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STATE OF STRUCTURAL TIMBER FIRE ENDURANCE[1, 2]

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ABSTRACT

The paper is motivated by the need for information relating to the design and behavior of wood structural components. Such information is critically reviewed. Most standard conventional components have been fire tested under the sponsorship of materials suppliers or designers. However, only the fire endurance of floors and columns have both models and experimental evidence available for use. Models for the fire endurance of heavy timber, or glulam, beams are presented that are based on reduction of the cross section with duration of fire exposure and a reduction of strength of the outer fibers. Essentially no experimental information is available on model effectiveness. No models for the performance of wood-base wall systems were found, but extensive experimental ratings exist. To facilitate further research, a review of the influence of fire on wood and wood properties is given. Included are strength and deformation under load, charring of solid sections and panels, temperature distribution, and thermal properties. Research needs, in addition to filling the gaps found, include: analysis of risk based upon both variability of the "fire load" and "structural fire resistance"; and benefit/cost analyses on fire protection.

Keywords: Fire endurance, fire resistance, timber, wood, columns, beams, walls, floors, panels, thermal properties, strength, wood assemblies, wood components.

WHY PREDICT STRUCTURAL FIRE ENDURANCE?

Fire growth in any building is largely dependent upon the design of the building and the combustible contents available for fuel. A current requirement in many codes is that the building walls and floors or ceilings provide a *barrier* to movement of fire. This is both to contain a fire within a compartment and to minimize structural collapse. Structural collapse, of course, is a hazard to occupants and firefighters as well as a contributor to further property damage.

Being able to design structural components to meet the desired fire endurance will save lives and property and is the primary motive for presenting available information. It will also be evident that some critical information and prediction procedures require further research. A useful general reference is by Hall et al. (1972).

CODE REQUIREMENTS

It is generally well known that national and state building codes require that structural components have a minimum fire endurance level as determined by type of building. For example, heavy timber construction (NFPA 1961), or mill-type construction, has long been recognized as having a 1-h "rating."

All of the major national codes accept the results of standard fire endurance tests on components to qualify them for a given building type. The standard test procedure normally specified is ASTM E 119 (ASTM 1973). In it, the full-scale component is subject to fire controlled to produce a given ambient temperature with the passage of time (Fig. 1). The component,

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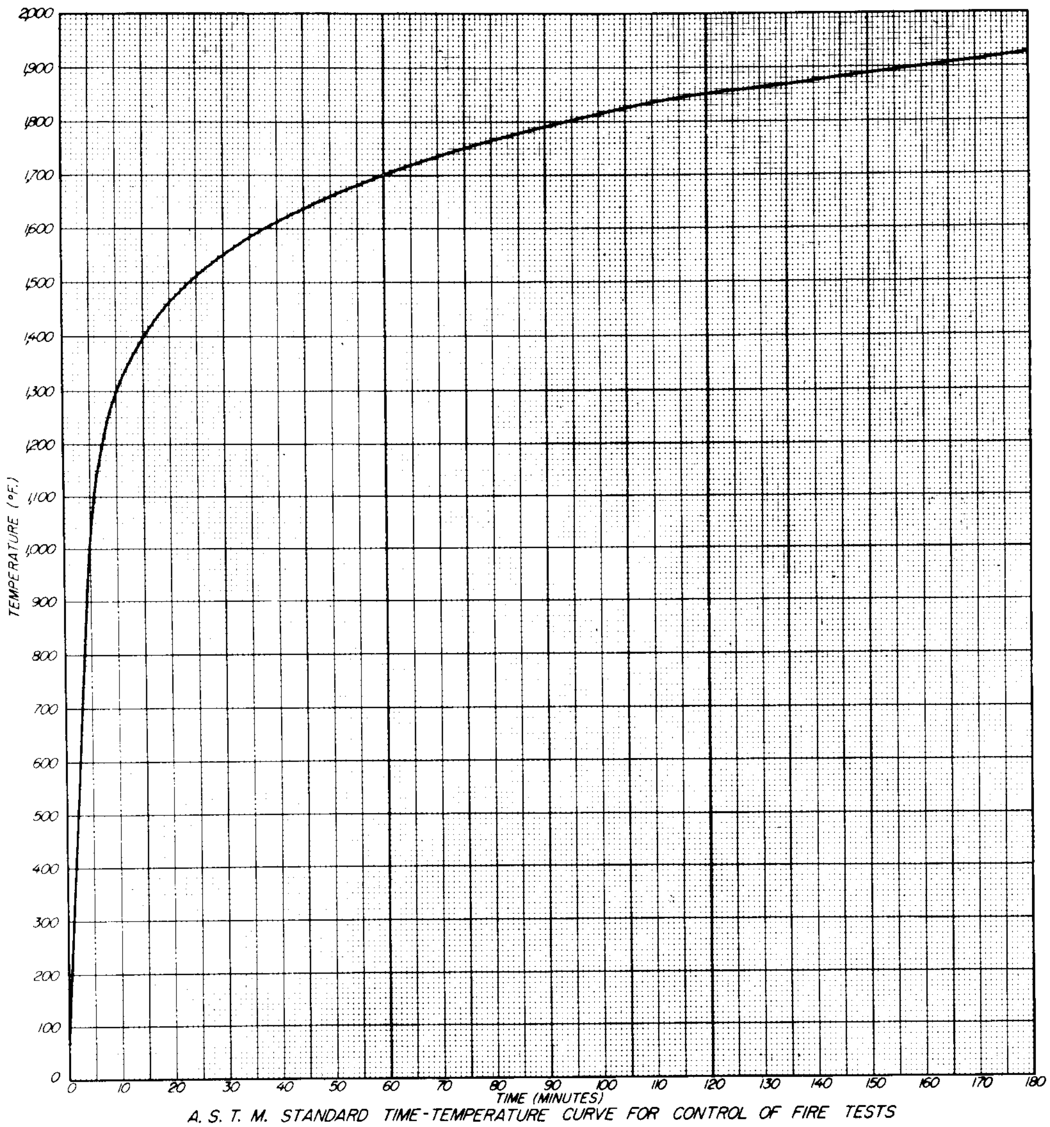

FIG. 1. ASTM E 119 time-temperature curve (ASTM 1973).
(M 75 340 F)

if load bearing, carries a superimposed load anticipated to develop the working stresses contemplated in its design. Conditions of acceptance as meeting a given rating period are that (briefly):

1. It sustain the applied load, if any, during the fire test.

2. If it is a wall or partition, floor, or roof, it shall not develop surface conditions on the non-fire-exposed face that will ignite cotton waste, nor shall the *average* surface temperature rise 139 C (250 F) above its initial temperature, nor shall a single surface temperature rise more than 163 C (325 F).

3. A wall or partition must withstand the impact of a fire hose stream, at a time half

that of the rating desired, without allowing the stream to pass through. After cooling, a load-bearing wall shall be able to sustain twice the design load without collapse.

The Basic Building Code (BOCA 1975) and some state codes, such as Wisconsin's (WDILHR 1972) will also consider for acceptance ratings based upon analysis. The monetary savings in not having to conduct full-scale fire tests in order to have unusual designs accepted are significant. However, being able to produce an acceptable engineering analysis can be formidable. One must be able to confidently predict component response to the fire conditions of the ASTM E 119 temperature-time curve using the *known* thermal and strength characteristics of the structural components (see Appendix A for Wisconsin code requirement). Steel and concrete designers are taking advantage of this procedure now.

If some components are "comparable" to other already test-rated components, the National Building Code (American Insurance Association 1976) will consider accepting an equivalent rating for the nontested component.

RATINGS FOR TIMBER STRUCTURES

Walls, partitions, floor-ceilings, and roofs

Most conventional components have already been fire tested under the sponsorship of the materials suppliers. As a result, most codes provide tables of the fire endurance ratings. In addition, other specific listings are available (e.g., UL 1974; NBFU 1964; NFPA 1976). Recent work by Son (1973a; 1973b; 1973c; 1973d; 1973e; 1973f) was employed in developing HUD Minimum Property Standard levels for fire resistance of walls and floors (U.S.D. HUD 1973). Eickner (1975) has compared the fire endurance of conventional and newer sandwich load-bearing wall systems. Generally, the use of combustible faces alone in the tested sandwich constructions results in performance well below that of conventional stud walls.

Analytically predicting the fire endurance of composite components employing some critical thermal property data has been advanced by Pachkis and Baker (1942), Lawson and McGuire (1953), Robertson and Gross (1958), and Harmathy (1961). These approaches attempted to predict the temperature rise on the unexposed surface of layered or solid walls and partitions. They appear satisfactory for brick walls and layered walls with air gaps as long as neither thermal degradation of the construction materials nor structural failure was a significant effect.

Harmathy (1965) prepared a list of ten rules as a guide in assessing the fire endurance of untested components (Fig. 2). They are especially useful when redesigning an existing component is desired for improved fire endurance.

Analyses that predict the sustained load-carrying capacity of either thermally degrading or nondegrading components are limited. The only model found applied to wood floor-ceiling constructions. The fire endurance of floor-ceiling components was experimentally measured by the British and an expression for time to failure was generated as a function of joist size (Lawson et al. 1951; 1952). Joists of actual sizes 1.5 × 7, 2 × 6, 7, and 9 inches (38 × 178, 58 × 152, 178, and 228 mm) were used in cross-braced spans of 12 ft (3.66 m). The relationship developed was:

$$(1 - T\sqrt{s})\left[1 - (T/2\sqrt{s})\right]^2 = 2\alpha^{\frac{1}{2}}, \qquad (1)$$

where

$$\alpha = \frac{\text{applied load}}{\text{breaking load}} = \frac{\text{design allowable stress}}{\text{ultimate stress}},$$

$s = D/B$ (depth/breadth),
$T = t/20\sqrt{A}$,
t = fire endurance (min), and
A = cross-section area (inch^2).

