Robert H. White[1]

An Empirical Model for Predicting Performance of Fire-Resistive Coatings in Wood Construction

REFERENCE: White. R. H., "An Empirical Model for Predicting Performance of Fire-Resistive Coatings in Wood Construction," *Journal of Testing and Evaluation.* JTEVA, Vol. 14, No. 2. March 1986, pp. 97–108.

ABSTRACT: Currently used fire-retardant coatings for wood products reduce flame spread: they are not designed specifically to provide fire resistance. Fire-resistive coatings designed for steel and foam plastics generally are not recommended for wood. However. these fire-resistive coatings have been tested for their ability to improve the fire resistance of plywood. We have developed an empirical model for predicting the fire-resistance performance of fire-resistive-coated wood based on these small nonload-bearing fire-resistance tests.

The equations in the model provide estimates for the times to reach either a temperature rise of 139°C or a temperature of 288°C. Using these equations. various applications for fire-resistive coatings in wood Construction were examined. Applications considered include thermal barriers, walls, floors, large timber members, and doors.

Predictions using the model compared favorably with the very limited experimental data available in the literature. Additional research is needed before use of fire-resistive coatings in wood construction can be realized.

KEY WORDS: fire-resistive coatings. wood, fire endurance, fire resistance, plywood

Traditionally designed structural wood members have had sufficient fire resistance to meet code requirements because of the low thermal conductivity of wood, the insulative char layer, the solid rectangular cross section of the structural wood member, and the generally conservative nature of traditional wood construction. However. progress in wood engineering and better understanding of the basic properties of wood have improved wood utilization in structural wood assemblies. As a result, there is a need for ways to improve the fire endurance of wood members and assemblies. Also. changes in the occupancy of a building or new requirements in the building codes may increase the required fire-resistance rating in an existing structure. Finally. the development of more fire-rated wood assemblies will increase the potential use of wood in nonresidential construction.

Fire-resistive coatings add fire resistance to the substrate. Fire resistance is the property of a material to withstand fire or give protection from it. The fire resistance of elements of buildings is characterized by the ability to confine a fire or to continue to perform a given structural function or both. Commercial coatings have been available for some years to improve the fire resistance of structural steel. More recently, they have been developed for foam plastics. However, no coatings specifically designed for improving the fire resistance of building materials are currently recommended for wood. Existing coatings for wood are fire retardants that reduce flame spread in the preflashover fire mode, as opposed to fire-resistant coatings that improve fire endurance of the protected substrate beyond the time of flashover. Fire-retardant coatings provide comparatively low flammability or flame spread properties to the substrate. Flashover, the sudden simultaneous ignition of most combustibles in a room. signals the start of a fully developed fire.

Fire-resistive coatings provide protection in a variety of ways. Insulative materials, energy-absorbing or ablative materials. and intumescent coatings are three basic types [1,2]. Newer fire-protective coatings for steel provide protection by a complex series of reactions involving various combinations of intumescence, sublimation. ablation, heat-absorbing chemical and physical reactions. transpiration. and reflection of radiation [3]. Based on thermal degradation studies of ordinary painted particleboard, Vovelle and co-workers [4] concluded that the solid residue remaining after paint pyrolysis shields the wood surface and reduces the rate of transfer of pyrolysis gases as well as oxygen diffusion to the surface.

The thickness of fire-resistive coatings for steel range from 3 to 50 mm or more. Intumescent mastic coatings have thicknesses ranging from 3 to 6 mm, whereas cementitious and fibrous coatings have thicknesses ranging from 9.5 to 50 mm or more [I]. Intumescent coatings swell up when exposed to heat (Fig. 1). Vandersall [5] provides a comprehensive general discussion of the development of intumescent coatings.

On the basis of 135 large fires. Soviet researchers concluded that fire-protective treatment of combustible structural components significantly increased the fire resistance of the structure and prevented fire from spreading over a large area before the arrival of fire-suppression forces in 22% of the fires. In 10% of the fires, fire-protective treatment was ineffective. In 68%, combustible structural components were not fire protected [6].

In a previous paper [7], we reported test results on the ability of fire-retardant and fire-resistive coatings to improve the thermal barrier performance of plywood. In this paper, we present an empirical model we developed from the 1983 data. The feasibility of using coatings to improve the fire resistance of wood joist floors, large timber beams, sandwich wall panels, doors, and wood sheathing is examined.

[1]Research Forest Products Technologist. USDA Forest Service, Forest Products Laboratory, One Gifford Pinchot Drive. Madison. WI 53705-2398. The Laboratory is maintained in cooperation with the University of Wisconsin. Member of ASTM.

0090-3973/86/0003-0097$00.00

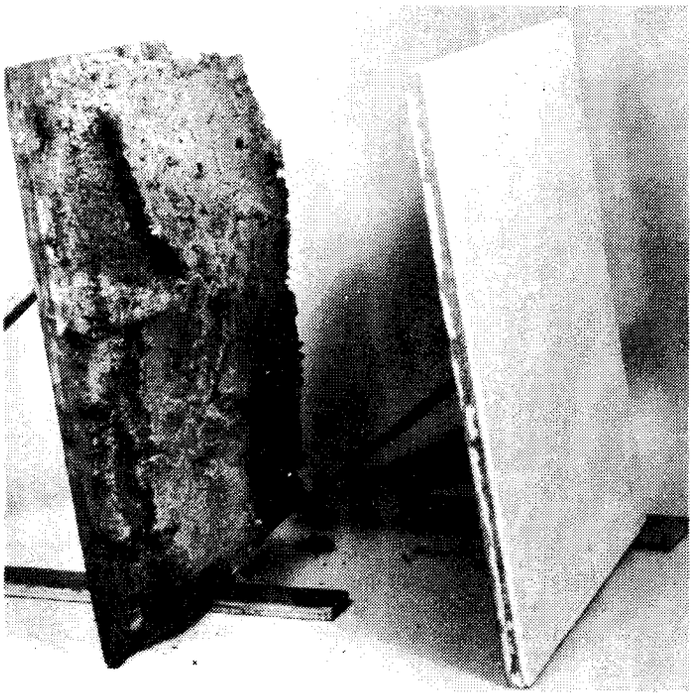

FIG. 1 –*Example of an intumescent coating before and after fire exposure (MB3 0122).*

TABLE 1 –*Description of fire-resistive coatings tested.*[a]

Designation	Coating
A	Flat latex emulsion, intumescent fire-retardant coating, applied at Forest Products Laboratory
B	High-build, two-component, catalytic, epoxy, intumescent fire-retardant coating. applied at Forest Products Laboratory
C	Catalytic polyurethane intumescent fire-retardant varnish over one coat of a clear single-component sealer, applied at Forest Products Laboratory
D	Flat, alkyd, intumescent fire-retardant coating, applied at Forest Products Laboratory
E	Water-based, single-component asbestos-free flexible mastic coating designed to halt fire propagation in grouped electrical cables, applied at Forest Products Laboratory
F	Sprayable, ablative, catalyst-cured fire-resistant coating using a polymer binder and containing no free water, sprayed on by manufacturer
G	Mineral fiber and binder, sprayed on by manufacturer
H	Ablative, epoxy, room temperature curing, two-component intumescent mastic fire-resistant coating approved for exterior use, sprayed on by manufacturer
I	Filled, amine-cured, two-component, epoxy intumescent coating with flame retardants, designed to provide relatively short-time (less than 20 min) fire protection, sprayed on by manufacturer
J	Vinyl-based, heavy-bodied, intumescent mastic fire-resistive coating formulated for interior applications, specially designed for fireproofing steel, sprayed on by manufacturer
K	Fiber-reinforced, solvent-base, asbestos-free intumescent mastic fire-resistant coating, sprayed on by manufacturer
L	Intumescent, mastic, fire-resistant coating, sprayed on by manufacturer
M	Intumescent, mastic, fire-resistant coating, sprayed on by manufacturer
NC	No coating

[a] Coatings were applied to substrates of plywood. See Appendix I for commercial names.

