Focusing on Environmental Sensitivity in Wood Products Research

Thomas E. Hamilton and Jerrold E. Winandy

(USDA Forest Service, Forest Products Laboratory, Madison, WI
One Gifford Pinchot Dr., Madison, WI 53705-2398)

Abstract The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service. The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin. This article was written and prepared by U.S. Government employees on official time, and it is therefore in the public domain and not subject to copyright. The theme for this anniversary celebration, "Environmental Sensitivity in Using Wood" has a broad application. Topics that immediately come to mind are technologies aimed at increased sensitivity to environmental concerns related to processing and use of wood. There are many opportunities here, and this paper will provide an overview of our work at the USDA Forest Service, Forest Products Laboratory (Madison, WI) on forest management and fiber production. It will then present an in-depth discussion of one of our recent major engineering programs; namely, our program to assess and extend the serviceability of fire-retardant-treated plywood.

Keywords environment service life modeling fire retardant treatment

1 Environmental Sensitivity in Forest Management

Environmental sensitivity in wood use is also a topic of great importance to forest managers. Sustainable development has become the umbrella objective for forest management in many countries of the world, and managers are increasingly faced with the challenges of balancing environmental health and economic health in their forest management decisions. Achieving this balance means that the wood resource will be changing. In some regions of the United States (for example, the Pacific Northwest), the wood supply from naturally regenerated forests has been declining. In this case, wood removal has become a secondary objective with the primary objectives being management to improve forest health, assure a continuing supply of good quality water, restoration of wildlife habitat, and/or altering the mix of species, trees sizes, or wood quality (Barbour and Skog 1997). In other regions (for example, the U.S. South), fast growing plantations are supplying an increased amount of wood. In the former case, since industrial processes tend to rely on a uniform raw material supply, some new technologies will be needed to make efficient use of the raw material. Maintaining a forest products industry that depends on a changing forest has the obvious economic benefits of covering management costs and supporting rural economies. But environmental benefits will also accrue through wood-use efficiency, removal of unwanted material, and extending forest land-use choices through effective use of available fibers. In the latter case, reliance on plantation forestry presents the challenge of maintaining wood quality while also producing large volumes of wood fiber. Here it is important to link wood quality characteristics to forest management practices and end-use requirements (Zhang et al. 1997).

Forest products technology also makes a significant environmental contribution by extending the available fiber resource, through recycling and reuse and through improved durability. Recycling rates are currently at an all time high. Research at the Forest Products Laboratory (FPL) and elsewhere is now focusing on the more difficult aspects of recycling such as contaminant removal and use of mixed waste. Use of recycled material for composites appears to have great potential. Improved treatments for insect and decay resistance can also pay large dividends, and the benefits can be significantly extended if environmentally friendly treatment methods are provided.

2 Environmental Sensitivity in Fiber Production Technology

The challenges faced by forest managers are matched by those facing wood product manufacturers. Public concern for air and water quality has paralleled interest in forest management issues. Now, more than ever, the wood products industry needs to avoid generating pollutants during the manufacturing process and environmental problems during product use. Such “avoidance” technologies will allow forest products to be manufactured with minimal environmental impact and reduce the need for regulation and restoration.

One example of such avoidance technology is just now beginning to change wood pulping in the United States. Kraft pulping has long been the dominant pulping technology used in the United States and worldwide, producing more than 250 million tons of pulp annually. More than 60 million tons of kraft pulp are produced in the United States alone. Kraft pulping dominates because it can be made from a wide variety of hardwoods and softwoods and it produces paper and paperboard of high strength. It can delignify wood to the point where it can be bleached relatively easily to the high whiteness levels required by the printing industry. However, kraft pulping is extremely capital-intensive. Newly sited mills cost in excess of $1 U.S. billion (× 10^9), and mills must process on the order of 1,000 to 2,000 tons of ovendry equivalent wood chips per day to be economically viable. Pulp yields are low, around 45% to 55%. and organic sulfur compounds are produced during pulping operations. The low yields, high capital intensity, enormous economy of scale. and production of troublesome organic compounds make it extremely desirable to develop alternatives to kraft pulping. New technologies such as biopuiping, which uses white-rot fungi to delignify wood chips, and nonchlorine bleaching are being developed at FPL.