For the species tested, an ultimate stress of 11,000 lb per square inch was employed. A plot of dimensionless time, T, versus s

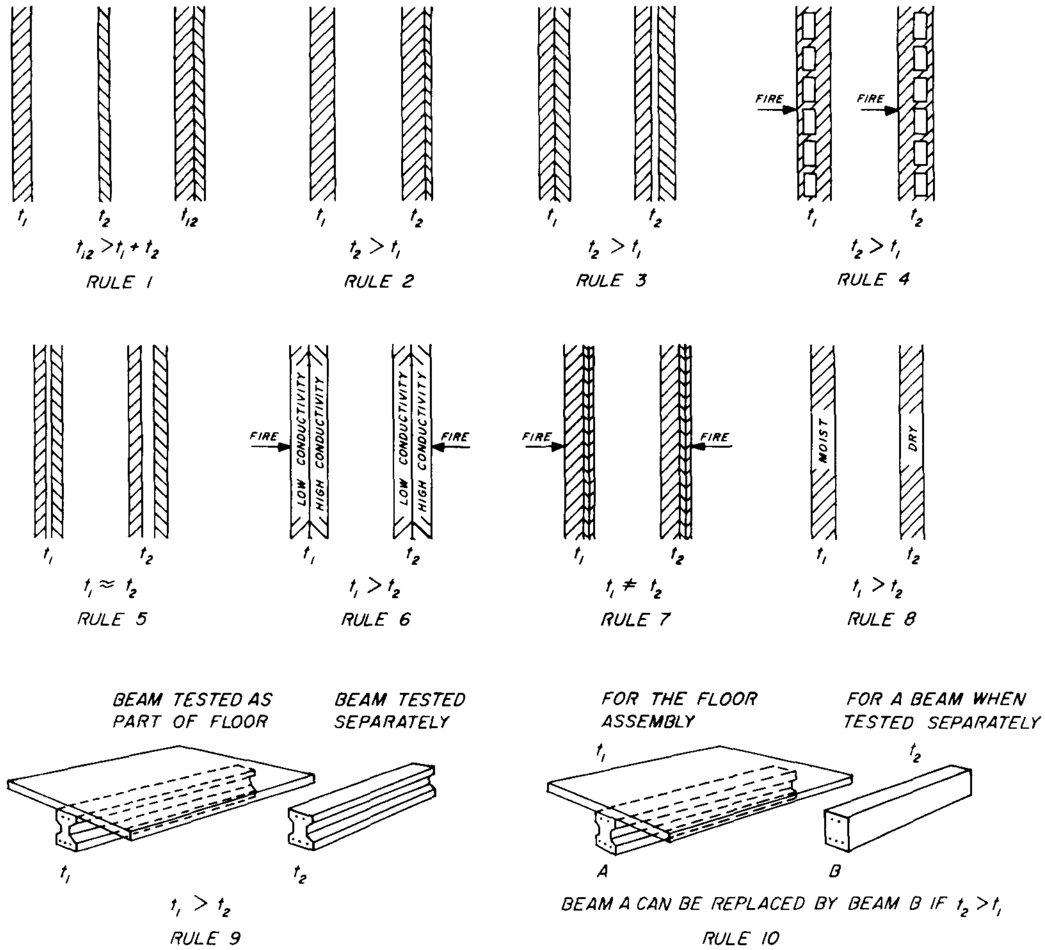

FIG. 2. Diagrammatic illustration of 10 rules for fire endurance (t: fire endurance) (Harmathy 1965).
(M 145 181)

is shown in Fig. 3 for various load ratios, α. for nominal North American 2 by 8's on 16-inch centers and a span of 12 ft with 40 lb per square foot live load ($\alpha = 1{,}090/11{,}000 = 0.099$), their expression predicts an endurance time of 9.4 min. This estimate is very close to that suggested by HUD Minimum Property Standards of 10 min (U.S.D. HUD 1973). Hence adjustments to the fire endurance of floors through control of joist dimension are readily made.

The employment of fire-retardant-impregnated materials in solid wood walls has been shown to increase their fire endurance or burn-through time significantly (Mitchell 1947; CSIRO 1962). Chemical treatment added 20 to 24% to the failure time of walls tested under load as compared to untreated. For walls tested without load, treatment improved time to failure 29 to 33% over that of untreated. [Treatment used was ammonium sulfate (60%), diammonium phosphate (10%), sodium tetraborate (10%), and boric acid (20%). Chemical retention in the wood was at least 5 lb of dry chemical per cubic foot of wood.]

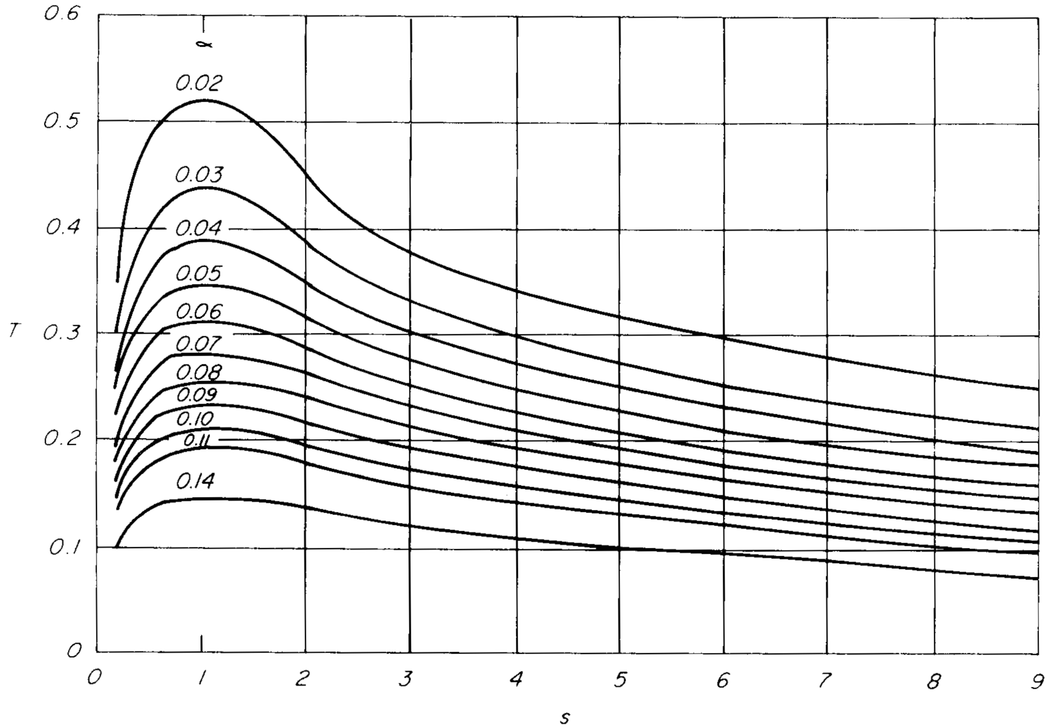

FIG. 3. The family of curves for fire endurance of wood floors $\alpha^{1/2} = \frac{1}{2}(1 - T\sqrt{s})[1 - (T/2\sqrt{s})]^2$ (Lawson et al. 1952).
(M 145 178)

Beams

Unconcealed beams can be exposed to fire from three or four sides depending upon design (Fig. 4). As mentioned previously, beams of given minimum dimension have historically satisfied heavy timber requirements for 1-h fire endurance in mill-type buildings (Table 1) (NFPA 1961). However, fire testing of loaded beams to failure has been negligible. Hence, absolute measures of strength under fire exposure are unavailable.

The simpler predictions of fire endurance of loaded beams have been based upon an estimate of the strength of the uncharred residual cross section as a function of duration of exposure to standard fire conditions (e.g., Dorn and Egner 1961; Imaizumi 1962; Odeën 1970; Lie 1972). The estimate is then made in the same fashion as any beam analysis by assuming:

1. The residual cross section is rectangular in shape during fire exposure.

2. The ratio, γ, of allowable bending

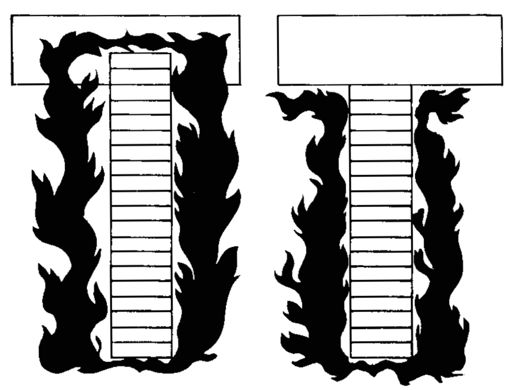

FIG. 4. Fire exposure of beams on three or four sides.
(M 145 066)

TABLE 1. *Minimum dimensions for heavy timber construction*

Component	Width	Depth
	In.	In.
Columns		
Floor	8	8
Roof	6	8
Beams and girders	6	10
Roof arches and trusses	4	6
Floor and roof deck		
Roof (T & G)		2
(Solid)		3
Floor (T & G)		3
(Solid)		4

strength before the fire and ultimate bending strength at room temperaure is known.

3. The ratio, α, of ultimate strength of the uncharred part of the beam at time of failure and the strength at room temperature is known.

