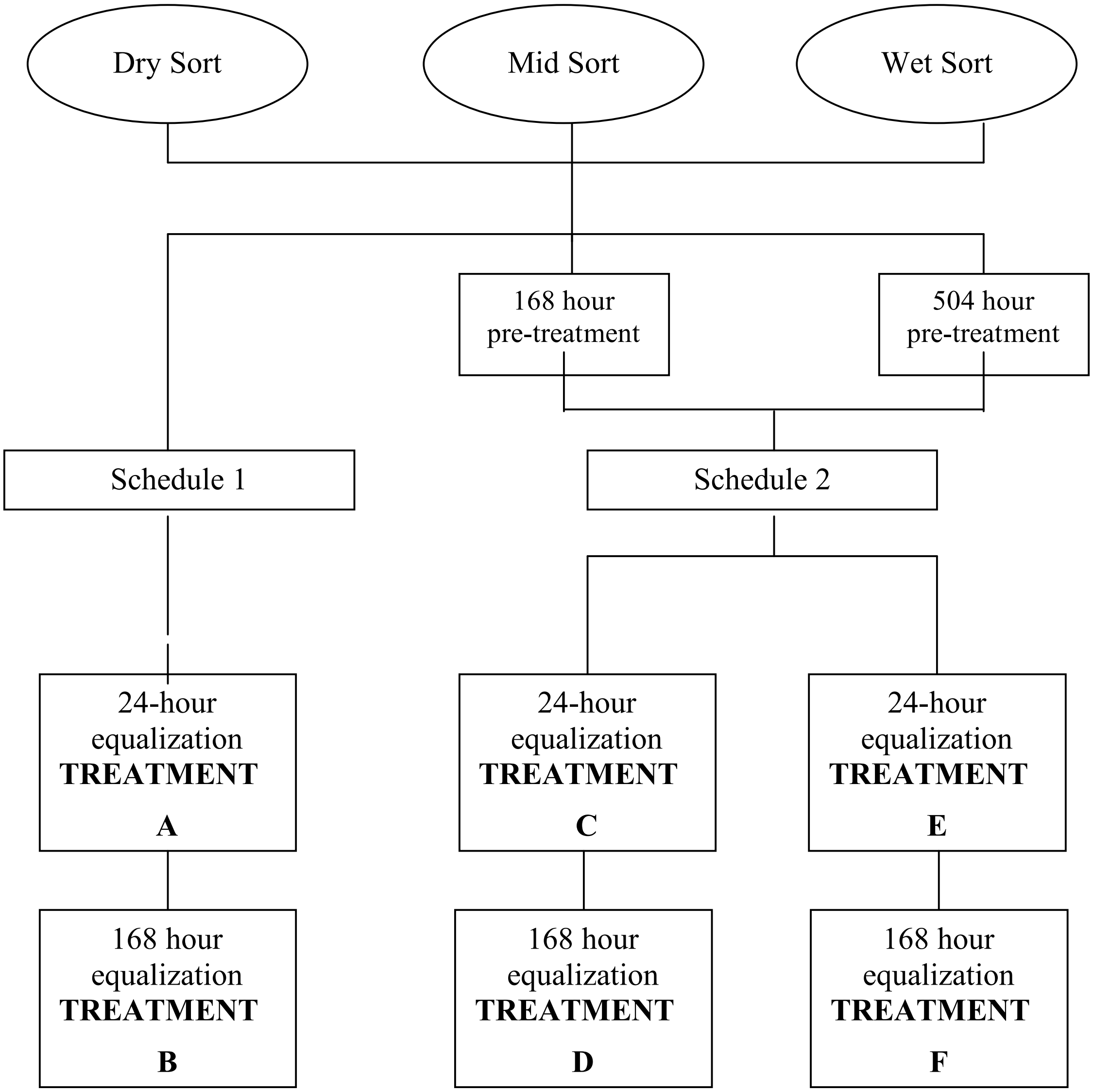


**Figure 7: Amended Research Plan**

**Figure 8: Air-drying in yard at Forintek**

### 2.3.3 *Analysis*

#### *2.3.3.1 Total Processing Time*

Total processing time was calculated as the sum of any pre-drying treatments (air-drying for 168 hours or 504 hours), kiln residency time and post-drying treatment (equalization for 24 hours or for 168 hours).

#### *2.3.3.2 Grade Recovery*

Grade recovery values were calculated based solely on warp, according to the National Lumber Grades Authority (NLGA) and Tolko's in-house rules. Splits, checks and stain were not considered. Each board was assigned a grade according to the rules and recovery is based on '#2 & Better'. A negative number indicates a loss in value and a positive number indicates an increase in value.

#### *2.3.3.3 Final Moisture Content*

The coefficient of variation was calculated by dividing the standard deviation by the mean of each charge.

#### *2.3.3.4 Energy Consumption*

Energy consumption values included all electrical energy used during drying (heating, air-circulation and vent actuation).

# 3 Results and Discussion

## 3.1 Industry Survey

According to the discussions with mill personnel, the following observations were made:

1. Initial moisture content variation in a kiln charge depends on the proportions of wood at different stages following infestation. Wood from gray stage trees exhibit considerably lower initial moisture content (believed to be lower than 20%) and therefore mill personnel make the necessary adjustments to sort MPB lumber that is usually drier than non-infested wood.

2. No data were available to substantiate the hypothesis that drying post-MPB wood would either produce more over-drying or more under-drying. It is speculated that kiln operators may need to use additional “hot checks” [Moisture content (MC) determinations done in the kiln towards the end of drying] to ensure that the final moisture content is within the target range and to avoid over-drying.

3. No data were available to compare variations of final moisture content for normal and infested wood.

4. Although industry representatives expect lower grade recovery, there is no evidence that a reduction in quality results directly from the drying operation of post-MPB wood.

5. Drying times for post-MPB wood, especially for material processed from dead pines, are significantly reduced when compared to those usually obtained for non-stained green wood. Thus, the infested wood may result in an increase in kiln productivity and a decrease in energy consumption.

In addition to the difficulties related to future access to the Japanese market due to staining, industry representatives are also concerned with the impact of MPB infestation on Machine Stress Rated (MSR) yields.

Some mill personnel indicated that significantly better drying results are obtained when the lumber packages (with stickers) are left in the yard for a period of time before kiln drying. It is perceived that this “pre-equalization” period may improve moisture content uniformity and therefore result in better final kiln drying. Thus, the study was amended to include some tests to verify the impact of the “pre-equalization” period before drying.

