CHARRING RATE OF COMPOSITE TIMBER PRODUCTS

Robert H. White

INTRODUCTION

Acceptance of calculation procedures for determining fire endurance ratings for wood beams and columns has permitted the use of large wood members in applications where fire-rated structural members are required. As a result, the potential market for wood products increased in North America. The calculation procedures have code acceptance in the United States and Canada for glued-laminated wood members (AITC 1994, CWC 1997, White 1995).

A critical parameter in the calculation procedures is the charring rate of the member while directly exposed to the fire exposure specified in ASTM E 119 (ASTM 1998) or ISO 834 (ISO 1999) which are the standard test methods for determining fire resistance ratings for structural members and assemblies. Parameters affecting the charring rate for solid wood have been extensively studied at the USDA Forest Service, Forest Products Laboratory (Schaffer 1967, White and Nordheim 1992, White and Tran 1996) and elsewhere (White 1988, White 1995). For solid wood and glued-laminated members, the value for charring rate generally used in the United States and Canada is 0.635 mm/mm (1.5 in./hour). The 0.60 mm/mm value was used in developing the currently accepted calculation procedures for large wood members (Lie 1977).

Increasingly, wood members used in wood structures are structural composite lumber products. Such products include laminated veneer lumber, parallel strand lumber, and laminated strand lumber (Green 1998). To apply the calculation procedures to composite timber products, it is critical that char rate data for such products be available in the public domain. Charring data on composite lumber products in the public domain has been limited (Mikkola 1991, Getto 1998, Uesugi and others 1999). The test program reported in this paper provides these char rate data.

Laminated veneer lumber (LVL) is produced by laminating veneers with the grain of each veneer parallel to the longitudinal direction of the member. Approximately 3-mm-thick laminates are glued together. Laminated strand lumber (LSL) is produced by gluing and pressing strands of wood together to form the lumber product. The strands are oriented to be parallel to the logitudinal direction of the member. In parallel strand lumber (PSL), veneers are clipped to produce 19-mm-wide strands that are aligned and pressed into the lumber product with adhesives. The adhesives in these composite lumber products are exterior-type adhesives, such as phenol-formaldehyde-based and isocyanate-based adhesives.

METHODS

We tested the structural composite lumber products in a small vertical furnace at the Forest Products Laboratory to obtain the one-dimensional charring rates. The procedures were consistent with that used to determine the char rate for eight species of solid lumber (White 1988, White and Nordheim 1992). A 300 °C criterion for char was used to calculate the charring rate. Twelve different commercial products were tested in this project (Table 1). Products included seven LVLs, two LSLs, and three PSLs. The LVL's were from four companies.

Table 1 List of composite lumber products

Material No.	Species	Composite Type	Density[1] (kg/m^3)	Moisture content (%)
1	Aspen	LSL	674	8
2	Douglas-fir	LVL	529	7
3	Douglas-fir	LVL	535	7
4	Douglas-fir	LVL	552	7
5	Douglas-fir	PSL	610	7
6	Southern pine	LVL	652	8
7	Southern pine	LVL	635	7
8	Southern pine	PSL	728	8
9	Yellow-poplar	LSL	678	7
10	Yellow-poplar	LVL	554	8
11	Yellow-poplar	LVL	554	6
12	Yellow-poplar	PSL	536	7

Density calculated from ovendried mass and volume as tested.

The small gas-fired furnace has a 510- by 510-mm opening for the test specimen. The gas supply is controlled so that the temperature, determined with a thermocouple in an iron-capped pipe near the exposed surface of the specimen, follows the ASTM E 119 time-temperature curve. A single center thermocouple is used to control the furnace, but there are four additional thermocouples at the centers of the quadrants. The test was terminated when the last of six thermocouples embedded at the 51-mm depth reached 300 °C.