4. Charring rate, β, when exposed to standard fire is known.

By performing the analysis, the critical residual depth, d, of a beam exposed on all four sides to fire is given by the solution

$$(d/D)^3 - (d/D)^2(1 - B/D) = \gamma B/\alpha D\ , \quad (2)$$

where

B = initial width of beam, and
D = initial depth of beam

and the time, t_c, to reach this critical depth (fire endurance time):

$$t_c = (D - d)/2\beta\ . \quad (3)$$

Similarly, for three sides exposed to fire, the critical residual depth is given by (Lie 1972):

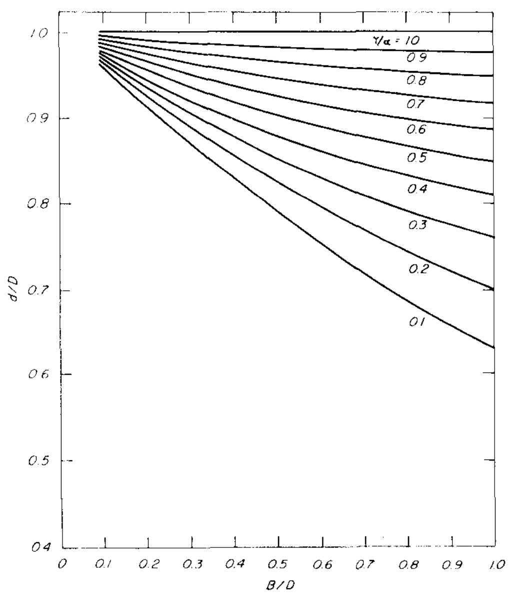

FIG. 5. Critical depth of solid timber beams of rectangular cross section exposed on four sides to fire (Lie 1972).
(M 145 179)

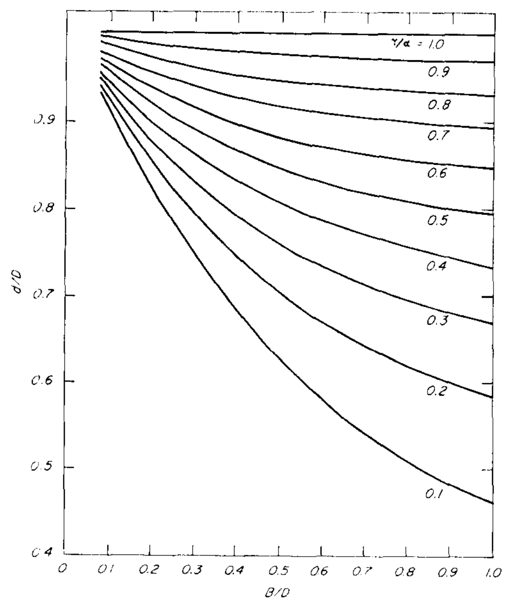

FIG. 6. Critical depth of solid timber beams of rectangular cross section exposed on three sides to fire (Lie 1972).
(M 145 180)

$$(d/D)^2[(B/D) - 2(d/D)^2] = \gamma B/\alpha D\,, \quad (4)$$

and respective time, t_c, to reach this depth by:

$$t_c = (D - d)/B\,. \quad (5)$$

The critical depths of beams are plotted by Lie (1972) in Figs. 5 and 6. With proper selection of the factors γ and α, it would be simple to find the critical depth, d.

The factors γ and β are easily obtained from the literature. In the U.S., the factor γ for bending stress is 0.476 (ASTM 1976) and the charring rate, β, is available for Douglas-fir and southern pine (Schaffer 1967). A β of 1/40 inch per min is the common rule of thumb.

Imaizumi (1962) and Odeën (1970) incorporate a correction for strength of the uncharred wood due to temperature rise and change of the cross-section shape in the factor, α. In so doing, the factor is estimated at 0.80. However, no fire tests of loaded timber beams are reported that substantiate this choice. New Zealand has reportedly (Wardle 1967) adopted a reduction factor for α of 0.50. Wardle claims that predictions made by his method (1966) gave results comparable to those occurring in fires. For periods of fire resistance up to 1 h, no additional material was required over that provided for by cold design. They also have reduced the imposed load below design load levels in fire tests because of the low probability of coincidence of fire and maximum load.

The only reported tests to destruction of loaded glulam beams were conducted on three beams of European whitewood bonded with resorcinol adhesive (Hall 1968). The sections were 139 by 228 mm (5.47 by 8.98 inches) on a span of 3.6 m (11.8 ft) and subjected to full design load. They failed after 53 min and charring rate was 0.6 mm per min. They predicted a failure time of 45 min using an assumed ratio of design load to failure load of 1:2.25 for the char-reduced section. This would indicate a ratio of design to failure load somewhat lower was justified (e.g., 1:3).

Imaizumi (1962) also indicates that lateral buckling may occur as the breadth to depth ratio decreases to a critical value, r. The critical burning time, t_c, for this to occur is given as:

$$t_c = [D(B/D - r)]/[2\beta(1 - r)]. \quad (6)$$

Determining critical values for r has not been done to date.

Columns

Predicting the fire performance of timber columns provides another dimension of difficulty because failure is normally due to instability of the member. However, more data on the performance of timber columns under fire exposure are available than for beams. The British (Rogowski 1967; Malhotra and Rogowski 1967) have presented information resulting from a most comprehensive test and analysis series. Included was a consideration of:

—wood species
—glue type
—section shape (B/D)

TABLE 2. *Empirical values of factors to determine fire resistance of columns (Malhotra and Rogowski 1967)*

Factor	Empirical value
T (Species)	
Douglas-fir	2.64
European redwood	2.56
Western hemlock	2.33
Western red cedar	2.06
G (Glue)	
Phenolic	2.64
Resorcinol	2.48
Urea	2.43
Casein	2.17
S (Section shape)	
α b/d = 1.00	2.64
β b/d = 1.74	2.46
δ b/d = 2.71	2.04
L (Load)	
100% design load	2.64
50% design load	3.74
25% design load	5.28

—load level
—wood quality or grade
—section size
—fire-retardant treatments
—encasement by a noncombustible material.

Column length was 3.1 m (10.25 ft). The design load was selected as a function of column area times clear wood stress modified by grade and slenderness ratio factors. Regressions of fire endurance time versus species (T), glue (G), section shape (S), and load (L) level (as percent of full allowable) resulted in a tabular listing of factors (Table 2) that can be employed to predict fire endurance time, t, for columns having initial cross sections of 53,000 mm^2 (82.2 inches^2):

$$t = T \cdot G \cdot S \cdot L \qquad \text{(minutes)}. \qquad (7)$$

For example, a Douglas-fir column, using phenolic glue, of square cross section ($B/D = 1$), and 100% design load is predicted to have a fire endurance time of 49 min. Actual result was 45 min.

Note that the predictive equation includes no additional factors for effect of grade (other than design load) or actual dimensions. In fact, no additional correction was found needed for grade over and above the effect on design load. Dimension does significantly affect the fire endurance time because of the influence of charring on the change in slenderness ratio of the column. For square columns, the fire endurance changed linearly with dimension, D (in mm):

$$t \propto D^{.7}. \tag{8}$$

No similar results were given for other shapes. The variability between predicted versus actual results is not given, but a coefficient of variation less than 10% is claimed.

The more universal application of the work of Malhotra and Rogowski (1967) suffers from a lack of correlation to a more suitable model. Odeën (1970) generates fire endurance time estimates based upon initial slenderness ratio, λ_0 ($= l/r$), applied load as percent of design load, p, for columns with a mean charring rate, β, of 0.6 mm per min. (Design load is taken as 0.50 ultimate.) In addition, application is limited to times that produce a char layer less than ¼ the initial column width. He proposes the fire endurance time as a function of initial slenderness ratio for a column of 19 by 19 cm (7.5 by 7.5 inches) on this basis (Fig. 7). His estimate provides a fire endurance time of 33 min for a Douglas-fir column of length 3.1 m (10.2 ft) which is much less than that obtained by Malhotra and Rogowski (1967) of 45 min (and predicted level of 49 min).

In order to determine the source of the difference, an examination of the approach of Odeën is warranted. He assumed that the limiting maximum stress will be 0.60 of the Euler-Hyperbola level, π^2E/λ^2 (Fig. 8). Malhotra and Rogowski used the Euler-Hyperbola level for one column which was ramp loaded to failure ($l/r = 61$)[4] and estimated failure at 0.75 π^2E/λ^2. This indicated that Odeën's limiting critical stress level is likely conservative (his endurance times are therefore short). Correcting Odeën's endurance time upward accordingly results in predicted failure at $t = 45$ min or equivalent to the Malhotra and Rogowski estimates.

It is evident that improved estimates for column performance can be made using

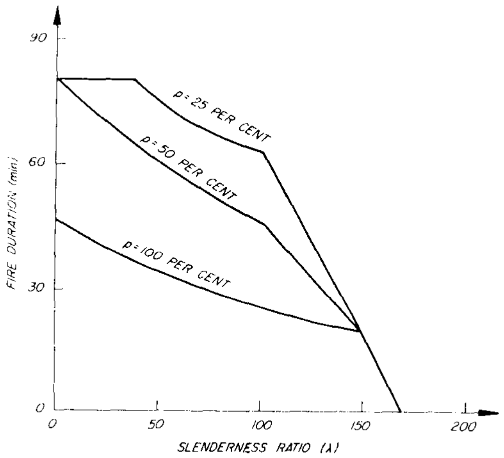

FIG. 7. Fire endurance versus slenderness ratio, λ, for 19- by 19-cm column (Odeën 1970). (M 145 183)

test data available. The model for predicting needs some work to make it more representative of changes in the strength and stiffness of wood.

Fire-retardant impregnations had a variable influence on the fire endurance times for columns (Malhotra and Rogowski 1967). One treated to a level of 53 kg/m³ (3.3 lb/ft³) improved endurance by 11 min. Another treated at 40 kg/m³ (3.3 lb/ft³) reduced the time, but insignificantly. Evidently the difference was due to the differing effect of each on strength properties, because both reduced the rate of charring by 20% (Rogowski 1967). A clear intumescent paint was not found to alter fire endurance time.

If columns survive a prescribed rating period, evidence shows that their ability to continue to carry the load on cooling or after cooling is likely (Malhotra and Rogowski 1967). On cooling, the timber regained much of the original strength available for the reduced cross section.

Increasing endurance time by *encasement* is an effective procedure (Malhotra and Rogowski 1967) and can be designed for.

Heat-conducting end caps for columns should be avoided. Such caps induce pre-

[4] It should be noted that both Odeën and Malhotra and Rogowski improperly employ Euler-Hyperbola equation because l/r is less than 100. This does not affect the comparative analysis, however.