Methods and Model

Test Methods and Data

We evaluated the ability of fire-resistive coatings to improve the fire performance of plywood [7]. Brief descriptions of the coatings tested are listed in Table 1. The specimens were of coated plywood Over a foam plastic substrate. Controls were uncoated plywood specimens.

We placed the 508 by 508 mm specimens in a small vertical furnace and subjected them to ASTM Method for Fire Tests of Building Construction and Materials (E 119) fire exposure. ASTM E 119 is the standard test method for evaluating the fire performance of walls, columns, floors, and other building members under fire exposure. Although the fire exposure was the standard time-temperature curve of ASTM E 119, full conformance to the standard requires the testing of much larger specimens. The testing of larger specimens better evaluates the overall performance of an assembly and the ability of the assembly or material to remain in place during the fire exposure. The small-scale tests reported in this paper reflect the thermal performance of the material or assembly being tested, which is critical to its performance in the large-scale test.

Numerical results of these tests were the exposure times when the temperature rise at the interface of the plywood and the foam plastic substrate was an average value of 139°C or a maximum value of 181°C. These are specified in ASTM E 119 and in building code requirements for thermal barriers on foam plastics. In most tests, we also recorded the times for the temperature to reach 288°C. The 288°C temperature criterion is approximately the temperature of the base of the char layer when wood is subjected to ASTM E 119 fire exposure. As such, it can be used to determine char depth.

Data included the total times for the coated plywood and the gain in time Over uncoated plywood. Additional test results for the 139/181°C temperature criteria obtained since publication of our initial report [7] are reported in Appendix I (see Table 7). previously unreported test results for the 288°C temperature criteria are listed in Table 8.

Empirical Model

Empirical models that could be used to predict the performance of fire-resistive-coated wood were developed. The development of the models is discussed in Appendix II. The models selected are

$$t_{1,x_w} = -161 + 0.0727\,(g_{1,16}\,x_w) + 48.9\,x_w \tag{1}$$

$$g_{1,x_w} = -27.5 + 0.0694\,(g_{1,16}\,x_w) \tag{2}$$

$$t_{2,x_w} = 123 + 0.0676\,(g_{2,16}\,x_w) + 46.1\,x_w \tag{3}$$

$$g_{2,x_w} = 94.7 + 0.0637\,(g_{2,16}\,x_w) \tag{4}$$

where

t = total time, s,
x_w = plywood. wood. or char thickness, mm.
g = gain over uncoated plywood. s,
1 = 139/181°C temperature rise criterion, and
2 = 288°C temperature criterion (char depth).

The forms of Eqs 1 to 4 are the results of a stepwise regression analysis of the 139/181°C data. For Eq 2. the product of the gain in time on nominal 16-mm (5/8-in.)-thick plywood and the plywood thickness was selected as the predictor (x-axis) of the gain for time to 139°C rise (y-axis) (Fig. 2). Equations 1 to 4 include the plywood thickness in each term; they are inappropriate for zero or a very small plywood thickness. When the temperature at the base of the coating is being used, alternative Eqs 5 to 8 are more appropriate:

$$t_{1,x_w} = -943 + 103\ x_w + 37\ x_c + 0.884\ g_{1.16} \quad (5)$$

$$g_{1,x_w} = -743 + 47.5\ x_w + 33.2\ x_c + 0.882\ g_{1.16} \quad (6)$$

$$t_{2,x_w} = -720 + 103\ x_w + 87.5\ x_c + 0.695\ g_{2.16} \quad (7)$$

$$g_{2,x_w} = -619 + 41.4\ x_w + 67.9\ x_c + 0.767\ g_{2.16} \quad (8)$$

where

x_c = coating thickness, mm.

These equations were not obtained from any stepwise regression. However, these equations do provide an adequate degree of prediction. The correlation coefficients for alternative Eqs 5 to 8 are slightly less and the standard deviations are slightly greater than those for Eqs 1 to 4.

For coating thicknesses not tested. the gain in times for the 139°C temperature rise on 16-mm (5/8-in.)-thick plywood. $g_{1.16}$ and $g_{2.16}$. is obtained using the linear regression equation

$$g_{16} = A x_c + B \quad (9)$$

For the different coatings, the values of A and B have been determined for the two temperature criteria (Table 2).

Using Eqs 1 to 4 and Eq 9. one can reasonably predict either the total time or gain in time at the two temperature criteria for a coated plywood of x_w plywood thickness and x_c coating thickness. Equations 1 to 4 can easily be rearranged to solve for the 16-mm plywood predictor when the time for the temperature criteria is known. Equation 9 can likewise be rearranged to solve for coating thickness. When x_w is small or zero (e.g., when the temperature at the base of the coating is being used). Eqs 5 to 8 can be used in place of Eqs 1 to 4.

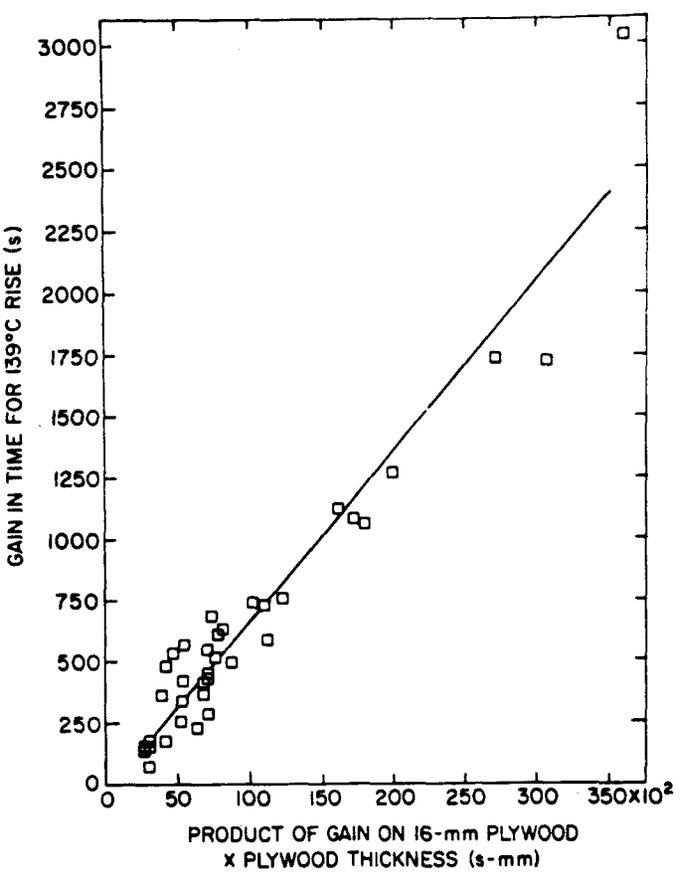

FIG. 2 — *Linear correlation of experimental gain in time for 139°C rise versus the product of gain in rime on 16-mm (5/8-in.) plywood and thickness of plywood. This figure corresponds with Eq 2.*

TABLE 2 - *Parameters for performance of coatings in nominal 16-mm plywood.*

Coating Designation	Range of Coating Thickness, mm	Parameters[a] for $g = Ax_c + B$	
		A	B
A	0.1 to 0.6	489	108
		805	67
B	0.1 to 0.5	1157	−47
		1516	−76
D[b]	0.1 to 0.5	1150	216
		2537	232
E	1 to 6	207	−31
		247	−25
F	1 to 3	244	−63
		255	−66
G	11 to 37	94	−648
		109	−573
H	2 to 7	362	88
		394	156
J	2 to 6	407	152
		619	72
K	3 to 7	138	139
		154	260
L	2 to 6	193	−35
		232	−61
M	3 to 7	287	−92
		460	19

[a] First value is for +139/181°C; second value is for 288°C. In the equation. g is the gain in time (s) for the temperature criteria over the performance of the uncoated nominal 16-mm plywood. and x_c is the coating thickness (mm).

[b] Parameters partially based on test results for 6- and 19-mm plywood.

Since the thermal conductivity for the foam plastics is less than that for wood, estimates for char depth using the data reported in this paper are likely to be high when wood is the substrate and the substrate is semi-infinite. In the case of a semi-infinite slab, a less conservative procedure for char depth would be to calculate for the 139°C temperature rise (i.e., 160°C) and adjust for the 8-mm distance typically found for the 160 to 288°C temperature gradient in a wood slab exposed to ASTM E 119 fire exposure.