The 250- or 264-mm-high specimens were constructed by gluing five 50-mm-thick pieces or six 44-mm-thick pieces together with phenol-resorcinol adhesive. Set-up depended on the available dimensions of the composite product. Specimens were 510 mm wide and 89 mm deep. Charring occurred in the 89-mm direction. For products available only in 45-mm thickness, it was necessary to also glue two pieces together to get the 89-mm dimension in the charring-perpendicular-to-laminates tests. Within each of three middle layers of the test specimen, two thermocouples were embedded at each of four distances from the exposed surface, 13, 25, 38, and 51 mm. For the test, the 250/264-mm-high specimen was placed at mid-height in the 510-mm-high furnace opening. Specimens were conditioned at 23 °C, 50 % relative humidity.

Because of their construction, the products are anisotropic. We obtained the charring rates for both transverse directions (perpendicular to wood grain). No tests were conducted for charring in the longitudinal direction (parallel to wood grain). The LVL specimens were tested with the direction of charring either parallel to or perpendicular to the plane of the veneer laminates. We tested the PSL and LSL specimens with the direction of charring either perpendicular to or parallel to the wide face of the original beam that was cut to obtain the pieces for the specimens, Two replicates of each specimen type and transverse direction were tested.

RESULTS AND DISCUSSION

Charring was assumed to have occurred when thermocouples embedded in the specimen recorded a temperature in excess of 300 °C. This criterion of 300 °C or that of 288 °C was successfully used in earlier charring studies (Schaffer 1967, White 1988). The 288 °C value is the exact conversion of 550 °F used in the early studies. Since temperatures are rapidly increasing at that point of the test, we consider the difference between 288 °C and 300 °C insignificant. Visual observations of char depths after the tests were consistent with depths calculated from the 300 °C criterion.

For each specimen, there were 24 pairs of time (t) and char depth (x_c) to calculate the char rates for each test (Figure 1). The following time-location models were considered (White and Nordheim 1992):

$$t = m_1 x_c \tag{1}$$

$$t = m_2 x_c - b \tag{2}$$

$$t = m_3 x_c^{a} \tag{3}$$

or its linear form

$$\ln t = \ln m_3 + a \ln x_c \tag{4}$$

and

$$t = m_5 x_c^{1.23} \tag{5}$$

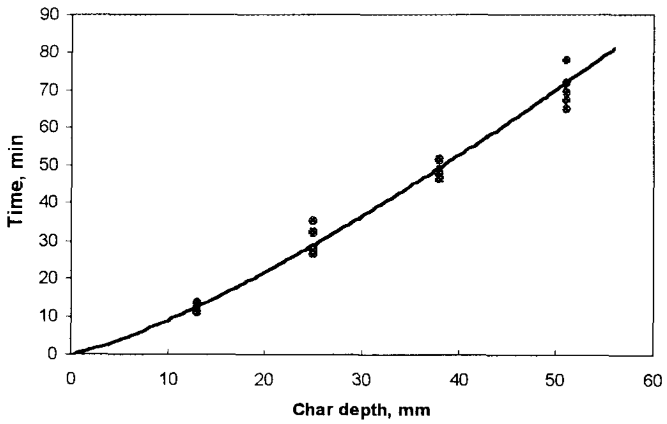

Figure 1 Example of the time-location data obtained from 24 thermocouples located at different depths in a specimen

We obtained estimates for the parameters (*m*, *b*, and *a*) by linear regression of the time-location (t - x_c) data (Tables 2 and 3). Results listed in the tables were obtained by regression of the combined data identified. There were two replicates for each direction (Table 2). Thus, the results for "both" directions (Tables 2 and 3) are based on data from four tests.