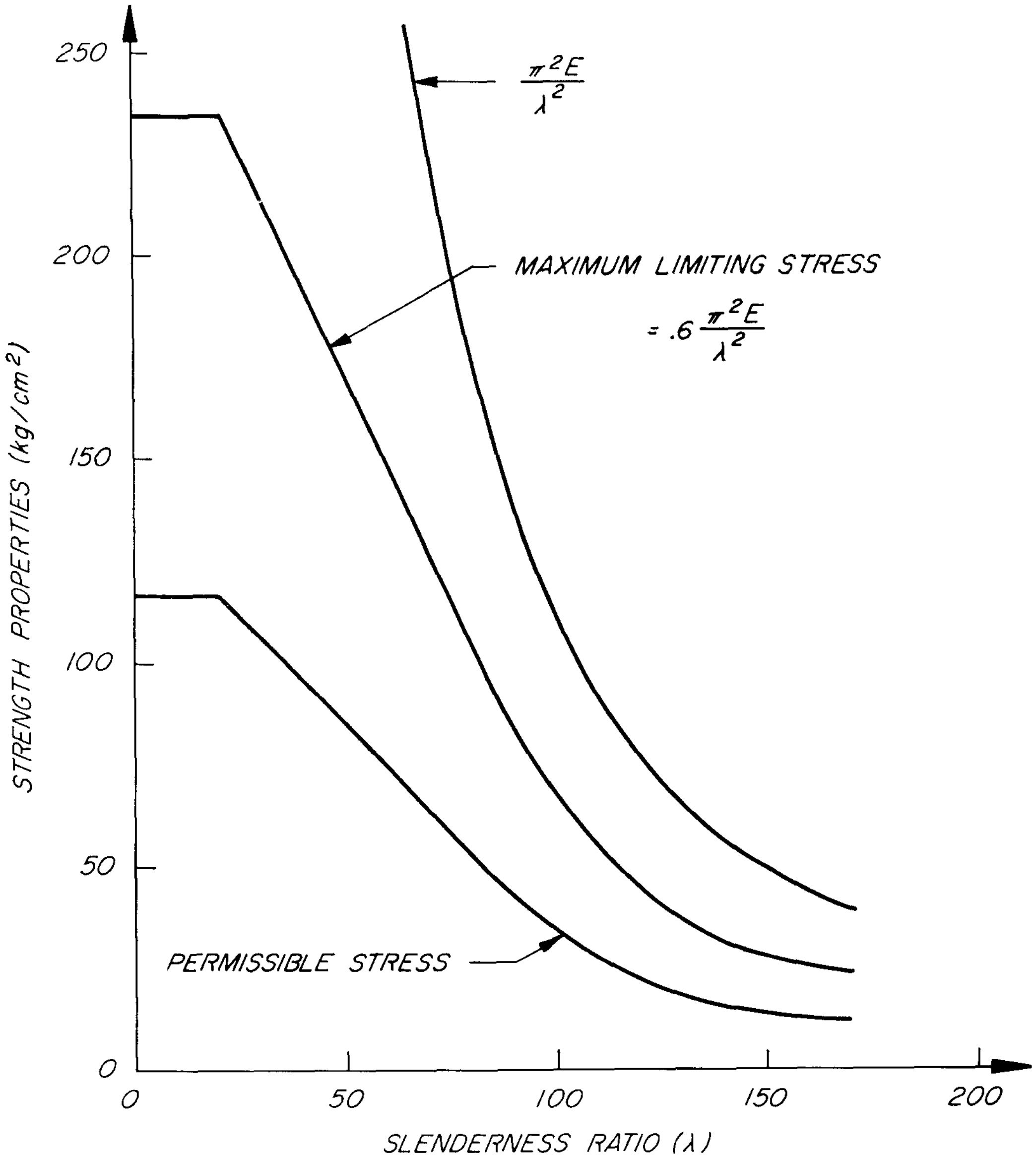

FIG. 8. Relation between slenderness ratio, λ, and permissible stress, proposal for maximum limiting stress under fire conditions, and Euler-Hyperbola (Odeën 1970).
(M 145 182)

mature failure by end crushing rather than by a buckling mode of collapse.

In laminated columns the *species* and *adhesive* employed can influence fire endurance (Malhotra and Rogowski 1967). Douglas-fir appears to be a better species than western hemlock, and phenolic, resorcinol, or urea adhesives are better than casein. The *grade* of the lumber used has no additional influence on fire endurance time. Its compensation in design stress is adequate to account for influence on endurance time.

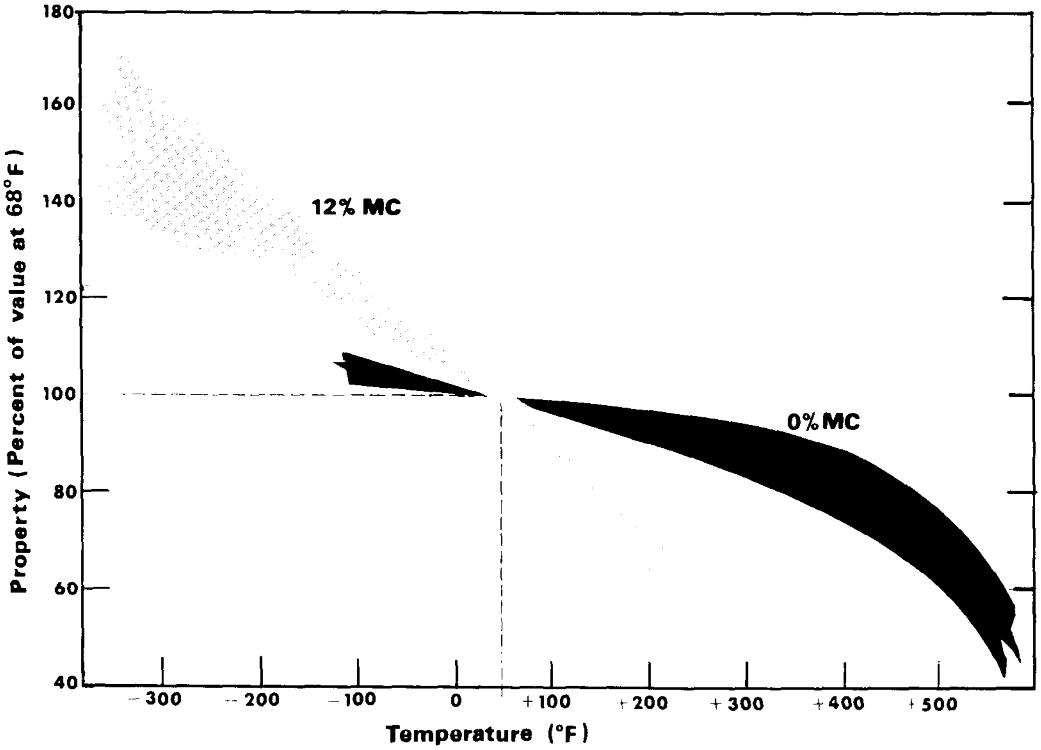

FIG. 9. Modulus of elasticity of wood versus temperature at 0 and 12% moisture content (Forest Products Laboratory 1974).
(M 141 136)

Reducing *applied load* (as a percent of maximum design load) substantially and controllably increases endurance time.

PREDICTING STRENGTH AND THERMAL RESPONSE OF WOOD

Fundamental to predicting the response of loaded structural elements is the need for basic data on the response of the material itself. Significant progress has been made in recent years in obtaining data requisite to predicting the response of structural wood elements subjected to elevated temperature. This information is briefly presented as an interpretation of the best available.

Modulus of elasticity

The change in modulus of elasticity with increasing temperature was surveyed by Galligan for the Wood Handbook (Forest Products Laboratory 1974) (Fig. 9). It is seen that the modulus decreases uniformly with increasing temperature. The width of the band reflects the variability found in the literature.

Compressive and tensile strength

Schaffer (1973) and Knudsen and Schniewind (1975) conducted tests of the properties of wood parallel to its grain at temperatures up to the charring point of wood (about 288 C or 550 F). Schaffer used bone dry specimens, and Knudsen and Schniewind used specimens initially at 12% moisture content.

Compressive strength decreases rather uniformly with temperature (Fig. 10), but, after cooling, much residual strength is retained.