Although not necessarily related to the MPB infestation, some mill representatives also expressed their interest in assessing the impact of “post-equalization” on drying results. “Post-equalization" refers to a period of time that the lumber is left in the yard before planing. This procedure is common in Japan but data on Canadian SPF is not available.

## 3.2 Determination of Permeability and Diffusion Coefficients

### *3.2.1 Permeability*

The results for average permeability in the radial direction ($K_R$) (average and standard deviation values) are presented in Table 5. As illustrated in Table 5, $K_R$ values for MPB wood are significantly larger than those for non-stained wood.

**Table 5: Permeability in the Radial Direction ($\times 10^{-14} m^3/m$)**

| **MPB Wood** | **Number of Samples** | **Density*** (kg/m$^3$) | **Average $K_R$** | **Standard Deviation $K_R$** |
|---|---|---|---|---|
| Specimen 1 | 22 | 404.69 | 6.491 | 1.862 |
| Specimen 2 | 15 | 435.82 | 6.628 | 1.680 |
| Specimen 3 | 30 | 437.54 | 2.444 | 0.712 |
| Specimen 4 | 19 | 402.49 | 4.858 | 1.198 |
| Specimen 5 | 10 | 429.78 | 3.778 | 1.201 |
| Specimen 6 | 24 | 421.06 | 3.124 | 1.034 |
| **Normal Wood** | | | | |
| Specimen 1 | 22 | 439.04 | 0.276 | 0.096 |
| Specimen 2 | 22 | 454.99 | 0.395 | 0.233 |
| Specimen 3 | 30 | 454.65 | 0.173 | 0.128 |
| Specimen 4 | 17 | 438.62 | 0.206 | 0.103 |
| Specimen 5 | 12 | 439.88 | 0.277 | 0.119 |
| Specimen 6 | 18 | 448.19 | 0.468 | 0.201 |

❖ $$OvenDryDensity = \frac{OvenDryWeight}{OvenDryVolume}$$

The results for permeability in the tangential direction ($K_T$) are presented in Table 6. Similarly to the results observed for $K_{R,}$ the values obtained for $K_T$ for MPB wood were also significantly larger than those of non-stained wood.

**Table 6: Permeability in the Tangential Direction ($\times10^{-14}m^3/m$)**

| **MPB Wood** | **Number of Samples** | **Density*** (kg/m$^3$) | **Average $K_T$** | **Standard Deviation $K_T$** |
|---|---|---|---|---|
| Specimen 1 | 13 | 436.88 | 5.872 | 1.859 |
| Specimen 2 | 10 | 418.32 | 5.789 | 2.917 |
| Specimen 3 | 23 | 428.31 | 1.773 | 0.457 |
| Specimen 4 | 12 | 422.78 | 3.858 | 0.981 |
| **Normal Wood** | | | | |
| Specimen 1 | 16 | 452.13 | 0.320 | 0.199 |
| Specimen 2 | 22 | 439.61 | 0.225 | 0.089 |
| Specimen 3 | 25 | 439.11 | 0.211 | 0.122 |
| Specimen 4 | 20 | 450.74 | 0.296 | 0.168 |

❖ $$OvenDryDensity = \frac{OvenDryWeight}{OvenDryVolume}$$

Both radial and tangential permeability values probably have been increased following the MPB attack as a result of:

a) rupture in the walls of ray parenchyma cells;
b) rupture of pit membranes;
c) checking in the middle lamella of tracheids;
d) damage to the pit membranes and, in some cases, pits were no longer aspirated.

The higher transverse permeability observed for MPB wood is similar to the results found by Woo et al. (2005) for longitudinal permeability in MPB sapwood. The $K_R$, in the current study appears to be higher than the $K_T$ in both MPB wood and non-stained wood. These results are consistent with the findings presented by Siau (1995) and Peng (2002) for non-stained wood. Pathways along the rays by bluestain fungi probably contribute to the larger values of $K_R$.

Even though the sample size was small, and the probability of a Type II error is high, the average density for post-MPB sapwood was lower when compared to non-stained sapwood (Table 5 and 6).

### *3.2.2 Diffusion Coefficients*

Figure 9 to 11 show average drying curves (moisture content versus time) for both post-MPB and non-stained wood obtained from fifteen experiments for each dry-bulb temperature set point. It is clear from the drying curves that post-MPB wood dries faster than non-stained wood for all three temperature set points used in the study.