White-rot fungi, such as *Phanerochaete chrysosporium* and *Ceriopsus subvermisporia,* are able to remove lignin, the “glue” that holds fibers together. Research is being conducted to pretreat wood chips with *C. subvermisporia* prior to mechanical pulping to reduce energy consumption during pulping and increase papermaking properties compared with those of untreated mechanical pulp. Research work has decreased the time necessary to pretreat wood chips from 6 to 8 weeks to 2 weeks. In addition, fungal pretreatment has been demonstrated to be effective in large (50-ton) chip piles using only 5 g of fungal inoculum per ton of chips. The treatment can be conducted even in the winter because the metabolic heat of the fungi warms the wood chip pile. Energy savings of about 30% are realized compared with untreated controls.

Research is now focusing on the use of white-rot fungal pretreatments in conjunction with chemical pulping to decrease the amount of chemicals needed and possibly increase pulp yields. In conjunction with this work, researchers at FPL are studying cell wall architecture and biosynthesis. Understanding how trees form the cell walls of tracheids can reveal important clues about how to remove lignin and retain cellulose and hemicelluloses.

More than 32 million tons of bleached and semi-bleached pulps are produced annually in the United States. Bleached pulps are used primarily for printing and writing papers. Chlorine and chlorine dioxide were once the most commonly used bleaching agents because they are effective and economical. However, they also produce chlorinated organic compound byproducts, which are environmentally troublesome.

Alternatives to the use of chlorine to whiten pulps include the use of chlorine dioxide, oxygen, ozone, and peroxides. In addition, extended delignification during kraft pulping can reduce the amount of lignin in kraft pulps that needs to be removed during bleaching operations. However, these alternatives are generally more costly than and not as effective as chlorine-based bleaching. Oxygen, ozone, and peroxide are not as specific for lignin in bleaching operations as is chlorine, and they generally attack cellulose and hemicelluloses as well as lignin. Therefore, their use must be carefully controlled.

The FPL has taken two novel approaches to develop nonchlorine bleaching technologies that are specific to lignin and do not produce troublesome byproducts. The first involves the use of enzymes produced by white-rot fungi, such as *P. chrysosporium,* in metabolizing wood. Research has revealed that *P. chrysosporium* produces enzymes that use lignin-specific oxidative reactions to break down lignin. By treating pulp with combinations of enzymes, it appears possible to produce pulps that are more easily brightened with peroxides.

The second approach involves the use of polyoxometalate (POM) chemistry. The POMs are a class of chemical compounds that react very specifically with lignin. They are nontoxic and reusable, and they can bleach pulp without attacking cellulose and hemicelluloses or weakening fiber structure. As a result, they do not reduce paper strength properties. The POMs also oxidize the organic byproduct compounds produced during bleaching operations, making possible effluent-free (closed mill) bleaching. The only byproducts from POM bleaching are water and carbon dioxide. The POMs greatly reduce the environmental impacts of pulp bleaching and its associated economic costs.

A second example of research to avoid environmental problems in production technology is in pressed wood products. In the early 1970s, the use of pressed wood products such as particleboard and hardwood plywood created indoor air quality problems, principally as a result of formaldehyde emissions from adhesives used to bond the wood products. Changes in adhesive formulations and processing modifications have greatly decreased formaldehyde emission problems. More recently, the concern about volatile organic compound (VOC) emissions resurfaced for wood products, both in use and during processing. Emissions from wood and wood-based materials may result from adhesives, natural components of wood. and byproducts of thermal degradation during wood processing, such as the drying of lumber in kilns or pressing of reconstituted board products in heated platen presses. Some compounds reported in wood or adhesive emissions are known to be hazardous to human health. Confirming the presence of such compounds is essential to evaluating risks and devising cost-effective and efficient risk management strategies. The FPL is developing new and novel methods to determine how many and what kind of VOCs are emitted from wood-based materials and how processing affects their production. With these new methods, effective, efficient, and economical control strategies can be developed that both protect the consumer and mitigate or prevent adverse environmental effects.