Equation (1) is the one-parameter model assumed when charring rate is calculated from residual section and duration of fire exposure. The traditional 0.635 mm/mm (1.5 in/h) charring rate is 1.575 min/mm (Eq. (1)). Regression of all the data for the different composite lumber products produced m_1 of 1.53 min/mm. Equation (2) is a two-parameter model that allows a fast initial char rate followed by a slower linear char rate. Equation (3) is a nonlinear charring model with two parameters. Equation (4) is the linear form of Eq. (3). Results for Eq. (3) in Table 3 were obtained by linear regression of Eq. (4). Regression of all the data together produced a value for a of 1.15 (Eq. (3) or (4)). The one-parameter model of Eq. (5) (Table 2) was obtained in the study of solid wood (White and Nordheim 1992) and is used in the new fire endurance calculation procedures of American Forest & Paper Association (1999). For a char depth of 38 mm (1.5 in.) at 60 min, m_5 is 0.684 min/mm$^{1.23}$. Regression of all the composite lumber data together produced a value for m_5 of 0.648 min/mm$^{1.23}$.

The thickness of the char layer after the test is less than the thickness of the wood that was charred. In previous studies (White 1988, White and Nordheim 1992) we used a char contraction factor to record this phenomenon. The factor is both an experimental result of the charring test and an important property to interpret the charring rate data. The char contraction factor is the ratio of the thickness of residual char layer to the thickness of wood charred to produce the char layer. Char contraction is due to char shrinkage, char oxidation, or ablation of the char layer. If charred veneer laminates were to drop off due to failure of the glue in the char layer, the char contraction factor would be reduced. Visual measurements of the char layer after the fire test were used to calculate the char contraction factor (Table 3).

We used two methods to compare these results for composite lumber products with results for solid wood. The first comparison was made with the predicted results for two empirical models for charring that were developed from solid lumber tests. The second comparison was with char rates obtained in individual tests of solid wood.

Table 2 Parameter estimates for the single parameter models [Eq. (1) and (5)].

Mat. No.	Species	Composite type	Direction of charring relative to lamination plane	Char contraction factor (-)	m_1 (Eq. (1)) (min/mm)	m_5 (Eq. (5)) (min/mm$^{1.23}$)
1	Aspen	LSL	Parallel	0.708	1.60	0.680
			Perpendicular	0.625	1.56	0.660
			Both	0.666	1.58	0.670
2	Douglas-fir	LVL	Parallel	0.580	1.53	0.650
			Perpendicular	0.575	1.53	0.647
			Both	0.577	1.53	0.648
3	Douglas-fir	LVL	Parallel	0.550	1.63	0.689
			Perpendicular	0.547	1.62	0.686
			Both	0.548	1.62	0.688
4	Douglas-fir	LVL	Parallel	0.574	1.66	0.705
			Perpendicular	0.616	1.56	0.661
			Both	0.594	1.61	0.683
5	Douglas-fir	PSL	Parallel	0.599	1.62	0.692
			Perpendicular	0.650	1.62	0.688
			Both	0.625	1.62	0.690
6	Southern pine	LVL	Parallel	0.575	1.44	0.612
			Perpendicular	0.567	1.40	0.600
			Both	0.571	1.42	0.604
7	Southern pine	LVL	Parallel	0.586	1.55	0.658
			Perpendicular	0.563	1.41	0.598
			Both	0.574	1.48	0.628
8	Southern pine	PSL	Parallel	0.579	1.62	0.690
			Perpendicular	0.601	1.63	0.693
			Both	0.590	1.63	0.692
9	Yellow-poplar	LSL	Parallel	0.671	1.54	0.650
			Perpendicular	0.649	1.59	0.676
			Both	0.660	1.57	0.663
10	Yellow-poplar	LVL	Parallel	0.587	1.40	0.593
			Perpendicular	0.565	1.32	0.562
			Both	0.576	1.36	0.578
11	Yellow-poplar	LVL	Parallel	0.541	1.46	0.617
			Perpendicular	0.561	1.32	0.562
			Both	0.551	1.39	0.590
12	Yellow-poplar	PSL	Parallel	0.604	1.56	0.663
			Perpendicular	0.584	1.58	0.670
			Both	0.594	1.57	0.667

Table 3 Parameter estimates for the two-parameter models [Eq. (2) and (3)].