The empirical models are based on results for coated plywood. It is reasonable to assume that they will provide satisfactory predictions for coatings on solid wood of similar density. Current data for the models are limited to plywood thicknesses of 6 to 19 mm. Extrapolation of the linear relationships to greater coating or plywood thickness may not be valid.

Applications

In this paper, we liberally use the models to evaluate possible applications for fire-resistive coatings. Some of the applications and predictions presented involve extrapolations beyond the limits of the supporting data and so should be interpreted with caution.

Thermal Barriers

Thermal barriers are membranes that protect combustible materials during a fire and are required to limit the temperature rise on the unexposed surface of the protected material to 139°C or less for a stated time period or finish rating. Two applications for thermal barriers are the protection of foam plastics and of the structural members in a wood assembly.

Building codes require that foam plastics be covered with a thermal barrier when the foam plastic is exposed to the interior of a building. In the U.S. model building codes. the requirement is for a 15-min thermal barrier. As a char-forming thermal barrier. uncoated plywood can effectively protect foam plastics. With a coating, thinner thicknesses of plywood could be used. The estimated coating thickness necessary for a coated 6-mm (1/4-in.)-thick plywood thermal barrier with a 15-min rating ranges from 1 to 24 mm (Table 3). Nominal 16-mm (5/8-in.) plywood has been shown to be equivalent to 13-mm (1/2-in.) gypsum board, which is considered to be a 15-min thermal barrier [8,9].

As part of its fire-resistance listing of wood-stud-wall assemblies, Underwriters' Laboratories (UL) [10] lists the finish rating for the protective membrane. A wall with two layers of UL-classified 16-mm-thick gypsum wallboard (Design No. U301) has an assembly rating of 120 min and a finish rating of 66 min. The estimated coating thickness necessary for a coated 16-mm plywood thermal barrier with a finish rating of 66 min ranges from 2 to 38 mm (Table 2).

Among the coatings we tested, only D, E, G, H, J, and M had estimated thicknesses (on 6-mm [1/4-in.] plywood) for a 15-min thermal barrier that were lower or only slightly higher than the maximum thicknesses tested (Table 2). Likewise. for the 66-min thermal barrier, estimated required thickness (on 16-mm plywood) for Coatings G. H. and J were only slightly higher than the maximum thickness listed in Table 3. The test results and the calculated finish ratings for the fire-resistive coatings indicate that they can provide the necessary thermal protection.

TABLE 3 —*Predicted coating thicknesses required to obtain two possible thermal barriers.*

Coating Designation	Coating Thickness (mm) for 15-min Barrier with 6-mm Plywood	Coating Thickness (mm) for 66-min Barrier with 16-mm Plywood
A	3.1	5.7
B	1.4	2.5
D	0.9	1.8
E	8.0	14.1
F	6.9	12.1
G	24.2	37.7
H	4.2	7.8
J	3.6	6.8
K	10.8	20.0
L	8.6	15.2
M	6.0	10.4

Walls

Walls are important in confining a fire to the compartment of origin. Thus building codes require fire-rated walls in certain applications.

Sandwich Panels —Sandwich panels consist of a low-density, low-strength core between two high-strength faces. Paper honeycomb and foam plastics are examples of the core material: plywood, hardboard, and sheet metal are examples of the facings. Fire tests have shown that load-bearing sandwich panels need to be protected to prevent early structural failure in a fire [11, 12]. Coatings are used to improve the fire endurance of sandwich panels in the Soviet Union [13].

Eickner [11] evaluated two mastic coatings in ASTM E 119 tests of coated plywood-foam plastics sandwich panels. The coatings provided significant improvements to the fire resistance. In the test of a polyurethane-foam sandwich panel. the coating was an earlier version of Coating E (Table 1). E_i. In the isocyanurate-foam sandwich panel test, the coating was J (Table 1). Coating J was applied on the sandwich panel at a wet thickness of 4.8 mm; Coating E_i was applied on the sandwich panel at a wet thickness of 2.3 mm. The faces of all the panels were 6-mm (1/4-in.)-thick plywood. In the ASTM E 119 tests, temperatures were measured on the back of the plywood on the fire-exposed side of the sandwich panel. and the structural failure times of the panels were recorded.

We calculated the estimated times for the 139°C temperature rise and the 288°C temperature. assuming dry thicknesses of 3.2 mm for Coating J and 1.1 mm for Coating E, on Eickner's panels (Table 4). The initial temperature in the ASTM E 119 time-temperature curve is 20°C. Thus a 139°C temperature rise corresponds to a temperature of 159°C.

Our predicted times for 139°C temperature rise were less than the experimental times (Table 4). In the no-coating and Coating E_i tests, structural failure of the sandwich panel before the 139°C temperature rise criterion was achieved accounts for part of the difference in times for the temperature rise. Structural failure resulted in the buckling of the faces.

The times for structural failure should be between the time for 139°C temperature rise (i.e., 159°C) and the times to achieve 288°C. At 159°C, the thermal degradation of the foam plastics is from 0 to 7% [14–16]. As the temperature increases above 159°C. failure of the foam plastic is more likely. When the back side of the fire-exposed plywood has reached 288°C. the plywood faces are completely charred and have no load-bearing capacity.

The estimated no-coating results (Table 4) are the average differ-

TABLE 4 –*Comparison of predicted rimes with experimental ASTM E 119 results for sandwich panels.*

Coating Designation	Predicted Times (min) for		Experimental Times (min) for	
	+139°C	288°C	+139°C	Structural Failure
None[a]	3.2	5.8	4.8	3.1
E_i	4.0	8.8	11.7	8.2
J	13.6	21.5	19.5	24.9

[a]Predicted times based on average differences between the total time and gain time for the two coatings.

ence between the total time and the gain time for the two coatings. Estimated times for the uncoated panel are both higher than the experimental results for structural failure. However, the predicted times for 139°C temperature rise are very close to the experimental structural failure times for the uncoated panels.

Structural failure time for Coating E_i was within the estimated times for Coating E (Table 4). Estimated times for Coating J were both lower than the structural failure time. The assumed 3.2-mm dry thickness for Coating J is likely a low estimate for the recorded 4.8-mm wet thickness. For a dry thickness equal to the wet thickness of 4.8 mm, the predicted times for Coating J would have been 18.6 min for 139°C temperature rise and 28.5 min for 188°C. The experimental time of 24.9 min is slightly greater than the 21.5-min prediction for 288°C, assuming dry-coating thickness of 3.2 mm, and less than the 28.5-min prediction for 288°C. assuming dry-coating thickness of 4.8 mm.

Coatings can effectively protect structural sandwich panels from early structural failure in a fire. Structural failure in the standard ASTM E 119 test is likely to be between the time predicted for 139°C temperature rise and the time predicted for the 288°C temperature criterion.

Wood-Stud Wall—The empirical models can predict the finish rating of a coated wood thermal barrier. The finish rating can be used to obtain a conservative estimate of the fire resistance of a wood-stud-wall assembly.

One can calculate the fire resistance of a wall assembly with the additive method of the National Building Code of Canada [17]. The method is being introduced into the U.S. model codes. In the method, the wood-stud wall (2 by 4 studs, 16 in. on center) is assigned a rating of 20 min. The time assigned to the wall membrane on the fire-exposed side is added to the 20 min to obtain the rating of the assembly. The times assigned to the membranes are based on ASTM E 119 ratings for various wall assemblies. They are not the finish ratings for the membranes. Finish ratings are generally equal to or lower than the time assigned to the membrane. Thus finish ratings are conservative estimates of the time assigned to a membrane for contribution to fire resistance of the wall assembly. For example, the 15-min thermal barriers of coated 6-mm ($^1/_4$-in.) plywood (Table 3) would be part of a 35-min fire-rated assembly. This is identical to the ratings for 13-mm ($^1/_2$-in.) gypsum board which is a 15-min thermal barrier. The 66-min coated plywood thermal barrier (Table 3) would be part of an 86-min fire-rated assembly according to the additive method. Double layers of 16-mm ($^5/_8$-in.) Type-X gypsum board has a finish rating of 66 min [10]. A stud wall with double layers of 16-mm Type-X gypsum board has a wall assembly rating of 120 min [10].