In the final end-use of products, VOCs can be emitted from not only the wood but also the finishes and coatings used to protect and preserve the wood. The FPL is also involved in developing new technologies that will help eliminate the use of VOC-based solvent systems for finishing and protecting wood from weathering and decay. Researchers are investigating new water-based solvent systems as well as determining the surface degradation mechanisms by which wood and wood-based materials weather. By understanding the mechanisms involved and combining this knowledge of the performance of water-based solvent finishing systems, new aqueous and dry-powder finishing systems can be devised that do not negatively impact the environment or adversely affect human health.

3 Environmental Sensitivity by Extending the Service Life of Structural Materials

Wood is an environmentally desirable material for fiber and for structural use. It is efficient in both economic and environmental cost to the user. Sometimes wood is treated with chemicals to extend its utility into new markets. In North America, fire-retardant-treated plywood is sometimes permitted as an alternative to noncombustible materials in structures where increased fire safety is required. However, some commercial fire retardant (FR) treatments failed to perform as expected when used as roof sheathing plywood and roof truss lumber. Elevated roof temperatures caused by solar radiation in combination with chemicals and moisture prematurely activated some FR, causing the plywood to exhibit a chocolate-brown color, become brittle, experience cross-grain checking, and crumble easily. This problem required costly roof replacement. Because of the regional nature of building codes in North America, the problem was most common in the eastern United States on nonresidential commercial and multifamily dwellings built without parapet walls since 1980. During the last few years. extensive research has defined the mechanism of the problem. To lessen the environmental costs of replacing up to 75 million FR-treated plywood panels, serviceability assessment methods were needed to evaluate the condition of FR-treated plywood and to estimate residual service life.

4 Serviceability Research on Fire-Retardant-Treated Plywood

This report now describes an intensive 10-year research program conducted at FPL in which methodologies were developed to determine the current condition of FR-treated plywood roof sheathing and to predict its residual serviceability.

In the United States, replacement costs for thermally degraded FR-treated plywood roof sheathing were originally estimated to exceed $2 U.S. billion (NAHB 1990). The first stage of a research program at FPL involved a systematic series of studies to identify chemical mechanisms and quantify strength loss (Winandy et al. 1991a). Preliminary investigations had indicated that field problems resulted from thermal-induced acid degradation of wood carbohydrates by the acidic FR chemicals (LeVan and Winandy 1990). More comprehensive work confirmed the proposed acid-degradation mechanism and showed that the relative effects of many FR treatments could be classified by the type of FR chemical employed and the time-temperature combination required to convert the FR formulation into its acidic form (LeVan et al. 1990, Winandy 1995).

Additional work found that the rate of strength degradation for untreated and FR-treated plywood increased as relative humidity increased; a test method was developed to evaluate commercial FR treatments (Winandy et al. 1991b). Subsequently, three consensus U.S. Standards evolved from that test method (ASTM 1998a, 1998b, 1998c). To evaluate the date derived from the test method, several kinetics-based models for thermal degradation of FR-treated material had previously been presented (Woo 1981, Pasek and McIntyre 1990, Winandy et al. 1991b). Winandy and Lebow (1996) and Lebow and Winandy (1998a) built on that work to develop a single-stage kinetics-based model to predict the magnitude of thermal degradation for a series of generic FR treatments. They further demonstrated that their single-stage model could accurately predict strength loss across a wide range of temperatures and exposure conditions. Additional work then found that strength losses from cyclic thermal exposure were generally similar to those from steady state temperature exposure when compared on a cumulative time-at-temperature basis (LeVan et al. 1996).

The next stage of research was the FR-treated plywood serviceability program (Winandy 1994). It involved a simultaneous progression of studies, each specifically designed to address important voids in our current technical knowledge. When evaluating the current and future serviceability of any structural system, such as roof sheathing, two questions needed to be addressed. First, what was the current level of performance of the system? Second, if the system currently meets some acceptable level of performance, what was the expected remaining service life? The service life model developed under this FR-treated plywood serviceability program addressed these two concerns. This research program used a multiple-path approach to develop a reliable tool for residual service life prediction for FR-treated roof sheathing.