When the wood is bone dry, tensile

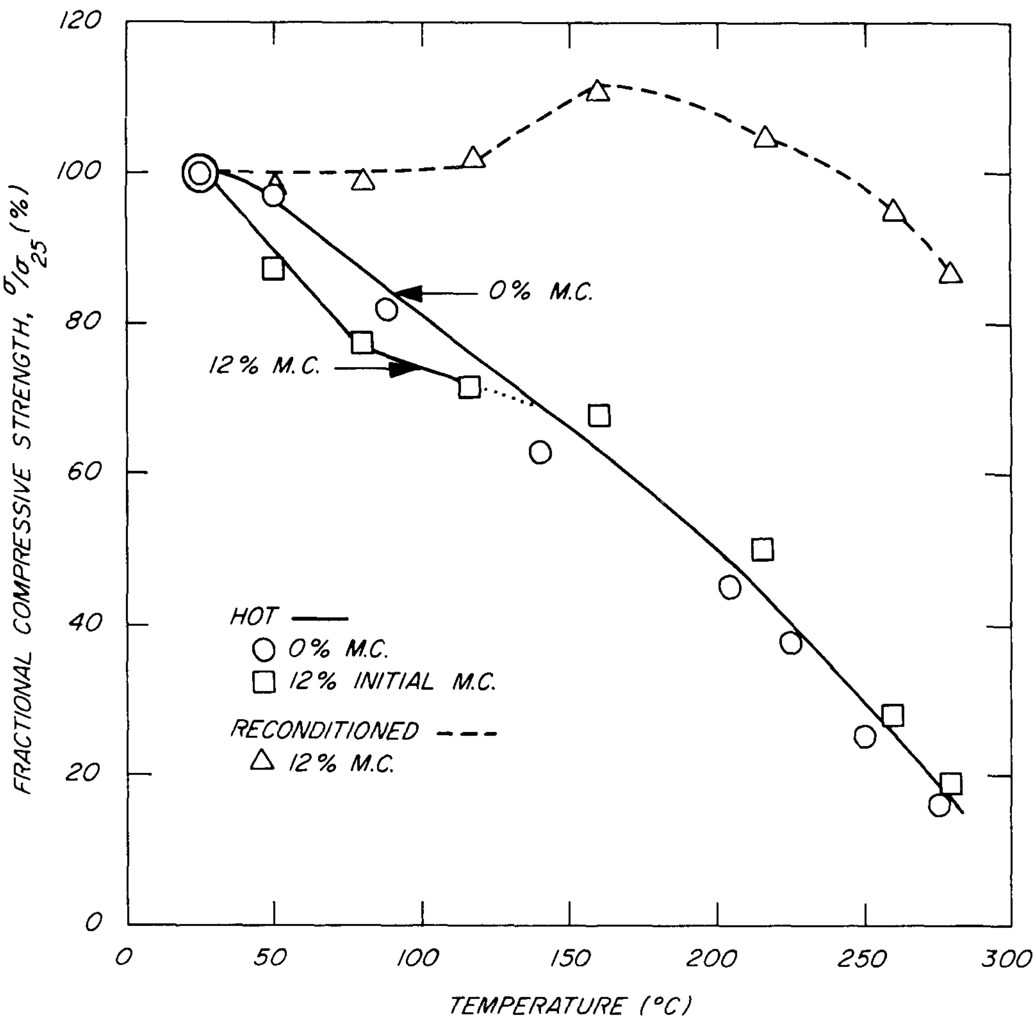

FIG. 10. Compressive strength as function of temperature while hot as well as after cooling (Schaffer 1973; Knudsen and Schniewind 1975).
(M 145 174)

strength (Fig. 11) appears to decrease slowly with temperature increase up to 200 C. Having some moisture present by testing with an initial 12% moisture content severely decreases tensile strength in the same range. Above 200 C the decrease is similarly independent of initial moisture content. Strength-after-cooling is only seriously reduced by temperatures above 200 C. Many of these effects can be explained on the basis of the changing physical character of the wood due to chemical alteration (e.g., see Schaffer 1973).

Strain to failure

As an indication of thermal changes in dry wood, the total strain to failure as measured in ramp loading tests is most informative (Fig. 12).

In tension, strain to failure is uniform to 140 C. Between 140 and 240 C, the strain

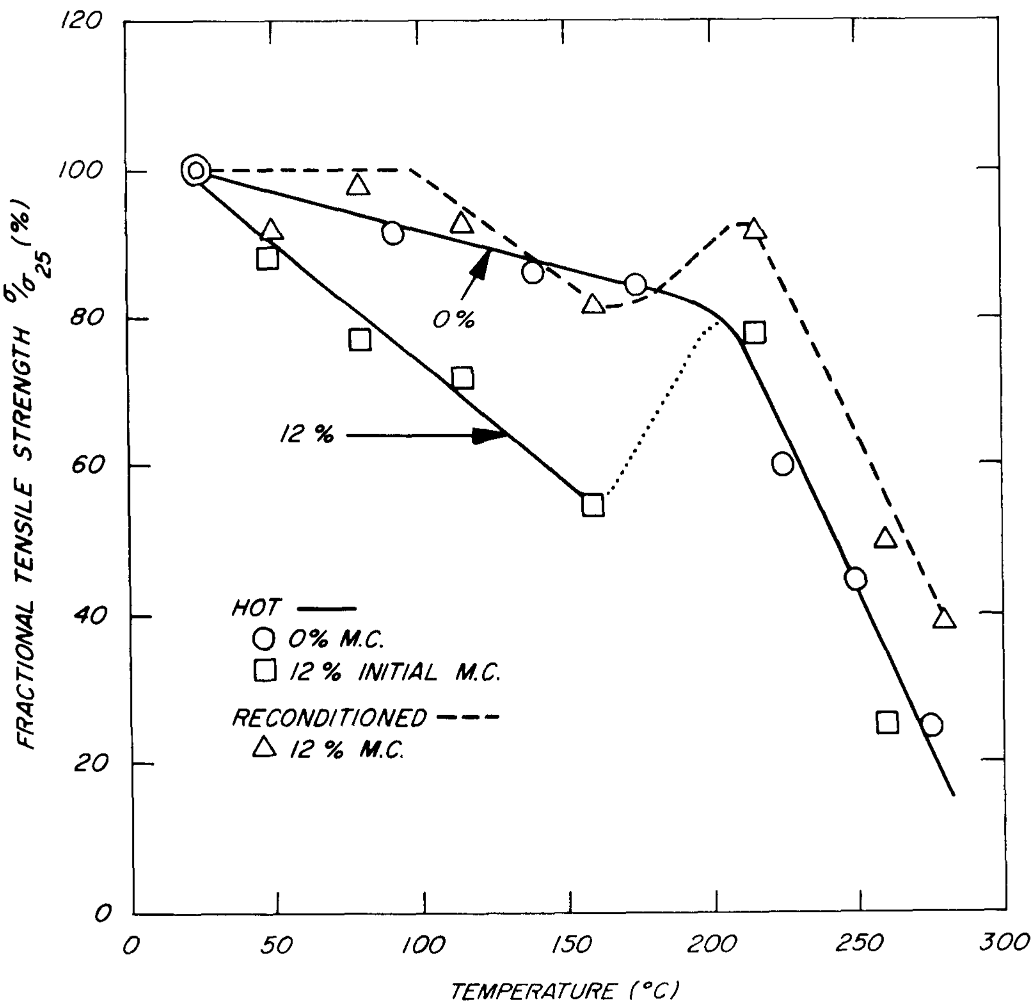

FIG. 11. Tensile strength as function of temperature while hot as well as after cooling (Schaffer 1973; Knudsen and Schniewind 1975).
(M 145 176)

becomes very large or almost plastic in its response. Above 204 C, the strain uniformly decreases. Compressive strain decreases uniformly with increasing temperature in contradiction to the tensile response found between 140 and 204 C.

Time-dependent deformation

The deformation response of wood is known to exhibit both elastic and time-dependent plastic (viscoelastic plastic) character under applied stress (e.g., see Schniewind 1968). In the parallel-to-the-grain direction, only the response of bone-dry Douglas-fir has been explored over a wide temperature range (25 to 280 C) (Schaffer 1971). It was concluded that creep deformation is best represented by a nonlinear (in stress) viscoelastic-plastic model that includes separate mechanically induced and thermally induced contributions. The thermally induced creep was largely irrecoverable shrinkage of the wood and was shown to be directly related to mass loss with duration of heating. The

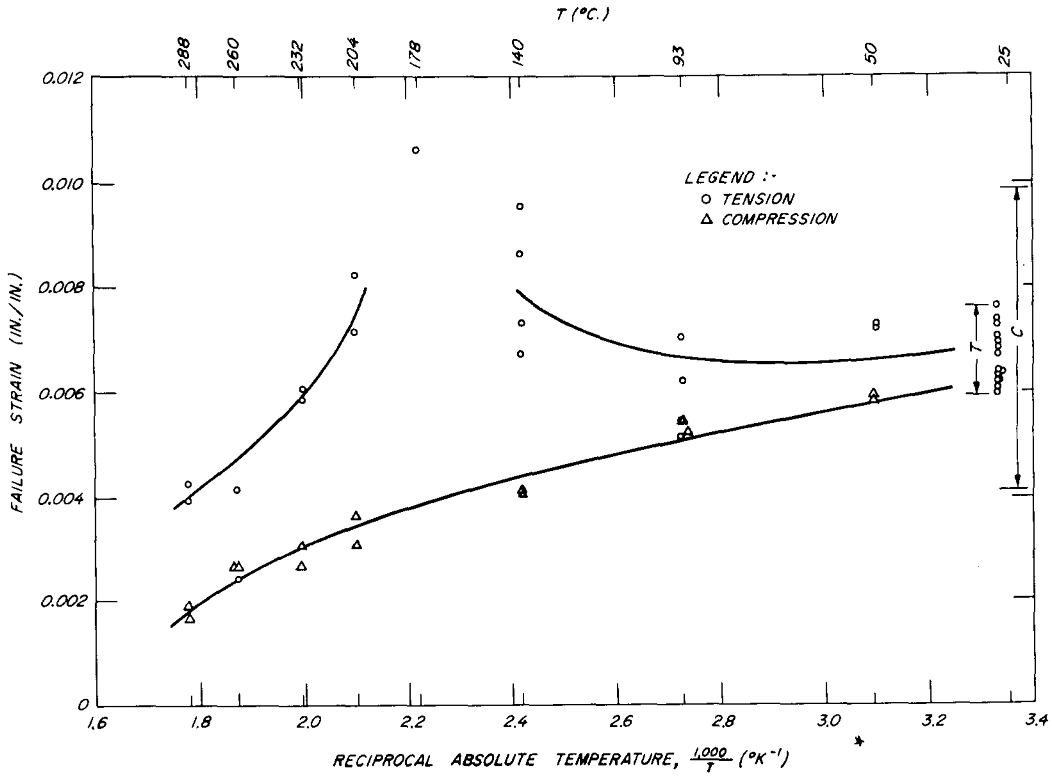

FIG. 12. Total strain to failure during ramp strength tests (T: range in tensile data at 25 C; C: range in compressive data at 25 C) (Schaffer 1973).
(M 138 481)

mechanically induced deformation was found to be a sum of a recoverable and an irrecoverable (viscous) component. This creep model was:

$$\epsilon_c = (\sigma_1/\sigma_0)^n \sum_{i=1}^{2} D_1^{(i)}[1-\exp(-t/a_T\tau_i)]/a_T$$
$$+ \zeta_1 \sum_{i=1}^{2} \alpha_1^{(i)}[1-\exp(-t/a_T\tau_i)]$$
$$+ (\sigma_1/\sigma)^n D_1^s t^m/a_T, \qquad (9)$$

where

σ_1 = applied stress,
σ_0 = strength at 25 C,
n = $\begin{cases} 1.07 \text{ tension,} \\ 1.54 \text{ compression,} \end{cases}$
$D_1^{(i)}$, D_1^s = constant terms of mechanical creep compliances,
ζ_1 = T_1 (°K) − 298,
T_1 = wood temperature,
$\alpha_1^{(i)}$ = constant terms of thermal creep compliance (shrinkage),
$a_T\tau_i$ = retardation times, and
a_T = $A\exp[-(\Delta E/R)(1/T_0-1/T)]$.