Light-Frame Floors

Floors are an ideal application for fire-resistive coatings. Fire-resistance ratings are assigned only for a fire beneath the floor assembly. Since weight is of concern in floor construction, light-weight coatings are particularly desirable. In addition to possible use in new construction, coatings are needed to upgrade the fire endurance rating of existing wood joist floors. Sprayed fiber has been used to protect wood joists in old European cathedrals [18]. Rehabilitation of existing buildings is a critical and active area of construction. Various methods for improving the fire resistance of existing floors have been described [19].

Existing fire-rated wood joist floor assemblies have ratings of 120 min or less. These floor assemblies generally have protective ceiling membranes of gypsum board. Fire-resistive-coated joists with a gypsum board ceiling on channels may be one way to achieve 120- or even 180-min-rated joist floor assemblies.

Floor Design

Using a char depth of 4.5 mm at the time of failure, we calculated the predicted coating thickness necessary for a 30-, 60-, and 120-min-rated floor (Table 5). In tests of five floors subjected to a maximum floor load as described in ASTM E 119, the failure of the third joist occurred at a time corresponding to a char depth of 4.5 mm [20]. In every case, the calculated thickness exceeded the coating thickness tested in the small-scale tests (Table 2). Coatings G, H, J. and M are possibilities for a 30-min-rated floor assembly with coating thicknesses somewhat close to the tested thickness. Coatings H, J, and M are mastic coatings for which the predicted thickness for a 60-min-rated floor was 27 mm or less.

A model for predicting the fire resistance of unprotected wood joist floors has been proposed [21]. Full-scale ASTM E 119 tests [20] support the validity of the model. For a given load. the model can be used to calculate the char depth at the time of joist failure. Thus the floor model can be combined with the char depth (Eqs 3 and 4) to predict the coating thickness necessary to obtain the required rating. For Douglas-fir joists at 9% moisture content, a charring rate of 0.64 mm/min or 1.5 in./h is appropriate.

A similar model for fire-exposed unprotected floor trusses has also been proposed [22]. An approach to coating protection as discussed may prove beneficial to floor-truss-assembly fire endurance as well.

TABLE 5 –*Coating thicknesses estimated for a 30-. 60-. and 120-min rated floor assembly.*

Coating Designation	Coating Thicknesses (mm) for Ratings of		
	30 min	60 min	120 min
A	6	13	28
B	3	7	15
D	2	4	9
E	20	44	92
F	19	42	89
G	50	104	212
H	12	27	57
J	8	17	36
K	30	68	145
L	21	46	98
M	10	23	49

Comparative Test Data

Some test data are available for coated wood joists. As part of HUD's Operation Breakthrough. a joist nominal 50 by 250 mm (2 by 10 in.) coated with an intumescent paint was tested for char depth [23]. The 250-mm sides of three joists were subjected to 45 min of ASTM E 119 fire exposure: one joist was bare, the second joist was painted with a 0.2-mm layer of an intumescent paint. the third joist was protected by one layer of 16-mm Type-X gypsum board. At the end of the test, the 40-mm bare joist was completely charred through, and the painted joist was 22 mm charred. Based on data for Coatings A. B. and D. the predicted char depths (Eq 3) are 52 mm for the unprotected joist and 27 to 43 mm for the coated joist. The gypsum-board-protected joist was 3 mm charred.

Underwriters' Laboratories of Canada tested a coated floor assembly in ASTM E 119 exposure [24]. The floor assembly was nominal 50 by 200 mm joists, 410 mm on center (2 by 8 joists, 16 in. on center) supported by a built-up beam consisting of four nominal 50 by 250 mm joists. The flooring consisted of 19-mm-thick plywood as a finish floor and 19-mm-thick plywood as the subfloor. The sprayed protection consisted of a layer of cementitious material reinforced by expanded metal lath and a top layer of an intumescent mastic coating covering the entire floor assembly and beam. A 90-min fire-endurance rating was achieved for the floor assembly. Without protection, the fire rating for the assembly is about 10 min.

The cementitious material had a density and thermal conductivity similar to wood. The intumescent mastic coating was Coating K. Predictions were computed for the fire resistance of the coated wood by assuming the wood thickness of Eqs 1 to 4 was equal to the thickness of the cementitious coating plus the thickness of the wood.

In addition to the joists, the plywood flooring was also coated. The thickness of the mastic coating was 4.8 mm and of the cementitious material was 23.8 mm. The predictions for the temperature criteria on the unexposed side of the plywood flooring were 108 min for the total 38-mm plywood and 74 min for just one 19-mm layer of plywood. The temperature failure criterion was reached over a joint at 91 min with the test. Thisfailure time is consistent with the predicted time for one and two layers of plywood.

For the joists. the cementitious material was 20.6 mm thick on the sides and 27.0 mm on the bottom, and the mastic coating was 3.2 mm thick on the sides and 6.4 mm thick on the bottom. On the beam, the cementitious material was 27 mm thick on the sides and 25.4 mm thick on the bottom, and the mastic coating was 6.4 mm thick on the sides and 3.2 mm thick on the bottom of the wood member.

For such a joist and beam assembly, the predicted temperature failure times are 29 to 52 min. In the test, average temperature failure was at 25 min, and individual maximum temperature failure occurred at 13 min. At 12 min, a small area of intumescent coating fell off in one comer of the assembly. During the period of 17 to 30 min, the mastic coating continued to intumesce, crack, and fall off over all the assembly.

Schultz tested an unloaded nominal 50 by 250 mm (2 by 10 in.) wood joist floor with 38 mm of sprayed mineral fiber [25]. The mineral fiber was applied to a metal lath that was attached to the underside of the joists. After 132 min of fire exposure, the depth of the joist was reduced to 184 mm or a char depth of 57 mm. According to the data for the mineral fiber coating (G), the predicted char depth for the coated joist was 31 mm. The two-dimensional aspect of the charring joist probably accounts for the large difference. The thermocouples on the bottom of the joists reach 288°C at 80 min. According to Eq 5, the estimated time for the thermocouple to reach 288°C is 85 min.

Large Timber Members

Protection for wood beams and columns has received attention for a long time. The 1942 report from the National Bureau of Standards [26] lists ratings for timber columns with 25.4 mm (1-in.) portland cement plaster on wire lath. More recently, coated beams and columns have been tested in Europe and Japan to determine the effect of a coating on char depth [27–30].

A recent development in the United States has made it more practical to design a fire-resistive-coated beam. The National Research Board [31] has approved a procedure for calculating the fire-resistance rating of large timber beams.

The fire rating for the uncoated beam multiplied by the charring rate will yield an estimate of the char depth needed to calculate the coating required for a higher fire-resistance rating. Using char depth for x_w. Eqs 3 or 4 and 9 provide an estimate of the necessary coating thickness. For a charring rate of 0.64 mm/min, the coating thickness required to improve the fire rating of a 30- and a 60-min-rated beam to 60, 90, or 120 min has been calculated (Table 6).

Predicted results indicate that Coatings G, H, J, and M are possible coatings for improving the fire resistance of a large wood beam. It must be noted that the 60-min unprotected rating is based on a char depth of 38 mm, which is double the maximum plywood thickness that Eqs 1 to 4 are based on. Additional research is needed to determine whether the extrapolation is valid.

In situations where the aesthetics of the wood member is important. fire-resistive coatings are not acceptable. The clear fire-retardant varnish (Coating C) alone would not provide enough improvement in fire resistance. In the rehabilitation of old heavy-timber buildings exceeding the height limitations of current building codes, thermal barrier protection for heavy-timber floor systems may be an acceptable alternative to fire-rated noncombustible contruction [32].