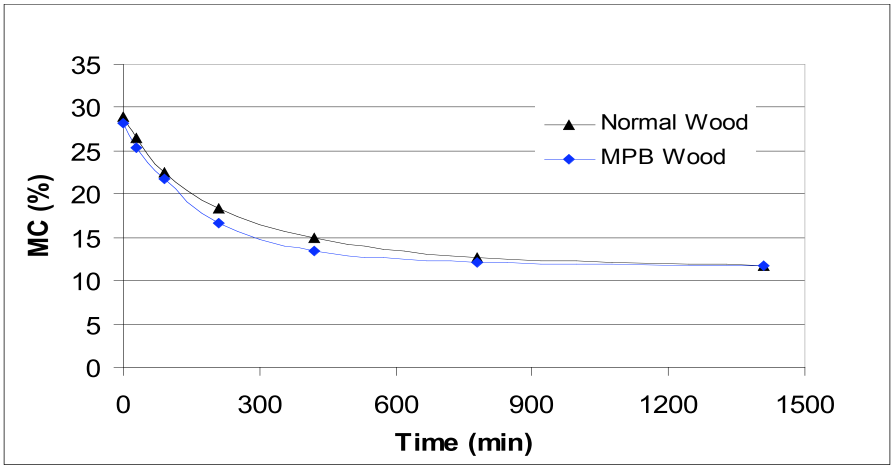


**Figure 9:** **Drying curves for post-MPB wood and non-stained wood at 50°C**

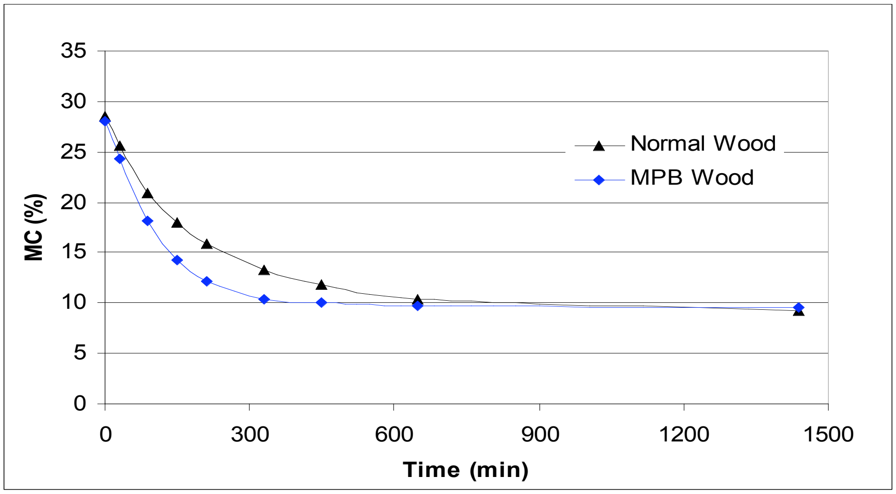


**Figure 10:** **Drying curves for post-MPB wood and non-stained wood at 70°C**

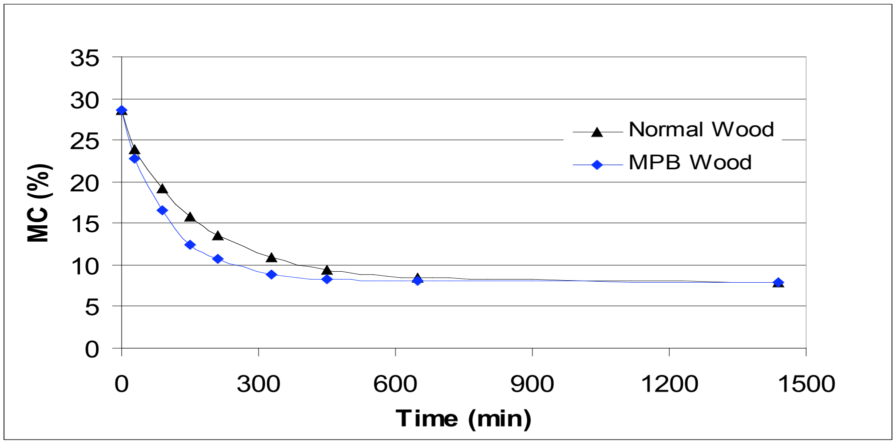


**Figure 11:** **Drying curves for post-MPB wood and non-stained wood at 90°C**

Diffusion coefficient (D) values for post-MPB wood and non-stained wood are shown in Table 7. Regardless of the dry-bulb temperature used, diffusion coefficients for post-MPB wood were significantly different from those measured for non-stained wood. These results are illustrated in Figure 12.

**Table 7: Diffusion Coefficients at different temperatures**

| Temperature (°C) | Transverse D ($mm^2$/h) | | Increase (%) |
|---|---|---|---|
| | Normal Wood | MPB Wood | |
| 50 | 0.4588 | 0.6176 | 34.6 |
| 70 | 0.5294 | 0.9353 | 76.7 |
| 90 | 0.7059 | 1.0571 | 49.8 |

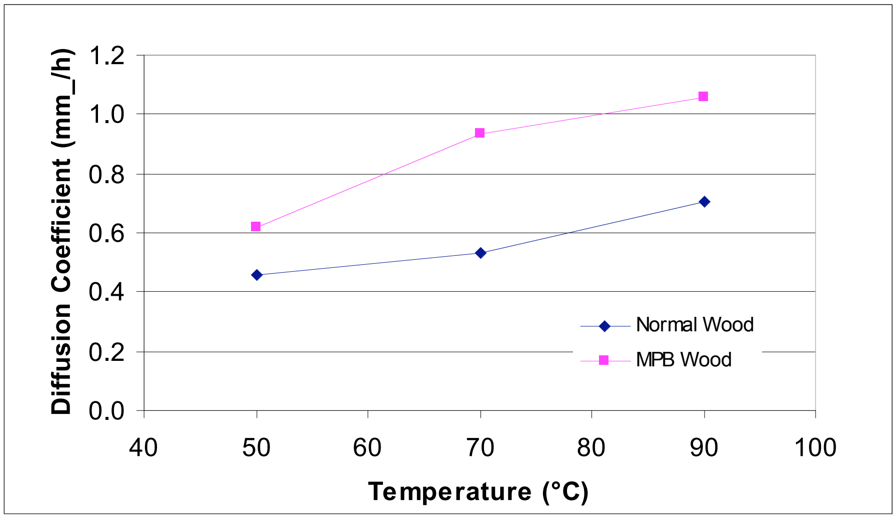


**Figure 12: Diffusion coefficient changes with temperature**

Even with the high probability of a Type II error, the higher diffusion coefficients for post-MPB wood can probably be attributed to the lower density observed for post-MPB wood (423.8 kg/$m^3$) in relation to non-stained wood (445.7 kg/$m^3$). According to Siau (1995) lower density reduces resistance to flow, which in turn is reflected in the increase in the diffusion coefficient.

Since the ratio of post-MPB wood (bluestain) and non-stained wood is rarely uniform, different drying rates might occur within a specimen. Bluestained areas will dry faster than areas without bluestain due to the differences in the diffusion rates. However, since the permeability is also increased in bluestained regions, equalizing the lumber after drying will allow the moisture to redistribute from the non-stained areas into the drier, bluestained areas. This will increase the possibility of having uniform moisture content throughout the specimen after drying and equalizing.

## 3.3 Evaluation of Drying Schedules

### *3.3.1 Air-drying at Quesnel*

The change in moisture content distributions for the three moisture sorts was monitored over a three-week period and the results are presented in Figure 13 to 15. The boxes represent the inter-quartile range, and include 50% of all values. The horizontal line in the box is the median. The upper and lower horizontal lines represent the maximum and minimum values of the specimens respectively. Any value that is greater than or less than 1.5 times the inter-quartile range is defined as a statistical outlier and is represented by a circle.