Further effort is underway to determine the parameter levels. Of special note was the finding that both recoverable and irrecoverable creep components exhibited the same temperature dependency necessary for simple thermo-rheologic behavior.

Similar effort for parallel-to-grain deformation response as influenced by both temperature and moisture was examined by Bach (1965). The range in temperature investigated was 30 to 70 C (86 to 158 F) and in moisture content from 4.3 to 15%. He correlated the total, recoverable, and irrecoverable time-dependent creep to the model:

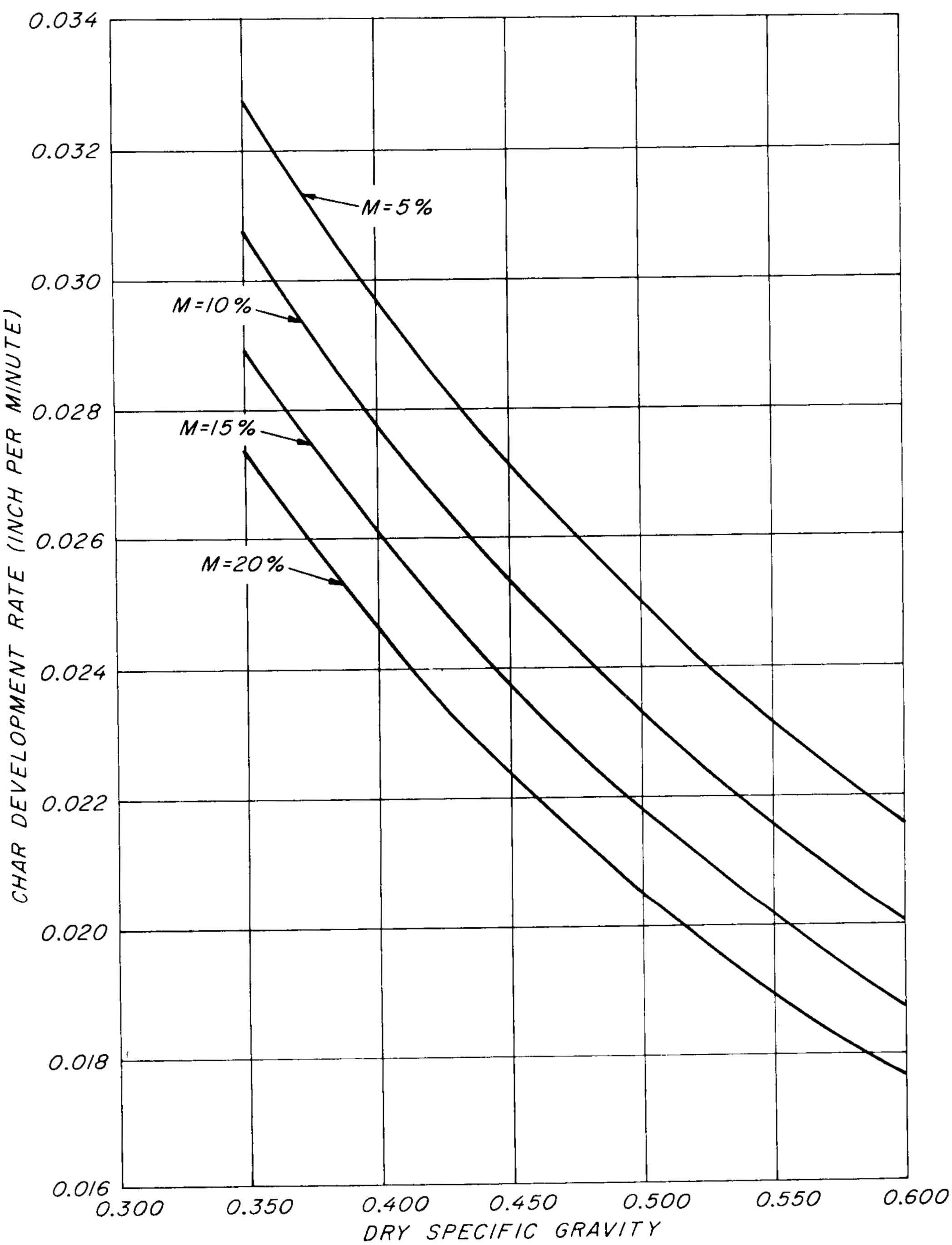

FIG. 13. Normal-to-the-grain charring rate of coast Douglas-fir under standard fire exposure (Schaffer 1967).
(M 130 376)

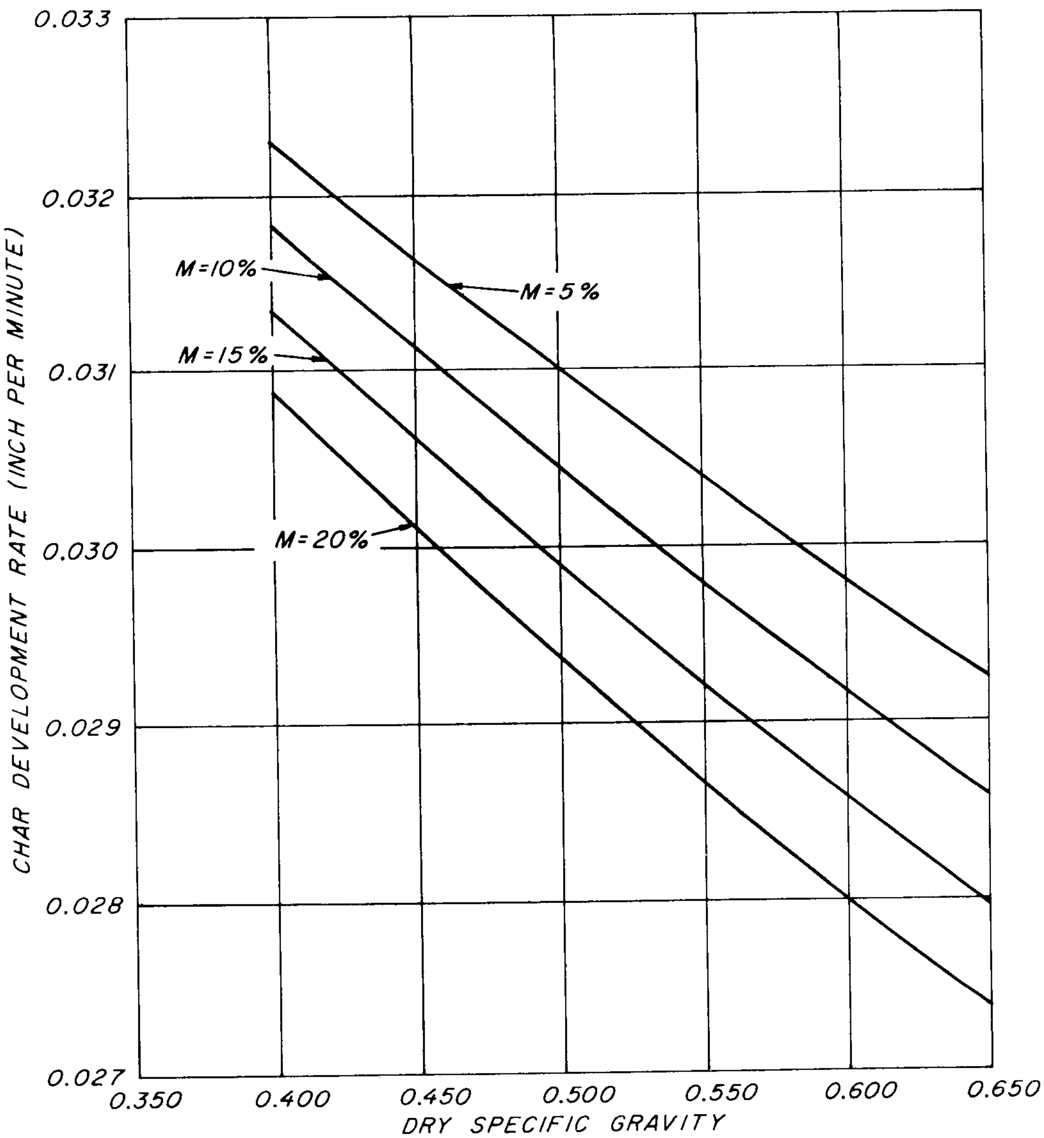

FIG. 14. Normal-to-the-grain charring rate of southern pine under standard fire exposure (Schaffer 1967).
(M 130 377)

$$\epsilon/\sigma = J(t) = [A(T, mc) + B(T, mc) \cdot \log t] \cdot \log t . \quad (10)$$

The creep was found nonlinear with respect to applied stress. The standard error of the estimate was rather large, which is a common problem in creep experiments with wood.

CHARRING OF WOOD[5]

Heavy members

Lumber bonded with phenolic or resorcinol adhesives will have charring rates (normal-to-the-grain) equivalent to solid

[5] See Appendix B for special nomenclature.