Doors

Doors are another possible application for fire-resistive coatings. In the rehabilitation of a building, the upgrading of the fire perfor-

TABLE 6 —*Predicted coating thickness required to improve fire rating of large timber beam.*

Coating Designation	Coating Thicknesses (mm) Required for			
	30-min Beam		60-min Beam	
	60 min	120 min	90 min	120 min
A	2.4	5.9	1.6	2.5
B	1.4	3.2	1.0	1.4
D	0.7	1.8	0.4	0.7
E	8.3	19.6	5.6	8.5
F	8.2	19.1	5.6	8.4
G	23.8	49.4	17.8	24.2
H	4.7	11.8	3.1	4.8
J	3.1	7.6	2.1	3.2
K	11.4	29.6	7.2	11.7
L	9.0	21.0	6.2	9.2
M	4.4	10.4	2.9	4.4

mance of the doors may be necessary. Problems include plain glass. panel inserts of insufficient thickness, and improper fit of a door in its frame [33]. Intumescent coatings are an alternative to infilling the paneled area with fire-protective media and/or overlaying the door with protective boarding [34]. In tests of doors coated with fire-retardant paints [35], the paints did not provide any significantly greater protection unless they contained glass fiber reinforcement. Equations 1 to 4 provide the means to estimate the coating thickness necessary to improve the resistance of the panel.

Lawson and Butcher [36] suggest that a paper honeycomb matrix be used to support a thick layer of intumescent paint. The intumescent paint is coated on the interior surfaces of the honeycomb. The coating expands and fills the pores exposed to heat. One possible application of such a panel is in doors.

Research Needs

Additional research needs to be done before fire-resistive coatings can be used in wood construction. Needed research falls into three areas: (1) small-scale fire tests and mechanistic modeling, (2) full-scale fire tests, and (3) related properties including economics.

Thermal barriers are required to remain in place for the time period for which they are rated. To fully qualify the coating effectiveness. large-scale testing is required to evaluate the ability of the coatings to remain in place. We found that the cohesive and adhesive performances of the coatings in the small-scale vertical tests ranged from poor to very good. When the expansion was substantial. the foam would sometimes slip from the top to the bottom of the vertical specimen or fall off the specimen. Other coatings would fall off the plywood either during or after the test. However, several coatings showed excellent cohesive and adhesive performance. In our estimation. the small vertical furnace test is inadequate as a test of adhesive or cohesive performance. A larger specimen and horizontal orientation of the specimen are needed.

To improve the adhesive and cohesive performance of a coating, glass fiber or other reinforcement is typically used. Additional research is needed to investigate what reinforcement or other mechanical fastening devices may be appropriate for the various applications.

Additional small-scale testing is needed to evaluate the adhesion/cohesion of the coating and its performance when the char depth is greater than 25 mm. Small-scale ASTM E 119 testing of specimens in horizontal orientation should be done to evaluate the adhesion/cohesion performance of the coating. Testing of coatings on thick wood slabs, where char depth could be as great as 38 min, is needed toevaluate the effect of greater char depth as well as longer fire exposures on performance.

Mechanistic models based on thermodynamics and heat transfer provide a more general methodology. Appropriate values for the physical and thermal properties of the coatings are needed. Castle and co-workers [37] analyzed a spray-on fiber material with an analytical model. Cagliostro and co-workers [38] applied a heat transfer model to intumescent coatings. Using heat transfer analysis, Bardell [39] predicted the temperatures that a protected steel column reached during a fire.

Full-scale ASTM E 119 tests are needed to verify the predictive models and fully evaluate the performance of the coated assembly. Specifically, the effect of deflection of the wood assembly during the fire exposure is a concern.

Performance of a coating in a fire-resistance test is not the sole criterion for field use. Other properties need to be considered. These include serviceability, durability, toxicity, flammability, and ease of application. ASTM Committee E-6 on Performance of Building Constructions has been developing standards related to serviceability of fire-resistive coatings for steel [40,41]. These test procedures are needed to evaluate the durability and the reliability of fire-resistive coatings under normal use as well as under conditions of fire exposure [42]. Brenden [43] has measured the smoke generation performance of coatings.

The relative costs of applying fire-resistive coatings to improve the fire resistance of wood members and assemblies will govern their future use. The cost of using a larger wood member or protective membrane such as gypsum board needs to be compared with the costs of fire-resistive coatings.

Summary

An empirical model for predicting the fire-resistance performance of fire-resistive coatings on wood has been presented. Various applications for fire-resistive coatings in wood construction have been discussed. These applications include thermal barriers, walls. floors. large timber members, and doors. Predictions using the model compared favorably with the very limited experimental data available in the literature. In combination with fire endurance models for the structural wood members. these empirical equations can effectively be used to design coated wood assemblies for specific fire endurance ratings. Additional research is needed before use of fire-resistive coatings in wood construction can be realized. The relative costs of applying fire-resistive coatings to improve the fire resistance of wood members and assemblies will govern their future use.

APPENDIX I

Coatings

The coatings are described in Table 1. The commercial names are:

A—Ocean Chemicals #320 (Savannah, GA)
B—Ocean Chemicals #477
C—Ocean Chemicals #777 and #776
D—Ocean Chemicals #987
E—Intumastic 285 (Carboline, St. Louis, MO)
F—STAYTEX 4119A (Stahl Industries. Youngstown, OH)
G—Clark-Tectonics, Inc. (Madison, WI)
H—Chartek 59 (Avco, Lowell, MA)
I—Flamarest 1600B
J—Albi-clad 89S (Stan Chem Albi, East Berlin, CT)
K—Ocean Chemicals #44 Mastic (Savannah, GA)
L—Ocean Chemicals #34 Mastic
M—Ocean Chemicals #2-47-390

The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture of any product or service to the exclusion of others which may be suitable.

Tables 7 and 8 list test results not previously reported [7].

Visual Observations

Intumescence of Coating I was 25 to 40 mm thick. When the specimens were removed from the furnace, parts of the intumescent layer had degraded and the wood surface was exposed.

TABLE 7 - *Test results, for 139/181°C criteria for Coatings I, J, K. and M.*

Coating Designation	Number of Tests	Dry Coating Thickness, mm	Dry Coating Weight, g/m²	Time to 139/181°C[a] Total Mean, s	COV, %[b]	Improvement, s[c]
			6-mm (1/4-in.) Plywood			
K	1	2.4	2890	340	...	160
	1	4.9	5840	520	...	340
	1	6.8	8090	740	...	550
L	1	3.2	3940	550	...	360
	1	4.5	4490	600	...	420
	1	6.1	6720	880	...	690
M	1	3.8	5300	700	...	520
	1	4.1	5890	820	...	633
	1	5.7	6870	780	...	590
NC	1	0	0	190	...	0
			16-mm (5/8-in.) Plywood			
I	3	0.3	700	1200	4	540
J	3	2.4	2660	1790	11	1100
	3	5.1	6560	2920	4	2240
K	1	6.1	7430	1580	...	920
	1	2.9	3200	1200	...	550
	1	6.9	8560	1790	...	1130
L	1	2.6	2400	1090	...	440
	1	4.1	4230	1470	...	810
	1	5.7	6070	1700	...	1050
M	1	3.1	3780	1700	...	1050
	1	4.7	5420	1980	...	1330
	1	6.6	8200	2700	...	2050
NC	4	0	0	670	2	0
			19-mm (3/4-in.) Plywood			
K	1	2.0	3080	1450	...	610
	1	5.3	7290	1970	...	1120
	1	6.1	7900	1910	...	1060
L	1	2.6	2380	1340	...	500
	1	5.0	5030	1920	...	1080
	1	7.8	8450	2580	...	1740
M	1	3.4	3680	2110	...	1270
	1	5.5	5760	2560	...	1720
	1	6.5	9210	3880	...	3030
NC	1	0	0	840	...	0

[a]Time for unexposed surface of the plywood to reach average of 139°C or maximum of 181°C above initial temperature.
[b]Coefficient of variation.
[c]Improvement over the time for uncoated plywood. Calculations are based on the individual test results. This may not be the same as the difference in average times.

Intumescence of the thin coating of Coating J was about 25 mm thick at the end of the test. The thick coating expanded to about 50 mm. The intumescence was reasonably intact and still adhering to the plywood at the end of the test.

Coatings K and L welled up to less than 25 mm. Intumescence consisted of a hard crust-like coating that included large hollow bubbles. In most of the tests, the coating remained intact during the test.