Material No.	Species	Composite type[i]	m_2 (Eq. (2)) (min/mm)	b (Eq. (2)) min	m_3 (Eq. (3))[ii] (min/mm^a)	a (Eq. (3))[ii] (-)
1	Aspen	LSL	1.71	–4.94	1.15	0.913
2	Douglas-fir	LVL	1.64	–4.17	1.14	0.924
3	Douglas-fir	LVL	1.70	–3.11	1.10	1.100
4	Douglas-fir	LVL	1.70	–3.34	1.11	1.080
5	Douglas-fir	PSL	1.75	–4.99	1.13	0.999
6	Southern pine	LVL	1.56	–4.99	1.17	0.762
7	Southern pine	LVL	1.64	–6.01	1.21	0.683
8	Southern pine	PSL	1.78	–5.78	1.14	0.592
9	Yellow-poplar	LSL	1.65	–3.39	1.11	1.035
10	Yellow-poplar	LVL	1.52	–6.30	1.14	0.676
11	Yellow-poplar	LVL	1.51	–4.69	1.15	0.788
12	Yellow-poplar	PSL	1.76	–7.27	1.20	0.752

[i] Data for both charring directions relative to the plane of the laminates are combined for these results.
[ii] Estimates for Eq. (3) parameters were obtained by linear regression of Eq. (4).

Comparison with empirical predictive models

Density and moisture content values were obtained (Table 1). These are the input for the empirical equations developed by Schaffer (1967) for charring of solid Douglas-fir, southern pine, and white oak. The predictive equations of Schaffer (1967) for m_1 (min/mm) (Eq. (1)) are

$$m_1 = (0.002269 + 0.0000457\,\mu)\,\rho + 0.331 \tag{6}$$

for Douglas-fir,

$$m_1 = (0.000461 + 0.0000095\,\mu)\,\rho + 1.016 \tag{7}$$

for southern pine, and

$$m_1 = (0.001583 + 0.0000318\,\mu)\,\rho + 0.594 \tag{8}$$

for white oak,.
where ρ is density (kg/m^3) and μ is moisture content (percent).

The above equations were used to predict the char rates, m_1, of the composites (Fig. 2). The diagonal line in Figure 2 represents equality between the two axes. Predictions were for faster charring of the southern pine but slower charring of the Douglas-fir and the hardwoods. Predictions for yellow-poplar and aspen were from the white oak equation. Douglas-fir data will be discussed later. For all data, the average difference between predictions and the experimental results was 12 percent.

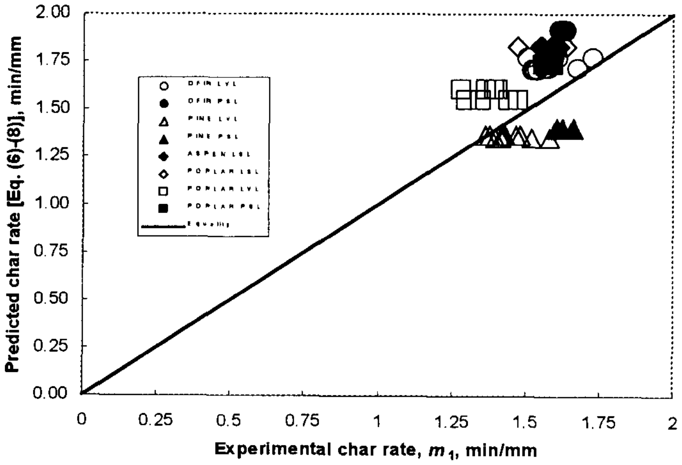

Figure 2 Comparison of experimental data with predicted char rates, m_1, from equations of Schaffer (1967) for solid lumber [Eq. (6)-(8)]

As noted previously, the char contraction factors (f_c) were obtained from the fire tests. Density (ρ, kg/m^3), moisture content (μ, percent), and char contraction factor (f_c, dimensionless) were used to calculate estimates for m_5 from an equation developed for solid wood (White and Nordheim 1992). The predictive model is

$$m_5 = -0.147 + 0.000564\ \rho + 0.0121\ \mu + 0.532\ f_c \tag{9}$$

Almost all the predictions from Equation (9) showed faster charring rates than those measured (Fig. 3). Average difference between predictions and experimental data was 11 percent.