5 Program Overview

To develop the nondestructive evaluation (NDE) procedure and service life model for FR-treated plywood roof sheathing, the following critical needs were identified. Each of these was evaluated to assess the influence of key environmental, chemical, and material parameters:

1. Determine the key NDE parameters to predict strength, determine how these parameters should be measured, and empirically define their relationship to strength.

2. Determine the governing relationships between treatment processing factors, mixtures of chemical components, and post-treatment temperature and moisture factors to in-service performance; then relate these relationships to in-service thermal-induced strength degradation rates.

3. Define relationships between field and laboratory exposures.

4. Verify and refine the FPL temperature history model for roofs.

5. Define the effects of initial plywood quality level and its possible interaction with in-service thermal degradation.

6. Select the best service life model to predict future performance.

Four of the FPL projects, two of which included extramural cooperative agreements, are now complete. The final two are now nearly complete. To the extent possible, the various research components of this program were performed concurrently. Each project will be briefly described.

6 Project I. Nondestructive Evaluation Techniques for In-Place Evaluation of Fire-Retardant-Treated Plywood

Considerable concern existed about the in-place strength of FR-treated plywood. In addition, building officials and inspection professionals were frustrated by the lack of NDE tools available for assessing the residual strength of these materials. Definitive relationships between nondestructively measured properties and engineering design properties were needed before NDE techniques could be completely useful. Two broad types of NDE methods exist – chemical and mechanical. Chemical-based NDE, related to wood pH or changes in carbohydrate chemistry and strength, is rapidly becoming better understood and more reliable (Lebow and Winandy 1998b). Still, chemical tests are often prohibitively expensive because of equipment needs, operator time, and lag time between field inspection-sample collection and test results. Mechanical NDE often involves proofloading-type tests or concomitant relationships such as the relations between stress wave speed and modulus of elasticity or stress wave attenuation and strength. The use of mechanical NDE in the field is often complicated by cumbersome equipment. Another problem is inappropriate boundary conditions that limit application by complicating signal processing.

Another variant of mechanical tests are probe (screw) withdrawal relationships to strength. Screw withdrawal tests have been found to be simple and reliable indicators of degradation (Winandy et al. 1997). Results from Project I defined constitutive relationships between nondestructively measured properties and engineering design properties for FR-treated materials. These constitutive relationships between screw withdrawal force and residual bending strength were then used in a similar manner as modulus of elasticity is used to predict bending strength in machine-stress-rated lumber grading. Currently, researchers and the engineering communities are working together to develop consensus precision estimates to enable third party interpretation of these constitutive relationships.

7 Project II. Effects of Chemical Treatment and Processing and Use Factors

Preliminary FPL results indicated that the level of degradation in mechanical properties and wood composition induced by steady state laboratory exposure was often less than the magnitude of the degradation experienced in-service in the field. Differences between field- and laboratory-induced property degradation rates appeared to be related to the severity of the processing factors employed in commercial treating and in preparing FR-treated material for field installation. These factors included the influence of the mixture of various FR chemical components used to form a commercial FR formulation, the temperatures employed in kiln drying

FR-treated material after treatment, or possibly the lack of post-treatment drying and/or wetting during construction. Overall, our work found that many product-manufacturing factors and treatment-processing factors contributed to the differential performance of laboratory and field materials.

In Phase I of Project II, key experimental factors were identified using dynamic mechanical analysis of small plywood veneers about 1 mm thick (LeVan 1993). Those key factors were FR retention and in-service moisture content. The results of that study were used to define experimental factors in Phase II studies using full-size, 19-mm-thick plywood specimens. In Phase II. we found that variation in redrying temperatures from 49°C to 88°C had little effect on the magnitude or rate of subsequent thermal degradation when the treated plywood was exposed at 65°C for up to 290 days (Winandy 1997). We also found that addition of borate-based buffers to FR treatment chemicals significantly mitigated the rate and extent of thermal degrade. Finally, we showed that the combined effects of phosphate retention and accumulated thermal exposure (from both redrying and in-service high temperatures) are additive and cumulative (Winandy 1997). Further work found that the use of remedial borate treatments were useful in avoiding additional thermal degrade (Winandy and Schmidt 1995).