Coating M at all three initial thicknesses swelled up to a thickness of 180 to 200 mm. Intumescence was a light fluffy foam that stayed attached to the plywood.

APPENDIX II

Development of Model

To develop an empirical model for predicting coating performance, we regressed the gain in times to reach the temperature rise on 139/181°C and times to reach the temperature of 288°C with the coating thickness and the plywood thickness. The times increased with increases in the coating thickness and with increases in the plywood thickness. The various coatings behaved differently on the three thicknesses of plywood. Linear lines provided reasonable estimates of the effect of plywood thickness but. as expected, the lines for the different coatings were not parallel (Fig. 3).

The slopes of the lines for the effect of plywood thickness versus the gain in times are not all the same for the different coatings. Plotting these slopes against the variable gain in time for the coating on 16-mm plywood resulted in a linear relationship (Fig. 4). Linear regression of the 139/181°C gain-in-time data resulted in a squared correlation coefficient of 85.2%. Similar results are obtained with the 139/181 °C total-time data and the two sets. gain and total times, of 288°C data. The 16-mm plywood variable can be the total time as well as the gain in times.

Thus one can use this relationship between the slopes for effect of

TABLE 8 —*Time to reach 288°C temperature criteria for all coatings.*

Coating Designation	Number of Tests	Dry Coating Thickness, mm	Dry Coating Weight, g/m²	Time to 288°C[a] Total Mean, s	Time to 288°C[a] Total COV, %[b]	Improvement, s
			6-mm (1/4-in.) Plywood			
A	3	0.5	720	520	1	250
D	1	0.4	600	830	...	530
	1	0.1	130	480	...	180
	1	0.2	300	650	...	350
	1	0.3	460	790	...	480
	1	0.5	760	900	...	640
NC	4	0	0	290	9	0
F	3	2.9	4940	916	8	640
K	1	2.4	2890	630	...	330
	1	4.9	5840	1020	...	720
	1	6.8	8090	1260[c]	...	960
L	1	3.2	3940	890[c]	...	590
	1	4.5	4490	960	...	660
	1	6.1	6720	1260[c]	...	960
M	1	5.7	6870	2010	...	1710
			16-mm (5/8-in.) Plywood			
A	3	0.5	670	1320	6	500
D	3	0.5	920	2240	3	1410
F	3	1.9	3320	1250	5	410
	3	2.8	4840	1480	2	660
K	1	6.1	7430	1940[c]	...	1120
	1	2.9	3200	1530	...	720
	1	6.9	8560	2190	...	1380
L	1	2.6	2400	1320	...	510
	1	4.1	4230	1770	...	950
	1	5.7	6070	2060	...	1240
H	3	6.4	8640	3550	14	2710
M	1	3.1	3780	2310	...	1500
	1	4.7	5420	2910	...	2090
	1	6.6	8200	3920	...	3100
A	3	0.1	140	1030	2	200
B	3	0.1	260	950	2	130
	3	0.5	920	1460	3	630
C	3	0.6	910	1580	2	750
E	3	1.4	2010	1160	3	310
	3	6.0	8720	2300	5	1470
G	3	34.8	6120	4060	8	3240
	2	12.7	1660	1640	2	810
H	3	2.6	3550	1980	16	1150
J	3	2.4	2660	2400	15	1520
	2	5.2	6500	4160	3	3280
I	3	0.3	700	540	8	760
NC	10	0	0	840	3	0
			19-mm (3/4-in.) Plywood			
A	3	0.5	670	1570	1	520
D	2	0.1	190	1640	4	590
F	3	2.6	5000	1820	2	770
K	1	2.0	3080	1860[c]	...	790
	1	5.3	7290	2460	...	1390
	1	6.1	7900	2360	...	1300
L	1	2.6	2380	1680[c]	...	610
	1	5.0	5030	2460	...	1390
	1	7.8	8450	3080	...	2020
M	1	5.5	5760	3960	...	3150
A	2	0.1	120	1210	9	150
NC	4	0	0	1060	1	0

[a]Time for unexposed surface of the plywood to reach average of 288°C.
[b]Coefficient of variation.
[c]Test terminated before temperature of 288°C obtained; available data extrapolated to obtain an estimated time.

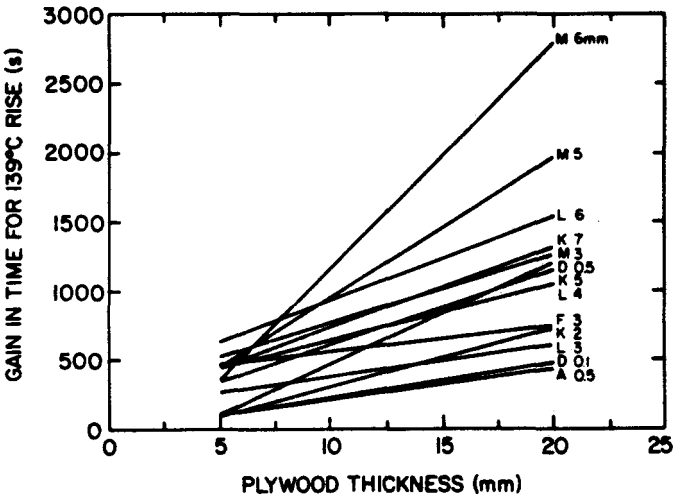

FIG. 3 —*Improvements in time tor increased plywood thickness. Number following coating designation is the approximate coating thickness in millimetres.*

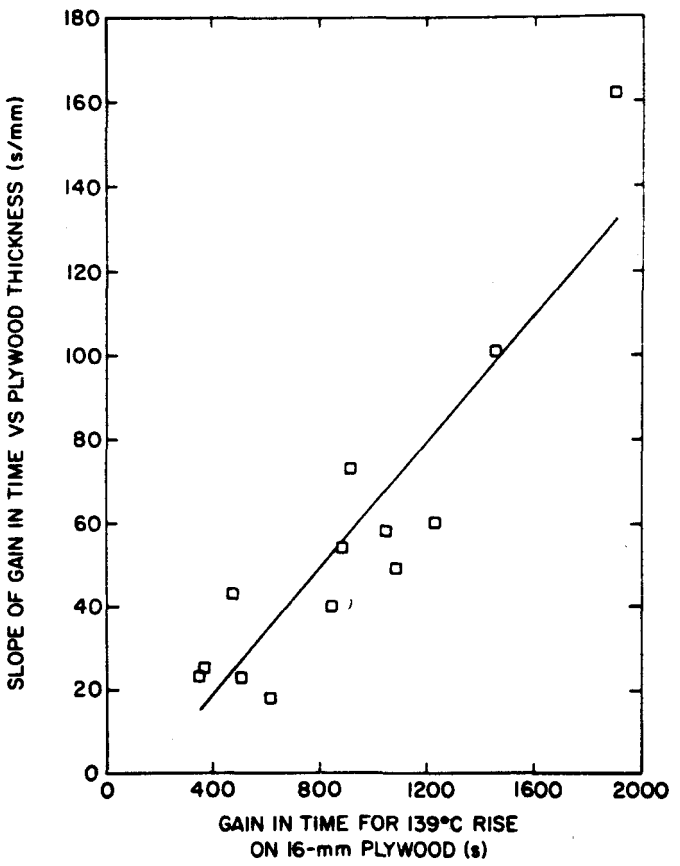

FIG. 4 —*Linear correlation of slopesfor the effect of plywood thickness on gain in rimes on 16-mm-thick plywood.*

plywood thickness and the 16-mm plywood test results to predict the performance of the coatings on any thickness of plywood. With these relationships, we obtained reasonably good estimates for the 6-mm and 19-mm plywood test data.

In addition to being statistically significant, the relationship between the relative insulative performance of the different coatings (i.e., 16-mm plywood results) and the relative effect of plywood thickness on the results is physically reasonable. For the same reason that the improvement shown for insulative coatings increases as the thickness of the plywood is increased [7]. the improvement shown for plywood thickness should increase as the insulative ability of the coating is increased. Since an insulative layer will reduce heat transfer into the substrate. the time for a temperature rise at a given location in the substrate will be increased. Thus insulative coatings increase the total time. The longer the total time. the longer the insulative layer will improve the performance of the thicker plywood specimen. As a result, the improvement obtained with the thicker plywood is greater with the more insulative coatings.