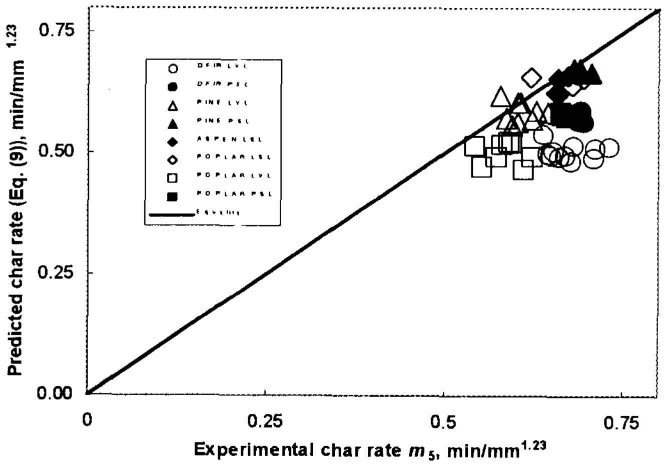

Figure 3 Comparison of experimental data with predicted char rates, m_5, from equations of White and Nordheim (1992) for solid wood (Eq. (9))

Predicted results (Fig. 3) were calculated using the composite lumber char contraction factor, not the char contraction factor for solid wood. For southern pine and yellow-poplar, the char contraction factors for composite lumber products (Table 2) were similar to solid wood (0.59 for southern pine and 0.67 for yellow-poplar (White and Nordheim 1992)). Available char contraction factor data for solid Douglas-fir are limited, but available data (White 1988) were around 0.75, which is higher than the approximately 0.60 obtained for the Douglas-fir composite lumber products (Table 2). The higher solid wood contraction factor would increase (i.e., slower charring) the predicted values for m_5 to values closer to the experimental data. Even with solid wood, Eq. (9) tends to predict char rates for Douglas-fir that are faster than the experimental data (White 1988).

The predictive equations were based on a char base temperature of 288 °C, the exact conversion of 550 °F, rather than the 300 °C used in the study. If 288 °C is used, the calculated m_1 is 0.02 min/mm less than that calculated with 300 °C.

Overall, the experimental data for composite lumber products were comparable with predictions obtained from empirical models developed from tests of solid wood.

Comparison with solid wood experimental data

Data for composite lumber products along with existing data for solid wood were plotted versus density (Fig. 4). Yellow-poplar and southern pine solid wood data are from White (1988). Douglas-fir and southern pine data are from tests of Schaffer (1967) and other studies (White 1988). The generally accepted value for wood charring of 1.5 in/h (1.575 min/mm) is shown as a dashed line (Fig. 4)