8 Project III. Correlation of Laboratory and Field Strength Temperature Effects

Initial FPL results indicated that thermal-induced acid dehydration of wood carbohydrates caused thermal-induced in-service degradation of FR-treated roof sheathing. However, the level of degradation in mechanical properties and wood composition induced by steady state high-temperature laboratory exposures was correlated to, but less than, the magnitude of the degradation sometimes experienced in the field. Thus, differences between field- and laboratory-induced property degradation rates had to be established for similarly processed FR-treated materials to extrapolate laboratory results to field serviceability.

In an on-going, cooperative project with Mississippi State University, test chambers have been built for both the laboratory and outdoor field exposure. Five field chambers, each holding 96 specimens, have been in use for more than 6 years in Madison, WI, (latitude = 43.4° North). The results of the first 3 years of field testing were recently reported (Winandy and Beaumont 1995). Roof system temperature histories were reported for interior attic air, exterior air, inner and outer veneers of plywood sheathing, and internal rafter temperatures for both black- and white-roofed structures. Temperatures were measured using thermocouples and recorded during a 3-year period from October 1991 through September 1994 using a datalogger/multiplexer device. Overall, black-shingled roof systems tended to be 5°C to 8°C warmer during the mid-afternoon of a sunny day than comparable white-shingled roof systems. The maximum sheathing temperatures recorded were 76°C for black-shingled roofs and 64°C for white-shingled roofs. The plywood roof sheathing of black-shingled roofs spent significantly more time at temperatures above 50°C than white-shingled roof systems. On sunny days, the top ply of plywood roof sheathing under black shingles generally experienced plywood roof sheathing temperatures that were 5°C to 8°C warmer than identical white-shingled roof structures. However, after dark, the black-shingled roof temperatures were similar to those of white-shingled roofs. The maximum temperatures recorded in our 3-year study for black-shingled roofs were 76°C, 58°C, and 54°C for the top-ply veneer, bottom ply, and internal rafter temperatures, respectively. The maximum temperatures recorded for the white-shingled roofs were 64°C 53°C, and 49°C for the top-ply veneer, bottom ply, and internal rafter temperatures, respectively. This data confirmed that the roof sheathing plywood and roof truss lumber temperatures, which are the primary factors influencing thermal degrade of FR-treated materials, are primarily controlled by solar gain. However, the effect of moisture content was not evaluated, nor was it controlled by attic ventilation.

Five additional field chambers were also constructed in 1994 under an extramural cooperative project with the Mississippi Forest Products Laboratory near Starkville, MS (latitude = 33.5° North). These five new chambers will provide for direct comparisons between northern and southern U.S. climates. In both Wisconsin and Mississippi, matched specimens exposed in steady state laboratory exposure chambers (65°C) and diurnal field exposure chambers will provide a basis to determine the relationship between laboratory strength-temperature effects and field (real world) strength-temperature effects. An empirical comparative relationship will be developed based on the correlation between matched laboratory and field data. This relationship will then be further modified based on historical weather data from other locations to predict field performance in those locations based on the model being developed in Project IV.

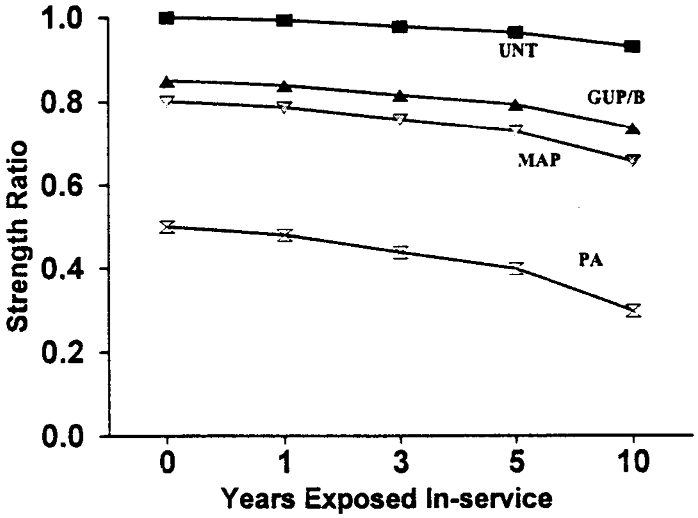
9 Project IV. Development and Verification of Forest Products Laboratory Roof Temperature Model