As part of an effort to develop an improved model. we used the 6-mm and 19-mm data to evaluate other empirical models. The various linear models included three variables: (1) coating thickness. (2) plywood thickness, and (3) gain in time on nominal 16-mm plywood. Using a stepwise regression procedure, we evaluated the three variables and the combinations of the variables as predictors. At each step of the stepwise procedure. the *F*-statistic is calculated for each predictor in the equation. The predictor with the largest *F*-statistic is added to the expression. For a model with one predictor. the product of the gain in time on nominal 16-mm-thick plywood and the plywood thickness were selected as the predictor (x-axis) of the gain for time to 139°C rise (y-axis) (Fig. 2). This predictor is dimensionally similar to previously discussed results obtained using the slopes of the effect of plywood thickness on the times. For total times. improved predictions were obtained by adding a second predictor, plywood thickness, to the model.

Verification

To judge the validity of the model. the linear regressions were done for three sets of data: (1) Coatings A to H. (2) Coatings K, L, and M. and (3) Coatings A to M (Tables 9 to 12). Coatings A to H were the coatings initially tested. Coatings K. L, and M were tested to verify and refine the model. The three sets of equations (Tables 9 to 12) are consistent. The wide variation in the constant reflects the high standard error for this coefficient. The squares of the correlation coefficients range from 64 to 98%. and the standard errors of the estimates ranged from 115 to 200 s (Tables 9 to 12).

TABLE 9 —*Coefficients for the equation* $t_{Lxw} = a + b\,(g_{L16}\,x_w) + cx_w$ *(total times for 139/181 °C temperature rise criteria).*

Data Set	Coefficients			Adequacy of Equation[a]	
	a	*b*	*c*	R^2, %	*S*, s
First					
Coefficient	−194	0.0674	53.2	94	117
Standard error	67	0.0111	5.2		
Second					
Coefficient	−110	0.0741	44.1	96	199
Standard error	109	0.0072	11.4		
Combined					
Coefficient	−161	0.0727	48.9	96	155
Standard error	59	0.0037	4.8		

[a] R^2 is the square of the correlation coefficient and *S* is the square root of the residual mean square. (The residual mean square estimates the variation of *y* about the line *x* if the model is adequate.)

TABLE 10 —*Coefficients for the equation* $g_{1,xw} = a + b\ (g_{1.16}\ x_w)$ *(gain in times for 139/181 °C temperature rise criteria).*

Data Set	Coefficients		Adequacy of Equation[a]	
	a	*b*	R^2, %	*S*, s
First				
Coefficient	−5.6	0.0640	72	115
Standard error	58.7	0.0091		
Second				
Coefficient	−11.2	0.0690	92	200
Standard error	81.5	0.0050		
Combined				
Coefficient	−27.5	0.0694	92	155
Standard error	39.1	0.0032		

[a] R^2 is the square of the correlation coefficient and *S* is the square root of the residual mean square.

TABLE 11 —*Coefficients for the equation* $t_{2,xw} = a + b\ (g2.16\ x_w) + cx_w$ *(total times for 288°C temperature rise criteria).*

Data Set	Coefficients			Adequacy of Equation[a]	
	a	*b*	*c*	R^2, %	*S*, s
First					
Coefficient	−41.1	0.0572	59.0	94	127
Standard error	77.6	0.0098	5.3		
Second					
Coefficient	399	0.0640	36.9	98	143
Standard error	88	0.0043	8.4		
Combined					
Coefficient	123	0.0676	46.1	95	175
Standard error	71	0.0037	5.5		

[a] R^2 is the square of the correlation coefficient and *S* is the square root of the residual mean square.

TABLE 12 —*Coefficients for the equation* $g_{2,xw} = a + b\ (g_{2.16}\ x_w)$ *(gain in times for 288°C temperature rise criteria).*

Data Set	Coefficients		Adequacy of Equation[a]	
	a	*b*	R^2, %	*S*, s
First				
Coefficient	116	0.0515	64	130
Standard error	70	0.0089		
Second				
Coefficient	269	0.0590	93	200
Standard error	89	0.0046		
Combined				
Coefficient	94.7	0.0637	91	184
Standard error	48.4	0.0035		

[a] R^2 is the square of the correlation coefficient and *S* is the square root of the residual mean square.

Based on the equationsfor Coatings A to H, predictions of the performance of Coatings K, L, and M were made and compared with the experimental results. With the exception of the thick coating of M on 19.1 mm (3/4-in.) plywood. the predicted results were from 232 s less to 81 s greater than the experimental results for the total times to reach the 139/181°C temperature rise criteria and from 224 s less to 79 s greater than the experimental results for the gain in times to reach the 139/181°C temperature rise criteria. The predictions for the thick coating of M on 19.1 mm (3/4-in.) plywood was about 930 s less than the experimental results for both total time and gain in times. With the exception of the thick coating of M on 6.4 mm (1/4-in.) plywood. the predicted results were from 430 s less to 56 s less than the experimental results for the total times to reach the 288°C temperature criteria and from 629 s less to 25 s greater than the experimental results for the gain in times to reach the 288°C temperature criteria. The 629 s error was for the medium thickness of Coating M on 19.1 mm (3/4-in.) plywood. The predictions for the thick coating of M on 6-mm plywood were about 1015 s less than the experimental results for both total times and gain in times.

With the exception of the few Coating M results. the errors in the predictions were generally conservative and consistent with the standard errors obtained in the linear regressions (Tables 9 to 12). Plotting of the residuals versus the predicted values indicated no problems with the models. Comparison of the time-temperature curves for the thick coating of M on the three thicknesses of plywood showed that the temperature range for the five thermocouples was small in the 6- and 19-mm plywood tests but not in the 16-mm test. In all three 16-mm plywood tests of Coating M, the individual time-temperature curves diverged as the test progressed. The low predictions reflected the performance of the coating in the 16-mm plywood tests. The linear regression analysis also indicated test data that potentially had a large influence on the regression due to the values of $g_{58}\ x_w$. These were generally Coating M data. Omitting the data had no significant effect on the regression equation.

Model

As a result of the analysis of the data. the regression equations for the combined data set were selected (Tables 9 to 12). These equations should provide reasonable estimates for fire-resistive-coated wood. Additional predictors resulted in only minor improvement in the correlation coefficients for Eqs 1 and 2. In the case of equations for the 288°C temperature criteria (Tables 11 and 12), additional predictors did improve the squares of the correlation coefficients to 98%. Because of the limited data. linear relationships for coating thickness and plywood thickness were assumed. Curvilinear relationships may be more appropriate. If so. one possible modification to the model would be to add an exponent to the variables for plywood thickness or coating thickness.

References

[1] Lieff, M., "Fire Resistant Coverings," in *Survey of United States Research Projects-Publications in the Field of Fire Safety of Buildings and Structures*, NBSIR 81-2294. U.S. Department of Commerce, National Bureau of Standards, Washington, DC, 1981.

[2] Lieff, M., "Fire Resistant Covering," in *Fire Resistive Coatings: The Need for Standards. ASTM STP 826*, American Society for Testing and Materials. Philadelphia, 1983, pp. 3-13.

[3] Rains, W. A., "A New Era in Fire Protective Coatings for Steel," *Civil Engineering*, Vol. 46, No. 9, Sept. 1976, pp. 80-83.

[4] Vovelle, C., Akrich, R., and Mellottee, H., "Thermal Degradation of Painted Wood—An Experimental Study," *Journal of Fire Sciences*, Vol. 1, No. 3, May/June 1983, pp. 191-199.

[5] Vandersall, H. L., "Intumescent Coating Systems, Their Development and Chemistry," *Journal of Fire and Flammability*, Vol. 2, No. 2, April 1971, pp. 97-140.

[6] Mikhaylov, D. N. and Fyodorov, V. V., "Fire Development Experience

in Soviet Industrial Buildings," *Fire Technology*, Vol. 19, No. 4, Nov. 1983, pp. 280-286.