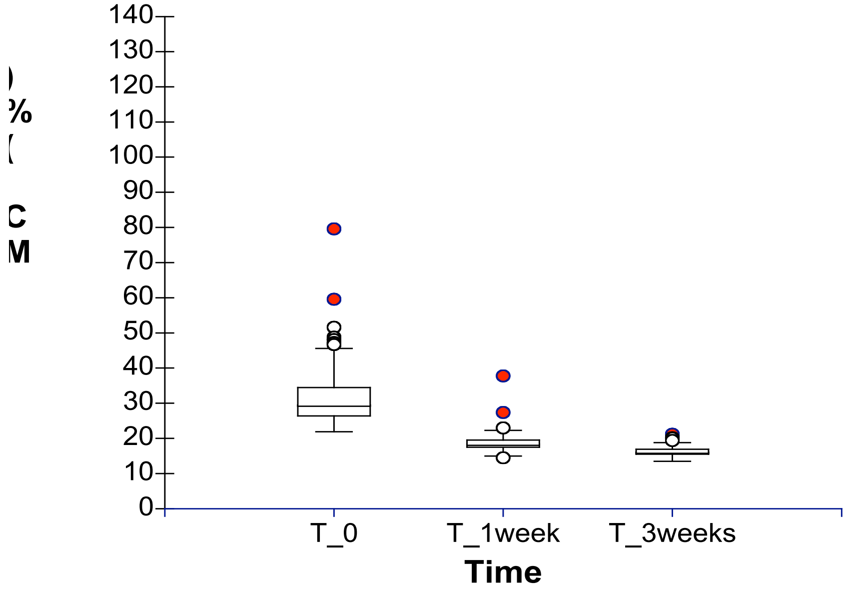


**Figure 13: Distribution of moisture contents of dry sort during three weeks of air-drying in Quesnel, British Columbia**

There was a significant change in the moisture content distribution over the three-week air-drying period for all three sorts. The dry sort (Figure 13) exhibited a decrease in the inter-quartile range from 8% to 1.9% after one week of air-drying. Two additional weeks of air-drying resulted in a further decrease to 1.4%. Similar trends were found for the mid sort (Figure 14) for which one week of air-drying resulted in the inter-quartile range decreasing from 20% to 4.7%. An additional two weeks of air-drying resulted in a further decrease to 1.2%. Similar trends were also found for the wet sort (Figure 15) but the most significant decrease in the inter-quartile range (16.5%) occurred after three weeks of air-drying.

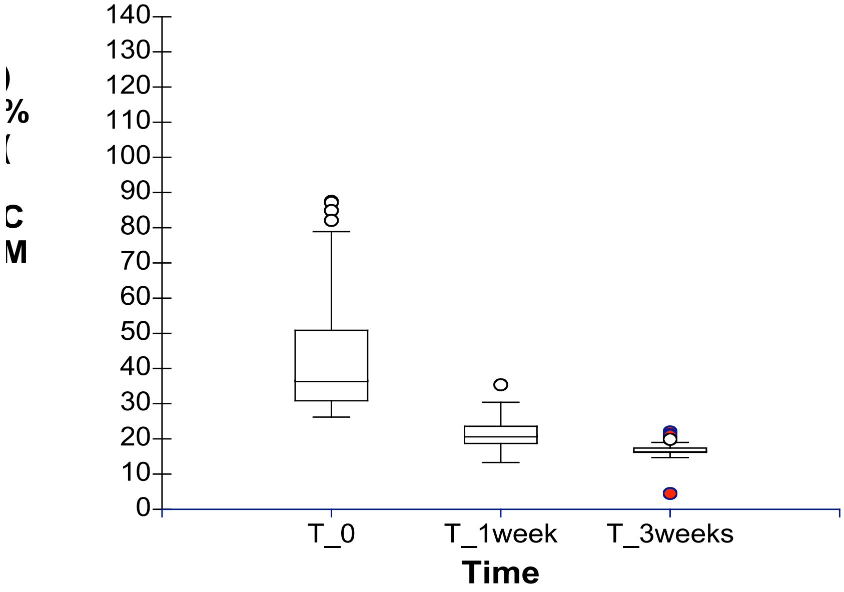


**Figure 14:** **Distribution of moisture contents of mid sort during three weeks of air-drying in Quesnel, British Columbia**

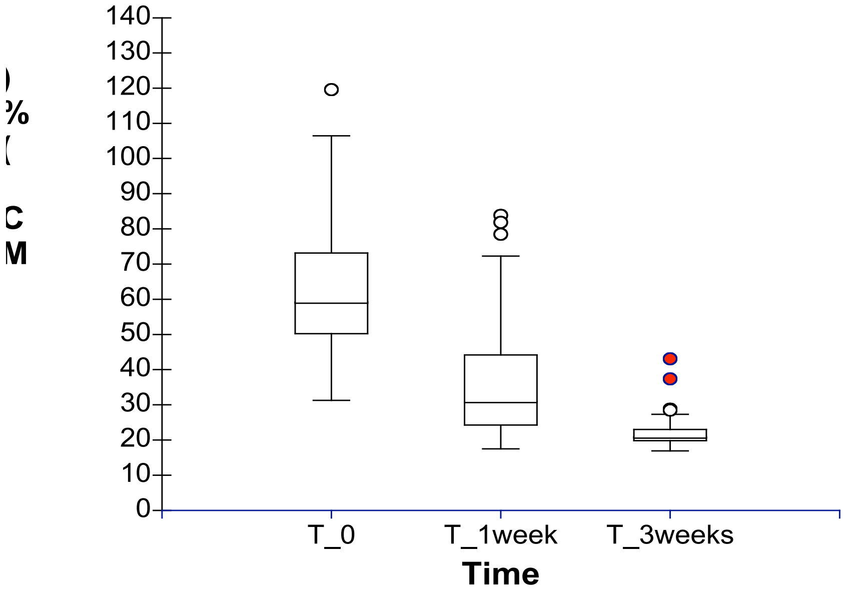


**Figure 15:** **Distribution of moisture contents of wet sort during three weeks of air-drying in Quesnel, British Columbia**

### *3.3.2 Drying Trials at Vancouver*

#### *3.3.2.1 Dry Sort*

Results regarding total processing time and treatment rankings are presented in Table 8. By convention, the total processing time is ranked from treatments A to F.