An empirical model to predict roof temperatures and moisture contents in plywood roof sheathing based on historical weather data from any location has been developed (TenWolde 1997). The FPL Roof Temperature Model has been adapted for FR-treated plywood and verified with moisture and temperature data, which are now being collected under an extramural cooperative project with the University of Illinois. In the serviceability models discussed in Project VI, the FPL Roof Temperature Model provides the basis for adapting in-service temperature and climate factors from locations with known conditions to other untested locations.

10 Project V. Interaction of Plywood Quality Data to Current Forest Products Laboratory Fire-Retardant-Effects Data

The existing data on thermal effects on FR-treated plywood originally related to only one level of plywood quality. To limit property variability, this data was obtained from tests of high-quality plywood, which was specially made from nearly clear veneers with no knots or interior voids and only minimal surface imperfections. Additional information was then needed to adapt the thermal-effects data in the data base to field applications using commercial quality plywood. Lebow and Winandy (1998c) evaluated four grades and two thicknesses of commercial plywood. That study found that the rate of strength loss in plywood resulting from FR treatment, post-treatment redrying, and subsequent high-temperature exposure was largely independent of plywood quality or grade. While the initial treatment effect differed for the two plywood thicknesses tested, the relative loss in strength resulting from exposure at high temperatures was similar for both plywood thicknesses. Although the various grades of plywood had large absolute

Figure 1. Predicted change in strength with time of untreated (UNT), phosphoric acid (PA)-, monoammonium phosphate (MAP)-, or guanylurea phosphate/boric acid (GUP/B)-treated wood during a simulated 10-year exposure (Winandy and Beaumont 1995) in North Central USA based on recently verified kinetics-based models (Lebow and Winandy 1998a).



differences in strength, these differences remained relatively constant after treatment and exposure. Thus, it appears that thermal degrade findings from previous studies (Winandy et al. 1991b) with high-quality N-grade plywood are readily applicable to commercial grades and thicknesses.

11 Project VI. Model for Evaluating Service-Life of Fire-Retardant-Treated Plywood

Predicting the service-life of FR-treated plywood sheathing requires a service-life model that incorporates information from the outlined studies and also provides a fundamental framework for adding site- and exposure-condition factors. The model uses a nondestructive assessment of residual strength (Project I), adjusted for predicted field exposure using structure-specific thermal performance models (Projects III and IV) and predicted material degradation rates derived from kinetic thermal degradation models (Projects II and V) to estimate the remaining service-life of FR-treated plywood roof sheathing. Such a model is now being more completely studied and further developed. A first attempt at such a residual serviceability model was recently reported (Winandy 1998). The predicted strength losses and field serviceability from these kinetic degrade models paralleled actual field performance (Fig. 1).

The results indicate that the worst generic FR treatment could be expected to experience an additional 20% loss in original in-service capacity when using our models (Lebow and Winandy 1998a) to simulate a 10-year exposure in Madison, WI, USA (Winandy and Beaumont 1995).

Untreated wood only experienced a predicted loss of 4% after the 10-year simulation. Other generic FR chemicals, such as 56 kg/m^3 of monoammonium phosphate (MAP) or a 70/30 mixture of guanylurea phosphate/boric acid (GUP/B), experienced intermediate levels of strength loss. Based on time-temperature superposition, the loss in capacity in warmer, sunnier climates would be greater. Some portions of this information are currently being introduced into U.S. design codes and standards. When finalized, these serviceability models will allow code officials, regulators, contractors, and engineers to determine replacement time schedules for any FR-treated plywood undergoing acid-catalyzed thermal degradation.