[7] White, R. H., "Use of Coatings to Improve Fire Resistance of Wood," in *Fire Resistive Coatings: The Need for Standards, ASTM STP 826*, American Society for Testing and Materials, Philadelphia, 1983, pp. 24-39.

[8] White, R. H., "Effect of Calcium Silicate Substrate on Thermal Barrier Fire Testing," *Forest Products Journal*, Vol. 32, No. 7, July 1982, pp. 25-27.

[9] White, R. H., "Wood-Based Paneling as Thermal Barriers," U.S. Department of Agriculture, Forest Service, Research Paper FPL 408, Forest Products Laboratory, Madison, WI, 1982, 12 pp.

[10] "Fire Resistance Directory," Underwriters' Laboratories, Inc., Northbrook, IL, 1983.

[11] Eickner, H. W., "Fire Endurance of Wood-Frame and Sandwich Wall Panels," *Journal of Fire and Flammability*, Vol. 6, No. 2, April 1975, pp. 155-190.

[12] Holmes, C. A., Eickner, H. W., Brenden, J. J., Peters, C. C., and White, R. H., "Fire Endurance Under Design Load: Walls of Structures of Sandwich and Wood-Frame Construction," U.S. Department of Agriculture, Forest Service, Research Paper FPL 364, Forest Products Laboratory, Madison, WI, 1980.

[13] Lieff, M., "Fire Resistive Coatings in the USSR: An Overview," in *Fire Resistive Coatings: The Need for Standards, ASTM STP 826*, American Society for Testing and Materials, Philadelphia, 1983, pp. 102-114.

[14] Taylor, W., "Evaluation of Thermal Barriers for Foamed Plastic Insulation," *Fire Technology*, Vol. 19, No. 2, May 1983, pp. 124-135.

[15] Condit, D. A. and Cianciolo, A. D., "Evaluation of Rigid Urethane Insulation for Residential Application by Compartment Corner Fire Test," *Fire Journal*, Vol. 71, No. 3, May 1977, pp. 32-38, 102.

[16] Lie, T. T., "Contribution of Protected Plastic Foams to Fire Growth," NRCC 14932, National Research Council of Canada, Ottawa, 1975.

[17] Associate Committee on the National Building Code, "The Supplement to the National Building Code of Canada," National Research Council of Canada, Ottawa, 1980.

[18] Stumpf, F. M., "Spray-Applied Fibrous Material Fire Resistive Coatings," in *Fire Resistive Coatings: The Need for Standards, ASTM STP 826*, American Society for Testing and Materials, Philadelphia, 1983, pp. 14-23.

[19] Fire Research Station, "Increasing the Fire Resistance of Existing Timber Floors," Building Research Establishment Digest 208, Her Majesty's Stationery Office, London, 1980.

[20] White, R. H., Schaffer, E. L., and Woeste, F. E., "Replicate Fire Endurance Tests of An Unprotected Wood Joist Floor Assembly," *Wood and Fiber Science*, Vol. 16, No. 3, 1984, pp. 374-390.

[21] Woeste, F. E. and Schaffer, E. L., "Reliability Analysis of Fire-Exposed Lightframe Wood Floor Assemblies," U.S. Department of Agriculture, Forest Service, Research Paper FPL 386, Forest Products Laboratory, Madison, WI, 1980.

[22] Schaffer, E. L. and Woeste, F. E., "Reliability Analysis of A Fire-Exposed Unprotected Floor Truss," in *Proceedings*, Metal Plate Wood Truss Conference, Forest Products Research Society, Madison, WI, 1981, pp. 131-137.

[23] Issen, L. A., "Tests of the Fire Resistance of Intumescent-Painted Structural Elements," NBS Report 10 412, U.S. Department of Commerce, National Bureau of Standards, Washington, DC, 1972.

[24] Underwriters' Laboratories of Canada, "Report on Cementitious Mixture and Intumescent Mastic Coating for Use in A Wood Floor and Ceiling Assembly (for Sylva-Gard Co. Ltd.)," Design M600, Scarborough, Ont., Canada, 1972.

[25] Schultz, N., "Fire Resistance Testing of A Wood Floor Assembly," VTEC Laboratories Inc., Bronx, NY, 1982.

[26] Central Housing Committee on Research, Design, and Construction, "Fire Resistance Classifications of Building Constructions, Building Materials and Structures," Report BMS 92, U.S. Department of Commerce, National Bureau of Standards, Washington, DC, 1942.

[27] Centre Technique du Bois, "Essais Comparatifs de Resistance au Feu sur Poteaux Revetus de Peinture Ignifuge," Bulletin D Information Techniques No. 52, Centre Technique du Bois, Paris, 1970.

[28] Imaizumi, K., "Stability in Fire of Protected and Unprotected Glued Laminated Beams," New Zealand Forest Service Information Series No. 47, New Zealand Forest Service, Wellington, 1963.

[29] Malhotra, H. L. and Rogowski, Barbara, F. W., "Fire Resistance of Laminated Timber Columns," in *Joint Fire Research Organization Symposium No. 3, Fire and Structural Use of Timber in Buildings*, Her Majesty's Stationery Office, London, 1970, pp. 16-51.

[30] Ödeen, K., "Fire Resistance of Glued, Laminated Timber Structures," in *Joint Fire Research Organization Symposium No. 3, Fire and Structural Use of Timber in Buildings*, Her Majesty's Stationery Office, London, 1970, pp. 7-15.

[31] National Research Board, "Design of One-Hour Fire-Resistive Exposed Wood Members (6-Inch Nominal or Greater)," Report No. NRB-250, Council of American Building Officials, 1984.

[32] Hansen, A. T., "Applying Building Codes to Existing Buildings," *Building Standards*, Vol. 50, No. 3, May-June 1984, pp. 13-14, 47.

[33] U.S. Department of Housing and Urban Development, "Guideline on Fire Ratings of Archaic Materials and Assemblies," *Rehabilitation Guidelines*, Vol. 8, Government Printing Office, Washington, DC, 1980.

[34] Adams, F. C., Morris, W. A., and Read, R. E. H., "Increasing the Fire Resistance of Existing Timber Doors," BRE Information Paper 8/82, Building Research Establishment, Borehamwood, England, 1982.

[35] Shoub, H. and Gross, D., "Doors as Barriers to Fire and Smoke," Building Science Series 3, U.S. Department of Commerce, National Bureau of Standards, Washington, DC, 1966.

[36] Lawson, D. I. and Butcher, E. G., "Intumescent Coated Honeycombs," *Fire Surveyor*, Vol. 1, No. 3, June 1972.

[37] Castle, G. K., Alexander, J. G., Tempesta, F. L., and Belason, E. B., "Analytical Prediction of the Thermal Response of Decomposing Materials in Fire Environments," *Journal of Testing and Evaluation*, Vol. 1, No. 5, Sept. 1973, pp. 416-421.

[38] Cagliostro, D. E., Riccitiello, S. R., Clark, K. J., and Shimizu, A. B., "Intumescent Coating Modeling," *Journal of Fire and Flammability*, Vol. 6, No. 2, April 1975, pp. 205-221.

[39] Bardell, K., "Spray Applied Fire Resistive Coatings for Steel Building Columns," in *Fire Resistive Coatings: The Need for Standards, ASTM STP 826*, American Society for Testing and Materials, Philadelphia, 1983, pp. 40-55.

[40] "E06.21 Nears Completion of Fire-Resistive Standards Group," *ASTM Standardization News*, Vol. 11, No. 2, Feb. 1983, p. 63.

[41] Skolnik, A. D., "Testing Sprayed Fireproofing," *Progressive Architecture*, Vol. 61, No. 10, Oct. 1980, p. 87.

[42] Seigel, L. G., "Performance Requirements for Fireproofing Materials," *Journal of the Engineering Mechanics Division*, American Society of Civil Engineers, Vol. 100, No. EM3, Paper 10598, June 1974, pp. 489-495.

[43] Brenden, J. J., "How Fourteen Coating Systems Affected Smoke Yield from Douglas-Fir Plywood," U.S. Department of Agriculture, Forest Service, Research Paper FPL 214, Forest Products Laboratory, Madison, WI, 1973.