**Table 8: Dying Time Ranking**

| Treatment | Air-drying Time (hrs) | Kiln Time (hrs) | Equalizing Time (hrs) | Total Processing Time (hrs) | Rank |
|---|---|---|---|---|---|
| A | 0 | 13 | 24 | 37 | 1 |
| B | 0 | 13 | 168 | 181 | 2 |
| C | 168 | 10.5 | 24 | 202.5 | 3 |
| D | 168 | 10.5 | 168 | 346.5 | 4 |
| E | 504 | 15 | 24 | 543 | 5 |
| F | 504 | 15 | 168 | 687 | 6 |

Grade recovery results and treatment rankings are presented in Table 9. Treatments with a one-week equalization period (B, D and F) appeared to have a positive impact on grade recovery values compared to treatments with a 24-hour equalization period (A, C and E). Treatments F and A exhibited the best and worst grade recovery values respectively.

**Table 9: Grade Recovery Ranking**

| Treatment | Grade Recovery (#2&Better) | Rank |
|---|---|---|
| A | -13.8 | 6 |
| B | -1.8 | 3 |
| C | -2.1 | 4 |
| D | -1.0 | 2 |
| E | -2.6 | 5 |
| F | 0.3 | 1 |

The coefficients of variation for moisture content and treatment rankings are presented in Table 10. There is only a small difference between values for each treatment and therefore Schedules 1 and 2 did not have any significant impact on final moisture content variability. In relation to final moisture content variability, Treatments A and F showed the best results (least variation). On the other hand, Treatment B exhibited the highest variation and therefore was the lowest ranked treatment.

**Table 10: Coefficient of Variation (Moisture Content) Rankings**

| Treatment | Coefficient of Variation | Rank |
|---|---|---|
| A | 0.08 | 1 |
| B | 0.13 | 6 |
| C | 0.12 | 5 |
| D | 0.09 | 3 |
| E | 0.10 | 4 |
| F | 0.08 | 1 |

Table 11 presents the total kilowatt-hours of electrical energy consumption and treatment rankings. The ranking results were obtained by combining the replicates and using averaged kilowatt-hour values.

**Table 11: Energy Utilization Ranking**

| Treatment | Utilization (kWhr) | Rank |
|---|---|---|
| A | 166 | 1 |
| B | 166 | 1 |
| C | 194 | 3 |
| D | 194 | 3 |
| E | 197 | 5 |
| F | 197 | 5 |

Four different scenarios are illustrated in order to compare treatments and develop drying strategies. The variables for each scenario are as follows:

- drying time (hrs)
- grade recovery (%)
- coefficient of variation for moisture content (ratio of the standard deviation to the average value)
- electrical energy consumption (kWhr).

In the first scenario (Table 12), it is assumed that all variables have the same degree of importance, that is, equal 'weights'. In the second scenario (Table 13), the degree of importance from highest to lowest was as follows:

1) grade recovery
2) moisture content
3) total processing time.

For the third scenario (Table 14), the degree of importance was as follows:

1) grade recovery

2) total processing time
3) moisture content.

Finally, the fourth scenario (Table 15) takes into account potential increase in energy costs and the following degree of importance for the variables was used:

1) grade recovery
2) energy consumption
3) moisture content.

**Table 12: Cumulative Ranking of Treatments**

| Treatment | Time (hrs) | Recovery (%) | CV (MC) | Energy (kWhr) | Total | Rank |
|---|---|---|---|---|---|---|
| A | 1 | 6 | 1 | 1 | 9 | 1 |
| B | 2 | 3 | 6 | 1 | 12 | 2 |
| C | 3 | 4 | 5 | 3 | 15 | 5 |
| D | 4 | 2 | 3 | 3 | 12 | 2 |
| E | 5 | 5 | 4 | 5 | 19 | 6 |
| F | 6 | 1 | 1 | 5 | 13 | 4 |

**Table 13: Drying Treatment Ranking: Recovery, Moisture Content and Time**

| Treatment | Time (hrs) | Recovery (%) | CV (MC) | Energy (kWhr) | Total | Rank |
|---|---|---|---|---|---|---|
| A | 1 | 6 | 1 | 1 | 11 | 1 |
| B | 2 | 3 | 6 | 1 | 21 | 3 |
| C | 3 | 4 | 5 | 3 | 23 | 5 |
| D | 4 | 2 | 3 | 3 | 20 | 2 |
| E | 5 | 5 | 4 | 5 | 28 | 6 |
| F | 6 | 1 | 1 | 5 | 21 | 4 |

**Table 14 Drying Treatment Ranking: Recovery, Time and Moisture Content**

| Treatment | Time (hrs) | Recovery (%) | CV (MC) | Energy (kWhr) | Total | Rank |
|---|---|---|---|---|---|---|
| A | 1 | 6 | 1 | 1 | 11 | 1 |
| B | 2 | 3 | 6 | 1 | 25 | 4 |
| C | 3 | 4 | 5 | 3 | 25 | 4 |
| D | 4 | 2 | 3 | 3 | 19 | 3 |
| E | 5 | 5 | 4 | 5 | 27 | 6 |
| F | 6 | 1 | 1 | 5 | 16 | 2 |

**Table 15: Drying Treatment Ranking: Recovery, Energy and Moisture Content**

| Treatment | Time (hrs) | Recovery (%) | CV (MC) | Energy (kWhr) | Total | Rank |
|---|---|---|---|---|---|---|
| A | 1 | 6 | 1 | 1 | 15 | 1 |
| B | 2 | 3 | 6 | 1 | 35 | 4 |
| C | 3 | 4 | 5 | 3 | 39 | 5 |
| D | 4 | 2 | 3 | 3 | 32 | 2 |
| E | 5 | 5 | 4 | 5 | 46 | 6 |
| F | 6 | 1 | 1 | 5 | 33 | 3 |

The results can be summarized as follows:

|  | Best Result | Worst Result |
|---|---|---|
| Scenario 1 | A | E |
| Scenario 2 | A | E |
| Scenario 3 | A | E |
| Scenario 4 | A | E |

When the variables were examined independently, treatments with a one-week equalization period exhibited better results. However, when the variables were ranked in the different scenarios the best strategy did not include the one-week equalization period. Since the variation in moisture content was so low, equalizing for one week was not as beneficial as increased productivity. Thus, regardless of scenario, Treatments A and E showed the best and worst results, suggesting that when processing lumber with initial moisture contents less than 20%, best overall results can be obtained if the lumber is dried according to Schedule 1 and planed only after 24 hours.

### *3.3.2.2 Mid Sort*

Results regarding total processing time and treatment rankings are presented in Table 16. Similar to the dry sort, the experimental plan determined the rankings from Treatment A to Treatment F.