12 Concluding Remarks

Research programs at the Forest Products Laboratory are increasingly addressing technologies aimed at reducing or avoiding environmental problems related to the processing and use of wood. Programs such as these will eventually decrease environmental impacts and increase the reliability and long-term efficiency of wood-based structures.

This paper has outlined some of the on-going environmental research programs at the Forest Products Laboratory and described an FPL research program that developed a predictive service-life model for thermally degraded fire-retardant-treated plywood. The FR Serviceability Program, which led to the final methodology that assessed the current residual strength of FR-treated material, predicted the future temperature history of that material and finally estimated the rate of future degradation of the material properties based on the predicted elevated temperature exposures.

13 Acknowledgments

The authors acknowledge the indispensable contributions of the staff of the Engineering Mechanics Laboratory at the Forest Products Laboratory (FPL) and of the entire FR-treated plywood serviceability team at FPL, which consists of Stanley Lebow, Patricia K. Lebow, Joseph F. Murphy, William Nelson, Antoni TenWolde, and Robert H. White. Past members of that team were Susan L. LeVan, Robert J. Ross, and Mitchell S. Sweet. Our extramural cooperators, H. Michael Barnes (Mississippi State University) and William Rose (University of Illinois), are also acknowledged.

References

1. ASTM. 1998a. Standard test method for evaluating the flexural properties of fire-retardant treated softwood plywood exposed to elevated temperatures. ASTM D5516-94. Annual Book of Standards Vol. 4.10. West onshohocken, PA: American Society for Testing and Materials.
2. ASTM. 1998b. Standard test method for evaluating the effects of fire-retardant treatments and elevated temperatures on strength properties of fire-retardant treated lumber. ASTM D5664-95. Annual Book of Standards Vol. 4.10. West Conshohocken, PA: American Society for Testing and Materials.
3. ASTM 1998c. Standard practice for deriving allowable stress design adjustments for fire-retardant treated

softwood plywood. ASTM D6305-98. Annual Book of Standards Vol. 4.10. West Conshohocken, PA: American Society for Testing and Material.

4. Barbour, R.J.; and Skog, K.E., eds. 1997. Role of wood production in ecosystem management: Proceedings of the sustainable forestry working group at the IUFRO All Division 5 Conference, Pullman, Washington. July 1997. General Technical Report, FPL-GTR-100. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 98 p.
5. Lebow, P.K., and Winandy, J.E. 1998a. Verification of kinetics-based model for long-term effects of fire-retardants on bending strength at elevated temperatures. Wood and Fiber Science 30(4):328–340.
6. Lebow, S.T., and Winandy, J.E. 1998b. Effect of fire-retardant treatments on plywood pH and the relationship of pH to strength properties. Wood Science & Technology (in press).
7. Lebow, S.T., and Winandy, J.E. 1998c. The role of grade and thickness in the degradation of fire-retardant-treated plywood. Forest Products J. 48(6):88–94.
8. LeVan, S.L. 1993. Parametric evaluation of dynamic mechanical analysis of variables influencing strength degradation. M.S. Thesis. Madison, WI: Dept. of Chemical Engineering, University of Wisconsin.
9. LeVan, S.L., and Winandy, J.E. 1990. Effects of fire retardant treatments on wood strength: A review. Wood and Fiber Science 22(1):113–131.
10. LeVan, S.L., Kim, J.M., Nagel, R.J., and Evans, J.W. 1996. Mechanical properties of fire-retardant-treated plywood after cyclic temperature exposure. Forest Products J. 46(5):64–71.
11. LeVan, S.L., Ross, R J., and Winandy, J.E. 1990. Effects of fire retardant chemicals on the bending properties of wood at elevated temperatures. Research Paper FPL-RP-498, Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory,
12. NAHB 1990. Home builders guide to fire retardant treated plywood: Evaluation, testing and replacement. Washington, DC: National Association of Home Builders, National Research Laboratory. 65 p.
13. Pasek, E.A., and McIntyre, C.R. 1990. Heat effects on fire retardant-treated wood. Journal of Fire Sciences 8:405–415.
14. TenWolde, A. 1997. FPL roof temperature and moisture model. Research Paper FPL-RP-561. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.
15. Winandy, J.E. 1994. Serviceability modeling of fire-retardant-treated plywood roof sheathing. p. 292–297. *In*: Proc. of Pacific Timber Engineering Conference. Vol. 2. Gold Coast, Queensland, Australia. 11–15 July 1994. Timber Research and Development Council. Fortitude Valley, Queensland, Australia.
16. Winandy, J.E. 1995. Effects of fire retardant treatments after 18 months of exposure at 150F (66C). Research
17. Note FPL-RN-0264. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.
18. Winandy, J.E. 1997. Effects of fire retardant retention, borate buffers, and redrying temperature after treatment on thermal-induced degradation. Forest Products J. 47(6):79–86.
19. Winandy, J.E. 1998. Using kinetics-based models to address serviceability concerns for fire-retardant-treated wood at elevated in-service temperatures. Proc. of 5th World Conference on Timber Engineering. 16–21 August 1998. Montreux, Switzerland. Swiss Federal Institute of Technology. Lausanne, Switzerland.
20. Winandy, J.E., and Beaumont, R. 1995. Roof temperatures in simulated attics. Research Paper FPL-RP-543. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.
21. Winandy, J.E., and Lebow, P.K. 1996. Kinetic model of the effects of fire retardants on properties of wood at