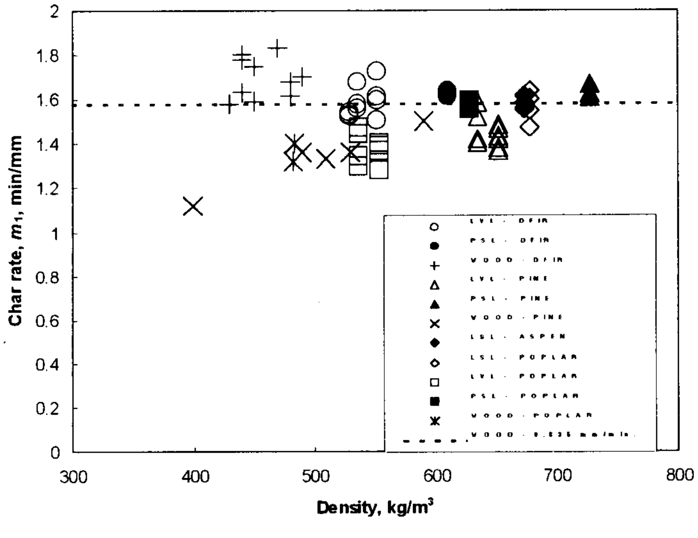

Figure 4 Char rate m_1 for both the composite lumber products and solid wood

As a result of the manufacturing process, the structural composite lumber products have higher densities than solid wood. The char rate results for the southern pine, yellow-poplar, and aspen composite products were consistent with the slower charring rates associated with higher densities. The influence of density on charring rate is also illustrated with the southern pine solid wood data (Fig. 4). Although the char rates for the Douglas-fir composite products were not faster than the char rate previously obtained for solid Douglas-fir, benefits from their higher densities were not observed. As noted previously, the char contraction factors obtained in these tests of Douglas-fir composites were 20 % less than that reported in tests of solid Douglas-fir. A lower contraction factor reflects a thinner char layer to protect the wood and a resulting faster char rate. Veneer lathe checks and failure of glue lines in the char layer may be causes for the reduced residual char layer thicknesses.

Effect of transverse orientation

Char rate results (m_1 and m_5) for the two transverse directions of the product were calculated (Table 2). The diagonal line in Figure 5 is equal charring in the two transverse orientations. In tests of PSL and LSL products, there were no apparent differences in the char rates in the two transverse directions (Fig. 5). In LVL tests, there is indication of slightly faster charring (less min/mm) perpendicular to the plane of the laminates (Fig. 5).

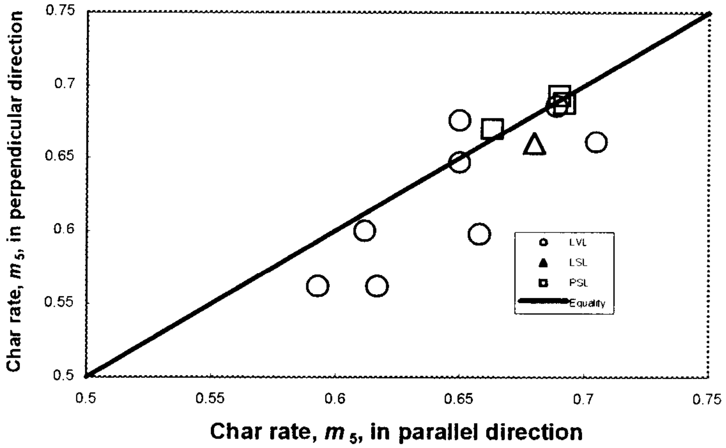

Figure 5 Comparison of charring m_5 (Eq. (5), $\text{minimm}^{1.23}$) parallel to laminates with that perpendicular to laminates

Possible explanations include anatomical delaminating of veneers in the char layer and effect of veneer lathe checks and fissures on changing the passage of the pyrolysis gases through the char layer. Since the veneers are peeled from the logs, the plane of the laminates generally corresponds to the tangential direction of the wood relative to its annual rings. Literature results on the effect of annual ring orientation on char rate of solid wood are contradictory. Delamination of charred laminates at the charred glue lines during the test would reduce the residual char layer and thereby increase the char rate. This does not appear to be the case because there was not a similar orientation effect for the char contraction factor. Other explanations involve the flow of the hot pyrolysis gases out of the wood and the effects of voids, delaminated charred glue lines, and veneer lathe checks on the passage of the gases through the char layer. It is likely that these effects are species dependent.

CONCLUSIONS

One-dimensional charring tests of structural composite lumber products including LVLs, PSLs, and LSLs confirmed that charring of these products in the standard fire endurance test may be considered comparable with solid wood. Such results support the use of the fire endurance calculation procedures for solid wood to estimate the ratings of composite lumber products.

With LVLs, the limited data indicated slightly faster charring in the direction perpendicular to the plane of the veneer laminates of the LVL. Any difference is small and can be ignored for design purposes.