**Table 16: Drying Time Ranking**

| Treatment | Air-drying Time | Kiln Time | Equalizing Time | Total Processing Time (hrs) | Rank |
|---|---|---|---|---|---|
| A | 0 | 34 | 24 | 58 | 1 |
| B | 0 | 34 | 168 | 202 | 2 |
| C | 168 | 13 | 24 | 205 | 3 |
| D | 168 | 13 | 168 | 349 | 4 |
| E | 504 | 11 | 24 | 539 | 5 |
| F | 504 | 11 | 168 | 683 | 6 |

Grade recovery results and the treatment rankings are presented in Table 17. Again, treatments with the one-week equalization period (B, D and F) appeared to have a positive impact on grade recovery values compared to treatments with a 24-hour equalization period (A, C and E). Treatments F and E have the best and worst grade recovery value respectively.

**Table 17: Grade Recovery Ranking**

| Treatment | Grade Recovery (#2&Better) | Rank |
|---|---|---|
| A | -4.4 | 5 |
| B | -4.2 | 4 |
| C | -1.6 | 3 |
| D | -1.3 | 2 |
| E | -5.4 | 6 |
| F | 0.3 | 1 |

The coefficients of variation for moisture contents and treatment rankings are presented in Table 18. The coefficient of variation was similar for all six treatments. Again, there is a small improvement in the coefficient of variations for the treatments with the one-week equalization period (B, D, F). Treatments F and A have the best and worst coefficients of variation for moisture content respectively.

**Table 18: Coefficient of Variation (Moisture Content) Ranking**

| Treatment | Coefficient of Variation | Rank |
|---|---|---|
| A | 0.19 | 6 |
| B | 0.12 | 3 |
| C | 0.13 | 5 |
| D | 0.11 | 2 |
| E | 0.12 | 3 |
| F | 0.08 | 1 |

The energy utilization values and treatment rankings are presented in Table 19. Even though the kiln residence time for treatments C and D and E and F were only two hours different (Table 16), differences in green moisture content requires considerably more energy to heat the lumber (and water) to kiln operating temperatures. Treatments E and F have the best energy consumption values while treatments A and B have the worst energy consumption values.

**Table 19:** **Energy Utilization Ranking**

| Treatment | Utilization (kWhr) | Rank |
|---|---|---|
| A | 378 | 5 |
| B | 378 | 5 |
| C | 261 | 3 |
| D | 261 | 3 |
| E | 173 | 1 |
| F | 173 | 1 |

The same four scenarios from the dry sort were applied for the mid sort in Table 20 to Table 23.

In the first scenario (Table 20), it was assumed that all variables had the same degree of importance. In the second scenario (Table 21), the degree of importance from highest to lowest was as follows:

1) grade recovery
2) moisture content
3) total processing time.

For the third scenario (Table 22), the degree of importance was as follows:

1) grade recovery
2) total processing time
3) moisture content.

Finally, the fourth scenario (Table 23) took into account potential increase in energy costs and the following degree of importance for the variables was used:

1) grade recovery
2) energy consumption
3) moisture content.

**Table 20:** **Cumulative Ranking of Treatments**

| Treatment | Time (hrs) | Recovery (%) | CV (MC) | Energy (kWhr) | Total | Rank |
|---|---|---|---|---|---|---|
| A | 1 | 5 | 6 | 5 | 17 | 6 |
| B | 3 | 4 | 3 | 5 | 15 | 4 |
| C | 2 | 3 | 5 | 3 | 13 | 3 |
| D | 4 | 2 | 2 | 3 | 11 | 2 |
| E | 5 | 6 | 3 | 1 | 15 | 4 |
| F | 6 | 1 | 1 | 1 | 9 | 1 |

**Table 21: Drying Treatment Ranking: Recovery, Moisture Content and Time**

| Treatment | Time (hrs) | Recovery (%) | CV (MC) | Energy (kWhr) | Total | Rank |
|---|---|---|---|---|---|---|
| A | 1 | 5 | 6 | 5 | 20 | 3 |
| B | 3 | 4 | 3 | 5 | 16 | 1 |
| C | 2 | 3 | 5 | 3 | 22 | 5 |
| D | 4 | 2 | 2 | 3 | 18 | 2 |
| E | 5 | 6 | 3 | 1 | 27 | 6 |
| F | 6 | 1 | 1 | 1 | 21 | 4 |

**Table 22: Drying Treatment Ranking: Recovery, Time and Moisture Content**

| Treatment | Time (hrs) | Recovery (%) | CV (MC) | Energy (kWhr) | Total | Rank |
|---|---|---|---|---|---|---|
| A | 1 | 5 | 6 | 5 | 25 | 5 |
| B | 3 | 4 | 3 | 5 | 17 | 3 |
| C | 2 | 3 | 5 | 3 | 24 | 4 |
| D | 4 | 2 | 2 | 3 | 16 | 1 |
| E | 5 | 6 | 3 | 1 | 25 | 5 |
| F | 6 | 1 | 1 | 1 | 16 | 1 |

**Table 23: Drying Treatment Ranking: Recovery, Energy and Moisture Content**

| Treatment | Time (hrs) | Recovery (%) | CV (MC) | Energy (kWhr) | Total | Rank |
|---|---|---|---|---|---|---|
| A | 1 | 5 | 6 | 5 | 42 | 6 |
| B | 3 | 4 | 3 | 5 | 32 | 3 |
| C | 2 | 3 | 5 | 3 | 38 | 5 |
| D | 4 | 2 | 2 | 3 | 28 | 2 |
| E | 5 | 6 | 3 | 1 | 35 | 4 |
| F | 6 | 1 | 1 | 1 | 25 | 1 |

The results can be summarized as follows:

|  | Best Results | Worst Result |
|---|---|---|
| Scenario 1 | F, D | A |
| Scenario 2 | B, D | E |
| Scenario 3 | D, F | A |
| Scenario 4 | F, D | A |

For most scenarios Treatments F and D represented the best results while Treatment A represented the worst result. This suggests that when processing lumber with moisture content between 20% and 30%, the lumber should be air-dried for one week prior to drying according to schedule 2 and equalized for one week before planing. During the one-week air-drying period, the wood freely gives up moisture to the environment while the one-week equalizing period (after drying) allows the moisture to redistribute within the specimens. The benefits of air-drying and equalizing-better grade recovery, reduced variation of moisture content and energy consumption-outweigh potential decreases in productivity.