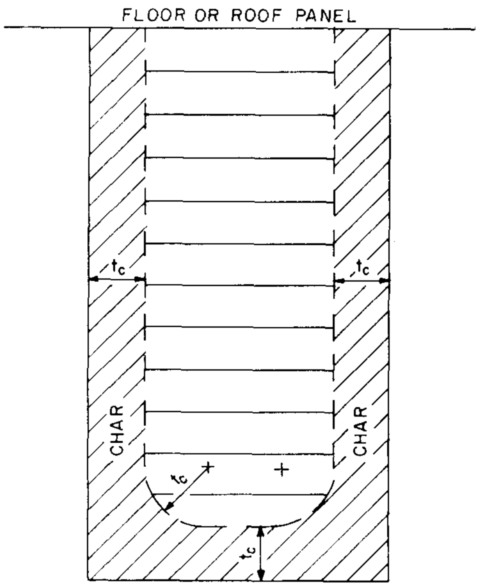

FIG. 15. Charring at corners of beams and columns produces a curve of radius equivalent to the char depth along the sides (Ollis 1968).
(M 141 777)

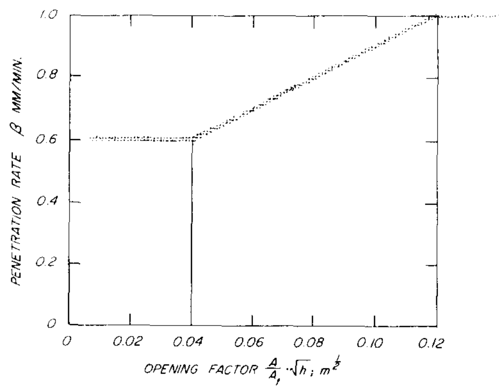

FIG. 16. Charring rate influenced by window opening in a compartment fire; A: Area of window, h: Height of window, A_t: Total room surface area.
(M 145 175)

wood (Rogowski 1967). The effect of moisture content and dry specific gravity of coast Douglas-fir is shown in Fig. 13 (Schaffer 1967). At 12% moisture content, Douglas-fir chars at 1/40 inch per min or 1.5 inch per h under standard fire exposure. The charring rate for southern pine is shown in Fig. 14. Several researchers report 30 to 60% higher charring rates into horizontal base laminates of glulam beams than into vertical sides (Dorn and Egner 1961; Imaizumi 1962).

It is important to recognize that the *corners* of beams and columns become increasingly rounded with increasing char depth. Ollis (1968) has estimated the radius of the "rounds" to be equivalent to the char depth (Fig. 15). The type of *adhesive* employed in the bonding of large members can have a significant effect on charring due to heat-induced delamination at a glueline that is uniformly heated (such as the glueline on the bottom laminate on beams and outer laminates on columns). Generally, phenolic or resorcinol adhesives have established reliability under fire exposure because of their thermal and moisture stability. Neither influences charring rate (Dorn and Egner 1961; Imaizumi 1962; Rogowski 1967; Schaffer 1967; 1968). Casein-glued laminations appear to have charring rates comparable to phenolic- and resorcinol-bonded wood if outer laminates are thick enough to meet desired fire endurance time (e.g., outer laminates greater than 1½-inch thick for 1-h endurance) (Rogowski 1967; Schaffer 1968). Urea glue presently allows both increased charring rate and separation as a heated zone develops in the timber.

Some fire-retardant impregnations can decrease the rate of charring by 20% (Rogowski 1967; Schaffer 1974). This is likely due to the higher proportion of char produced and resultant improved thermal protection afforded the wood beneath it. Fire-retardant coatings do not reduce the charring rate, but do inhibit the onset of surface charring.

For one coating, this delay was about 8 min in a standard fire (Granholm n.d.) and corresponded to a char depth difference of 5 mm (0.2 inches). Note: It is important to recognize that though charring rate can be slowed by using fire-retardant impregnations, it is possible that wood strength is affected deleteriously. This can result in

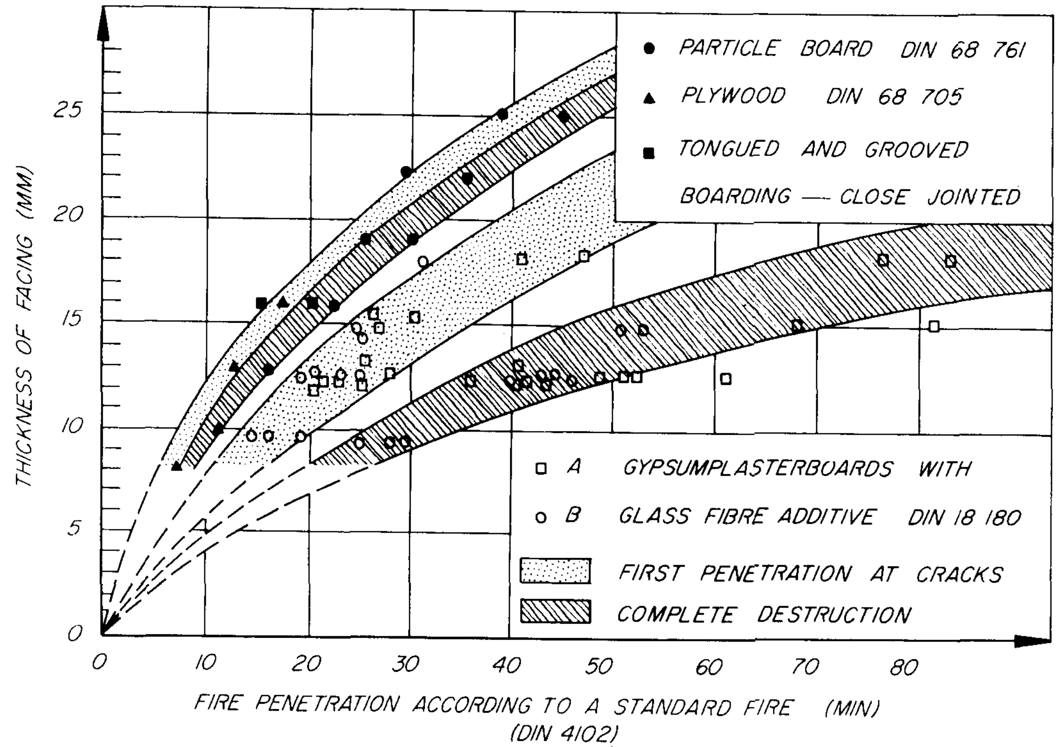

FIG. 17. Fire penetration of panels according to a standard fire (DIN 4102) (Meyer-Ottens 1967). (M 145 184)

negligible improvement in fire endurance of loaded members (Rogowski 1967).

There is presently no reported effect of the *load* applied to beams or columns on charring rate (Rogowski 1967).

Species can have a distinct influence on charring rate and is largely dependent upon density and permeability. The less dense and more permeable species char at a higher rate. White oak is especially resistant to charring due to its low permeability (Schaffer 1966, p. 168; 1967; Tenning 1967; Rogowski 1967).

Ventilation rate is known to have an effect on fire severity for a given combustible load in compartments. Tenning (1976) has reported that the charring rate increases with window opening to room size ratio (Fig. 16). This is of importance in cases where nonstandard fire exposures are of interest.

Fire exposure level as indicated by temperature also affects the char development rate. Charring data and a predictive model are given by Schaffer (1967).

Panels

Meyer-Ottens (1967) reports that the charring through of particleboard (DIN 68-761) and plywood (DIN 68-705) panels varies with the square of the thickness (Fig. 17). A 25-mm (1-inch) panel requires about 44 min to completely destruct. The charring through of 25-mm-thick vertical wood boards of several species varies from 23 to 43 min (Schaffer 1966, p. 168) in ASTM E 119 fire exposure. The time appears to be influenced by species density, grain orientation, and permeability (Table 3).

Kanury (1973; 1975) indicates that the char depth, χ_c, of wood panels of thickness l is given approximately as a function of time by:

TABLE 3. *Burn-through rate for vertically fire-exposed 1-inch boards of ten American species under ASTM E 119 fire exposure (Schaffer 1966)*

Species	Rate
	In./hr.
White oak	
quartersawn	1.39
mixed	1.50
flatsawn	1.625
White pine	
quartersawn	1.64
Cypress	1.74
Chestnut	
quartersawn	1.76
Red oak	
quartersawn	1.87
Birch	
flatsawn	2.03
Sugar maple	
flatsawn	2.12
Sugar pine	2.13
Basswood	
flatsawn	2.50
Southern pine	
flatsawn	2.59

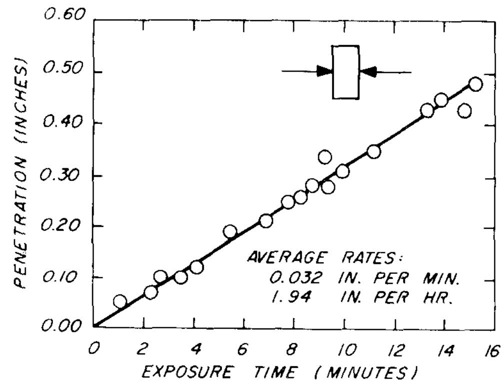

FIG. 18. Charring of Douglas-fir 2 by 4's (1⅝ × 3⅝ actual) perpendicular to the grain as function of duration of standard fire exposure. (M 145 173)