The Douglas-fir composite lumber products had thinner char contraction factors compared with that observed in tests of solid Douglas-fir wood. The Douglas-fir composite char rates were not slower than solid Douglas-fir wood as would be expected for their higher density. Thinner protective char layer for high-density composite lumber products would contribute to their char rates only being comparable with solid wood.

ACKNOWLEDGMENT

The Canadian Wood Council funded this study. The manufacturers provided the test materials. They were Georgia-Pacific, Trus Joist MacMillan, Boise Cascade, and Willamette Industries. Such support and assistance is greatly appreciated. Como Caldwell of the FPL fire research group made the specimens and conducted the tests.

LITERATURE CITED:

AF&PA. 1999. *Calculating the Fire Resistance of Exposed Wood Members,* Technical Report 10, Washington, DC: American Forest & Paper Association.

AITC. 1994. *Timber Construction Manual.* 4th edition. American Institute of Timber Construction. New York: John Wiley & Sons.

ASTM. 1998. *Standard Test Methods for Fire Tests of Building Construction and Materials* ASTM E 119-98. West Conshohocken, PA: American Society for Testing and Materials.

CWC. 1997. Wood Design Manual. Ottawa: Canadian Wood Council.

Getto, H.; Ishihara, S. 1998. The functional gradient of fire resistance laminated board. Fire and Materials 22:89-94.

Green, D.W. 1998. Standards for structural wood products and their use in the United States. Wood Design Focus, Fall.

ISO. 1999. Fire resistance tests - Elements of building construction. ISO 834. Geneva: International Organization for Standardization.

Lie, T.T. 1977. A method for assessing the fire resistance of laminated timber beams and columns. Can. *J. of Civil Eng.* 4:161-169.

Mikkola, E. 1991, Charring of wood based materials. p. 547-556. *In: Fire Safety Science - Proceedings of the Third International Symposium.* London: Elsevier Applied Science.

Schaffer, E.L. 1967. Charring rate of selected woods-transverse to grain. Res. Pap. FPL 69. Madison, WI: USDA Forest Service, Forest Products Laboratory.

Uesugi, S.; Harada, T.; Maeda, Y.; Yamada, M. 1999. Fire endurance of laminated veneer lumber. Mokuzai Gakkaishi 45(1):57-61.

White, R.H. 1988. Charring rates of different wood species. Ph.D. thesis, Madison, WI: University of Wisconsin-Madison.

White, R.H. 1995. Analytical methods for determining fire resistance of timber members. p. 4-217 to 4-229. In: The SFPE handbook of fire protection engineering. 2nd ed. Boston, MA: Society of Fire Protection Engineers.

White, R.H.; Nordheim, E.V. 1992. Charring rate of wood for ASTM E 119 exposure. Fire Technology 28(1):5-30.

White, R.H.; Tran, H.C. 1996. Charring rate of wood exposed to a constant heat flux. In: *Proc. of Wood and Fire Safety Conference.* Zvolen, Slovak Republic: Technical University Zvolen. p. 175-183.

Address:
Robert H. White
USDA Forest Service, Forest Products Laboratory
One Gifford Pinchot Drive, Madison, WI,
USA, 53705-2398

Technická univerzita vo Zvolene *Technical University of Zvolen*
Drevárska fakulta *Faculty of Wood Sciences and Technology*
Katedra požiarnej ochrany *Department of Fire Protection*
T. G. Masaryka 24, 960 53 Zvolen
Slovenská republika *Slovak Republic*

WOOD & FIRE SAFETY

May 14 -19, 2000
Slovak Republic
4 th International Scientific Conference
The High Tatras, Hotel Patria, Štrbské Pleso

Drevo a požiarna bezpečnosť

Štvrtá medzinárodná vedecká konferencia

PROCEEDINGS

PART I.

The proceedings of Wood & Fire Safety 2000 (part one)

Published by the Technical university of Zvolen, printed in NIKARA Krupina
Editor: Prof. Anton Osvald
The authors of papers are responsible for their contents.
Language of the manuscripts has not been corrected
1. edition

ISBN 80-228-0774-5