### *3.3.2.3 Wet Sort*

Results regarding processing time and treatment rankings are presented in Table 24. Treatments A and F have the best and worst rankings respectively.

**Table 24: Drying Time Ranking**

| Treatment | Air-drying Time (hrs) | Kiln Time (hrs) | Equalizing Time (hrs) | Total Processing Time (hrs) | Rank |
|---|---|---|---|---|---|
| A | 0 | 44 | 24 | 68 | 1 |
| B | 0 | 44 | 168 | 212 | 2 |
| C | 168 | 35.5 | 24 | 227.5 | 3 |
| D | 168 | 35.5 | 168 | 371.5 | 4 |
| E | 504 | 30 | 24 | 558 | 5 |
| F | 504 | 30 | 168 | 702 | 6 |

Grade recovery and treatment rankings are presented in Table 25. Once again, treatments with a one-week equalization period (B, D and F) had better grade recovery than treatments with a 24-hour equalization period (A, C and E). Treatments F and C had the best and worst grade recovery rankings respectively.

**Table 25: Grade Recovery Ranking**

| Treatment | Grade Recovery (#2&Better) | Rank |
|---|---|---|
| A | -1.6 | 5 |
| B | -.8 | 3 |
| C | -3.9 | 6 |
| D | -1.3 | 4 |
| E | -0.5 | 2 |
| F | 0.0 | 1 |

The coefficients of variation for moisture content and the treatment rankings are presented in Table 26. Treatments with the one-week equalization period did not produce the positive benefits found for the dry and mid sorts. Treatments B and D have the best and worst rankings respectively.

**Table 26: Coefficient of Variation (Moisture Content) Ranking**

| Treatment | Coefficient of Variation | Rank |
|---|---|---|
| A | 0.18 | 3 |
| B | 0.15 | 1 |
| C | 0.16 | 2 |
| D | 0.22 | 6 |
| E | 0.20 | 4 |
| F | 0.20 | 4 |

Energy utilization values and treatment rankings are presented in Table 27. Treatments E and F and A and B had the best and worst rankings respectively.

**Table 27: Energy Utilization Ranking**

| Treatment | Utilization (kWhr) | Rank |
|---|---|---|
| A | 969 | 5 |
| B | 969 | 5 |
| C | 899 | 3 |
| D | 899 | 3 |
| E | 792 | 1 |
| F | 792 | 1 |

The same four scenarios presented for the dry and mid sorts were applied to the wet sort (Table 28 toTable 31).

In the first scenario (Table 28), it was assumed that all variables have the same degree of importance. In the second scenario (Table 29), the degree of importance from highest to lowest was as follows:

1) grade recovery
2) moisture content
3) total processing time.

For the third scenario (Table 30), the degree of importance was as follows:

1) grade recovery
2) total processing time
3) moisture content.

Finally, the fourth scenario (Table 31) took into account potential increase in energy costs and the following degree of importance for the variables were used:

1) grade recovery
2) energy consumption
3) moisture content.

**Table 28: Cumulative Ranking of Treatments**

| Treatment | Time (hrs) | Recovery (%) | CV (MC) | Energy (kWhr) | Total | Rank |
|---|---|---|---|---|---|---|
| A | 1 | 5 | 3 | 5 | 14 | 4 |
| B | 2 | 3 | 1 | 5 | 11 | 1 |
| C | 3 | 6 | 2 | 3 | 14 | 4 |
| D | 4 | 4 | 6 | 3 | 17 | 6 |
| E | 5 | 2 | 4 | 1 | 12 | 2 |
| F | 6 | 1 | 4 | 1 | 12 | 2 |

**Table 29: Drying Treatment Ranking: Recovery, Moisture Content and Time**

| Treatment | Time (hrs) | Recovery (%) | CV (MC) | Energy (kWhr) | Total | Rank |
|---|---|---|---|---|---|---|
| A | 1 | 5 | 3 | 5 | 14 | 2 |
| B | 2 | 3 | 1 | 5 | 11 | 1 |
| C | 3 | 6 | 2 | 3 | 19 | 3 |
| D | 4 | 4 | 6 | 3 | 28 | 6 |
| E | 5 | 2 | 4 | 1 | 25 | 4 |
| F | 6 | 1 | 4 | 1 | 27 | 5 |

**Table 30: Drying Treatment Ranking: Recovery, Time and Moisture Content**

| Treatment | Time (hrs) | Recovery (%) | CV (MC) | Energy (kWhr) | Total | Rank |
|---|---|---|---|---|---|---|
| A | 1 | 5 | 3 | 5 | 16 | 2 |
| B | 2 | 3 | 1 | 5 | 10 | 1 |
| C | 3 | 6 | 2 | 3 | 18 | 3 |
| D | 4 | 4 | 6 | 3 | 30 | 6 |
| E | 5 | 2 | 4 | 1 | 24 | 4 |
| F | 6 | 1 | 4 | 1 | 25 | 5 |

**Table 31: Drying Treatment Ranking: Recovery, Energy and Moisture Content**

| Treatment | Time (hrs) | Recovery (%) | CV (MC) | Energy (kWhr) | Total | Rank |
|---|---|---|---|---|---|---|
| A | 1 | 5 | 3 | 5 | 30 | 3 |
| B | 2 | 3 | 1 | 5 | 23 | 1 |
| C | 3 | 6 | 2 | 3 | 29 | 2 |
| D | 4 | 4 | 6 | 3 | 46 | 6 |
| E | 5 | 2 | 4 | 1 | 35 | 4 |
| F | 6 | 1 | 4 | 1 | 37 | 5 |

The results can be summarized as follows:

| | Best Result | Worst Result |
|---|---|---|
| Scenario 1 | B | D |
| Scenario 2 | B | D |
| Scenario 3 | B | D |
| Scenario 4 | B | D |

Thus, regardless of the scenario, Treatment B showed the best results while Treatment D showed the worst results. This suggests that when processing lumber with moisture content greater than 30%, the lumber should be dried according to schedule 1 and planed only one week after drying. Since the initial moisture content distribution for the wet sort is essentially the same distribution found for non-stained lumber (not attacked by the MPB), the potential benefits of air drying are mill-specific. One week of equalizing after drying probably redistributes the moisture from the non-stained areas to the bluestained areas, thereby improving the uniformity of moisture content throughout the whole specimen.