elevated temperatures. Wood and Fiber Science 28(1):39–52.

22. Winandy, J.E., and Schmidt, E.L. 1995. Preliminary development of remedial treatments for thermally degraded fire-retardant-treated wood. Forest Products J. 45(2):51–52.
23. Winandy, J.E., Lebow, P.K., and Nelson, W. 1997. Development of models to predict bending strength from a test of screw-withdrawal force for FRT plywood roof sheathing. Research Paper FPL-RP-568. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.
24. Winandy, J.E., LeVan, S.L., and Ross, R.J. 1991a. Fire-retardant-treated wood: Research at the Forest Products Laboratory. p. 69–74. *In*: Proceedings of the 2nd International Timber Engineering Conference. TRADA. London, United Kingdom. Vol. 4.
25. Winandy, J.E., LeVan, S.L., Ross, R.J., Hoffman, S.P., and McIntyre, C.R. 1991b. Thermal degradation of fire-retardant treated plywood: Development and evaluation of a test protocol. Research Paper FPL-RP-501. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.
26. Woo, J.K. 1981. Effect of thermal exposure on strength of wood treated with fire retardants. Ph.D. Thesis. Berkeley, CA: University of California. 112 p.
27. Zhang, S.Y., Gosselin, R., and Chauret, G. 1997. Timber management toward wood quality and end-product value. Proceedings of the CTIA/IUFRO International Wood Quality Workshop, August, 1997, Quebec City, Canada. Sainte-Foy, Quebec, Canada: Forintek Canada Corporation. 529 p.
28. Figure 1. Predicted change in strength with time of untreated (UNT), phosphoric acid (PA)-, monoammonium phosphate (MAP)-, or guanylurea phosphate/boric acid (GUP/B)-treated wood during a simulated 10-year exposure (Winandy and Beaumont 1995) in North Central USA based on recently verified kinetics-based models (Lebow and Winandy 1998a).

木材产品环境敏感性研究

Thomds E. Homilton , Jereold E. Winandy
(美国农业部林务局林产品研究所)

摘要　这次我们年会的主题“木材利用对环境产生的敏感问题”包含的内容比较广泛。有些解决日益增加的环境敏感性的技术问题与木材的加工和利用有关。这方面要探讨的问题很多，而本文主要谈我们在森林管理和纤维制品生产方面所做的工作概况，其中将深入探讨我们最近制定的主要工程计划中的一个问题，即经防火处理胶合板的适用性评价和推广问题。

Proceedings of the Workshop for the 40th Anniversary
of Chinese Academy of Forestry

Forestry Towards the 21st Century

—Forestry Science and Technology under the Global Strategy of Sustainable Development

Edited By Chinese Academy of Forestry

China Agricultural Scientech Press

面向21世纪的林业

编委会

Forestry Towards the 21th Century

Editorial Board