# 4 Conclusions

(a) The results found in this study indicated that tangential and radial permeability of post-MPB wood increased 8 to 25 times and 6 to 23 times respectively when compared to non-stained wood.

(b) Diffusion coefficients for bluestained sapwood were larger than those observed for non-stained sapwood. Since the amount of bluestained and non-stained wood vary within a given piece of lumber, different drying rates are likely to occur within a specimen resulting in moisture content variations.

(c) One week of air-drying of rough lumber during the summer months significantly decreased the average moisture content and standard deviation for both the dry sort (MC<20%) and mid sort ($20\% \le MC \le 30\%$).

(d) Three weeks of air-drying during the summer months significantly decreased the average moisture content and standard deviation of the wet sort (MC>31%).

(e) Drying Strategies:
The best results were obtained as follows:

- i. For the Dry Sort (MC<20%):
    1. lumber was not air-dried
    2. lumber was dried according to typical industrial schedules
    3. lumber was planed only 24 hours after drying.
- ii. For the Mid Sort ($20\% \le MC \le 30\%$):
    1. lumber was air-dried for one week
    2. lumber was dried according to typical industrial heat-treatment schedules
    3. lumber was planed only one week after drying
- iii. For the Wet Sort (MC>31%):
    1. lumber was not necessarily air-dried
    2. lumber was dried according to typical industrial schedules
    3. lumber was planed only one week after drying.

## 5 Acknowledgements

This project was funded by the Government of Canada through the Mountain Pine Beetle Initiative-a six-year, $40 million Program administered by Natural Resources Canada, Canadian Forest Service. Publication does not necessarily signify that the contents of this report reflect the views or policies of Natural Resources Canada, Canadian Forest Service.

The authors gratefully acknowledge Tolko Industries, Quest Wood Division for their contribution to the project including the lumber for the tests, suggestions related to the experimental plan and numerous discussions involving mill personnel. We also acknowledge the following companies for their input and meaningful guidance towards this project:

Lignum – Williams Lake
Riverside – Soda Creek Division
Riverside – Williams Lake Division
Tolko Industries – Quest Wood Division

## 6 Literature Cited

Ferguson, A. 2003. Challenges and Solutions – An Industry Perspective. *In* T.L. Shore, J.E. Brooks and J.E. Stone (eds). Mountain Pine Beetle Symposium: Challenges and Solutions. Pacific Forestry Centre, Canadian Forest Service, Natural Resources Canada, Victoria, BC.

Natural Resources Canada Website. http://mpb.cfs.nrcan.gc.ca/introduction_e.html.

Peng, S. 2002. Effects of sawing pattern on lumber drying: model simulation and experimental investigation. Drying Tech. 20(9): 1769-1787

Siau, J.F. 1984. Transport processes in wood. Springer Verlag, New York. Pp. 24 –103

Siau, J.F. 1995. Wood: Influence of moisture on physical properties. Department of wood Science and Forest Products, Virginia Polytechnic Institute and State University, Blacksburg, VA. Pp. 1-63

Woo, K.L., P. Watson and S.D. Mansfield. 2004. The effects of mountain pine beetle attack on lodgepole pine wood morphology and chemistry: implications for wood and fibre quality. Wood & Fibre Science. 37(1): 112-126

**Contacts:**

Dr. Luiz C. Oliveira
Forintek Canada Corp.
2665 East Mall,
Vancouver, BC.  V6T 1W5

Mr. John Wallace
Forintek Canada Corp.
2665 East Mall,
Vancouver, BC. V6T 1W5

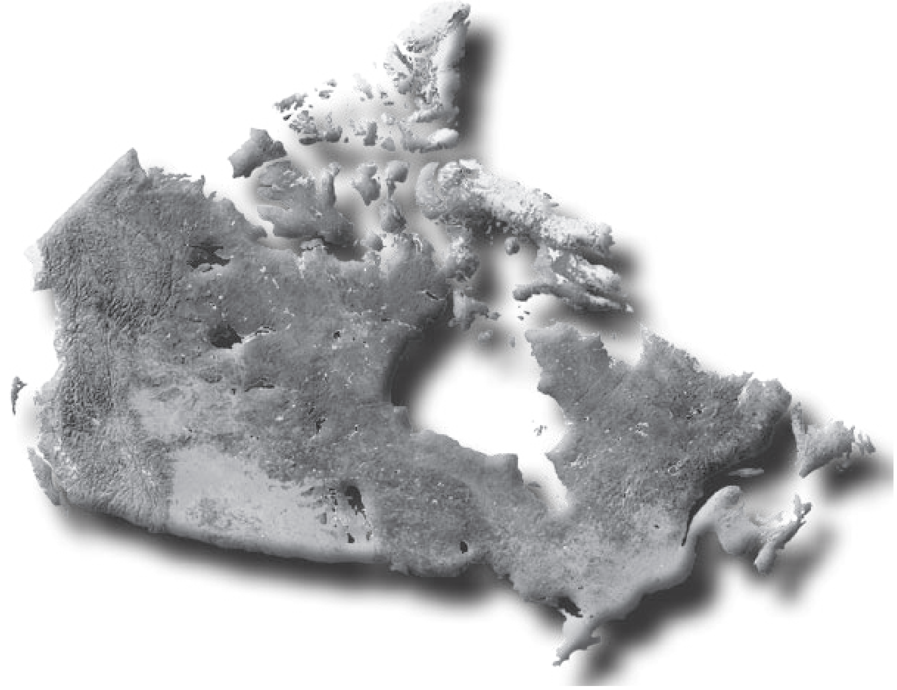
Dr. Liping Cai
Forintek Canada Corp.
2665 East Mall,
Vancouver, BC. V6T 1W5

This publication is funded by the Government of Canada through the Mountain Pine Beetle Initiative, a program administered by Natural Resources Canada, Canadian Forest Service (web site: mpb.cfs.nrcan.gc.ca).

## Contact:

For more information on the Canadian Forest Service, visit our web site at:
**www.nrcan.gc.ca/cfs-scf**

or contact the Pacific Forestry Centre
506 West Burnside Road
Victoria, BC V8Z 1M5
Tel: (250) 363-0600 Fax: (250) 363-0775
**www.pfc.cfs.nrcan.gc.ca**



**To order publications on-line, visit the Canadian Forest Service Bookstore at:**
**bookstore.cfs.nrcan.gc.ca**