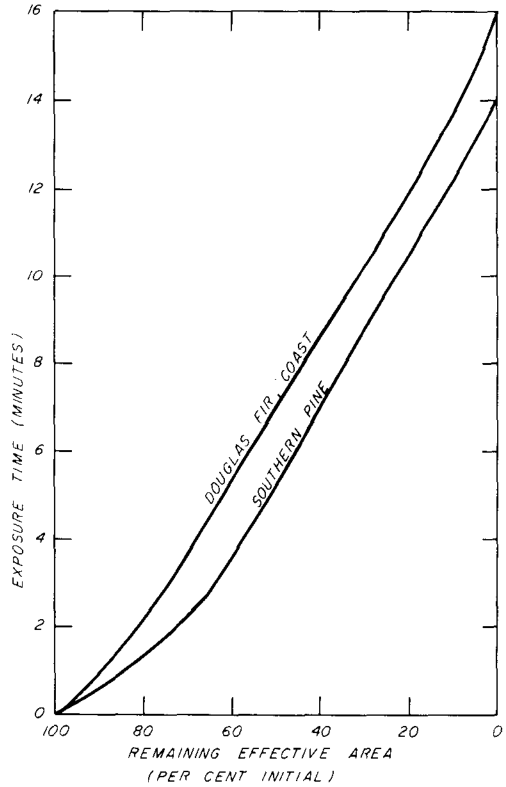

FIG. 19. Residual uncharred area of Douglas-fir 2 by 4's (1⅝ × 3⅝ actual) as function of standard fire exposure. (M 145 177)

$$(1-\chi_c/l)^2 \approx (1-t/t^*), \qquad (11)$$

where t^* is the time to char initiation on the non-fire-exposed face as given by:

$$t^* = al + bl^2, \qquad (12)$$

where a is a function of heating rate $\dot{q}_0$, heat of pyrolysis, Q_p, and heat storage of wood:

$$a = (1/\dot{q}_0) \cdot [\tfrac{3}{2}Q_p(\delta_w - \delta_c) + \delta_w C_{pw}(T_p - T_\infty)], \qquad (13)$$

and b is a function of thermal diffusivity, α_w:

$$b = l/6\alpha_w . \qquad (14)$$

For times, t, much less than the time to char through, t^*, equation (11) indicates that the char depth develops at a linear rate:

$$\chi_c/l \approx t/2t^*. \qquad (15)$$

In addition, the rate of charring, β, for thick panels (or beams) may then be approximated by "$2/a$" for fire exposure times that do not significantly increase interior regions above that initially. Employing typical values for the parameters in the equation for "a" results in charring rates close to the rule of thumb rate of 0.6 mm per min ($1/40$ in./min) (Kanury 1975). Because $a/b = 10$ for wood, the term bl^2 only begins to add significantly to the burn-through time when the thickness is greater than 1 cm. This prediction is similar to the phenomena found by Meyer-Ottens (1967).

Vorreiter (1956) observed the most interesting fact that plates held horizontally over gas flames char at a rate higher than when vertical. This is consistent with the findings of higher charring rate along the bottom of beams when exposed to fire (Dorn and Egner 1961; Imaizumi 1962).

Lumber

Information on the charring of dimension lumber was developed by this author for nominal 2 by 4's (1⅝ by 3⅝ inches). Douglas-fir 2 by 4's that were subjected to tensile load and standard fire condition (ASTM E 119/(ASTM 1973)) on all sides resulted in dimension and area reductions with time (Figs. 18 and 19).

British works on the depth of char development on the sides of Douglas-fir and spruce joists, from 2 by 4's through 2 by 9's, report an average rate of 1/40 inch per min (Lawson et al. 1951; 1952). No predictive charring models have been proposed for lumber exposed to fire.

TEMPERATURE DISTRIBUTION

Accurately predicting the temperature distribution in a charring material requires the solution of interacting mass and energy equations employing digital computer techniques (Bamford et al. 1946; Kung 1972; Kanury 1972; 1973; 1975). Kanury (1975) offers solutions that vary from the approximate to the exact.

For practical purposes, designers would appreciate either single solutions in the form of an equation or dimensionless parameters in graphical solutions for the temperature distribution in the virgin wood. This is so that changes in deformation and strength properties may be properly corrected for the influence of temperature.

For heating of thick materials prior to onset of charring, Carslaw and Jaeger (1965) provide temperature distribution estimates for constant heat input, $\dot{q}_0$:

$$T - T_0 = (2\dot{q}_0/k)(\alpha t)^{\frac{1}{2}}\, \mathrm{ierfc}[x/2(\alpha t)^{\frac{1}{2}}], \quad (16)$$

where $\mathrm{ierfc}(u) = \dfrac{2}{\sqrt{\pi}}\displaystyle\int_u^\infty (\phi - u)e^{-\phi^2}\,d\phi.$

It can be assumed that this will predict the temperature distribution for the first 5 min of standard fire exposure.

A second equation has been proposed (Schaffer 1965) to practically prescribe the temperature distribution in the virgin wood below the char wood interface at a distance, ξ, once a quasi-steady-state charring condition has been reached. (This occurs about 15 to 20 min after initiation of fire exposure.) The equation is:

$$T - T_0/T_c - T_0 = \exp[-\beta\xi/\alpha], \quad (17)$$

where:

T_c = char-wood interface temperature of 290 C (550 F), and
T_0 = initial wood temperature.

The temperature distribution for times between 5 and 15 min would require interpolation, as no satisfactory solution is evident at this time.

Kanury (1972) provides estimates for the temperature distribution in solid panels exposed to fire on one side. Improved predictions of temperature and degrade of wood are currently being sought (e.g., Kansa et al. 1977).

MOISTURE CONTENT DISTRIBUTION

Because moisture can be driven by a thermal gradient, and moisture can significantly affect the strength properties, the moisture distribution should be ascertained with respect to time. Schaffer and Duff[6] examined the distribution in charring thick wood slabs of Douglas-fir and found the response with time (Fig. 20). The maximum moisture peak seemed to coincide with a temperature level of 60 C (140 F) and settled into only a 2% difference from the initial level of 16% well into the exposure period. The moisture content peak can be described as a "front" that moves into a fire-exposed section in a fashion that is correlated with location of the interface between charred and uncharred wood (Fig. 21). In these cases, the moisture front stabilizes its location with respect to the char interface (char base) at about 1 inch. This 2% difference and gradient shape was also measured by Dorn and Egner in a beam after fire exposure (1961). Temperature level associated with the peak was about 71 C (160 F). From this information one can conclude that the wood progressively becomes drier above 60 to 70 C in fire exposure. Modeling of this response is an active research area.

FUTURE DIRECTIONS AND NEEDS

Because of the current requirements to provide effective *barriers* to fire growth, this paper has largely focused on what is

[6] Schaffer, E. L., and J. Duff. 1965. Unpublished research. U.S. Dep. Agric. For. Serv., For. Prod. Lab., Madison, Wis.

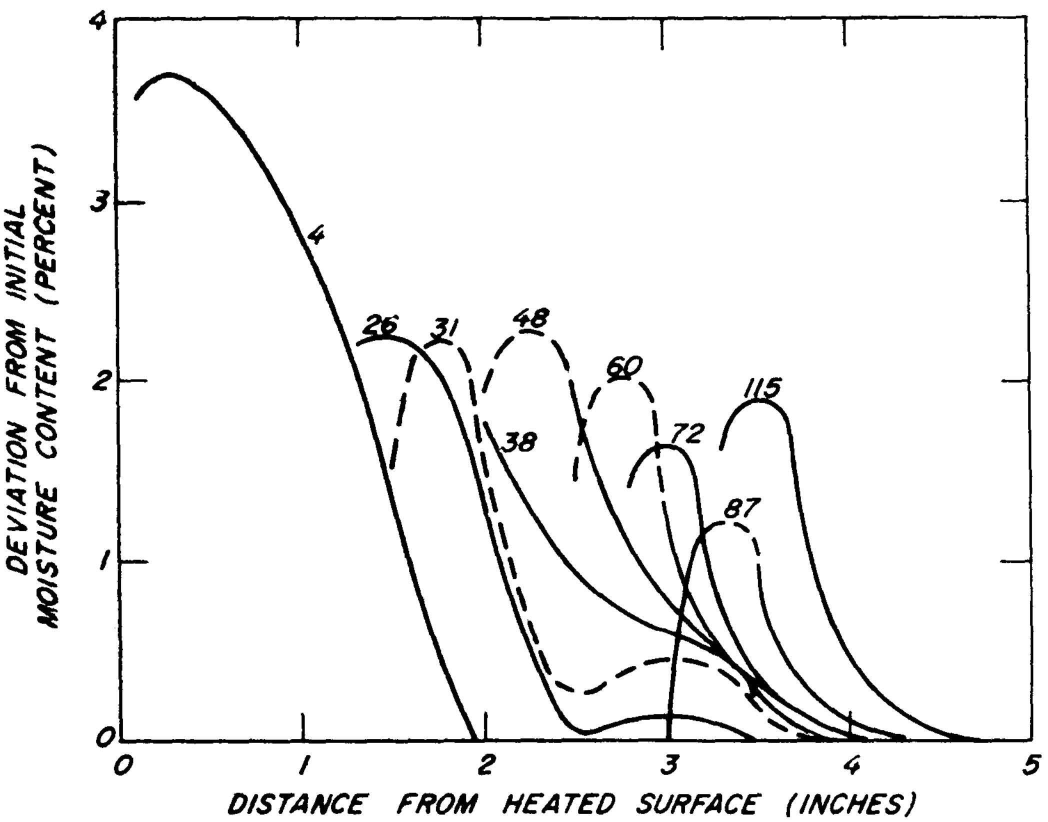

FIG. 20. Moisture gradients in charring Douglas-fir slab (7.5 in. thick) exposed to standard ASTM E 119 fire on one surface (time in minutes is indicated at each peak) (Schaffer and Duff 1965, unpub.).
(M 132 348)

available to predict the fire endurance of beams, columns, and components of wood-base materials under "standard" fire conditions. This has been useful in comparing one design type with another. However, it has been known for some time that actual fires grow and decline as a function of fire load and local conditions (e.g., vent size, if any; moisture present; etc.). As a result, engineers have been concerned with providing practical answers to barrier performance under "standard" fire conditions without being sure they are realistically measuring the actual fire protection being furnished by such barriers.

STOCHASTIC MODELS AND ANALYSIS

Assessing the likelihood of failure of materials or structures when exposed to variable fire conditions is analogous to current efforts to estimate failure probability of structural elements under loads encountered, with varying frequency, in buildings. Successes in the latter area are already being recognized as providing realistic views of failure likelihood, and code changes to accommodate such information are well underway.

Such risk analyses require estimates (or measures) of both the variability in properties of structural elements and variability of in-service expected loads. The same type of analysis can be developed for fire performance of materials and structures. Needed is the definition of the common variable that describes both "fire load" and

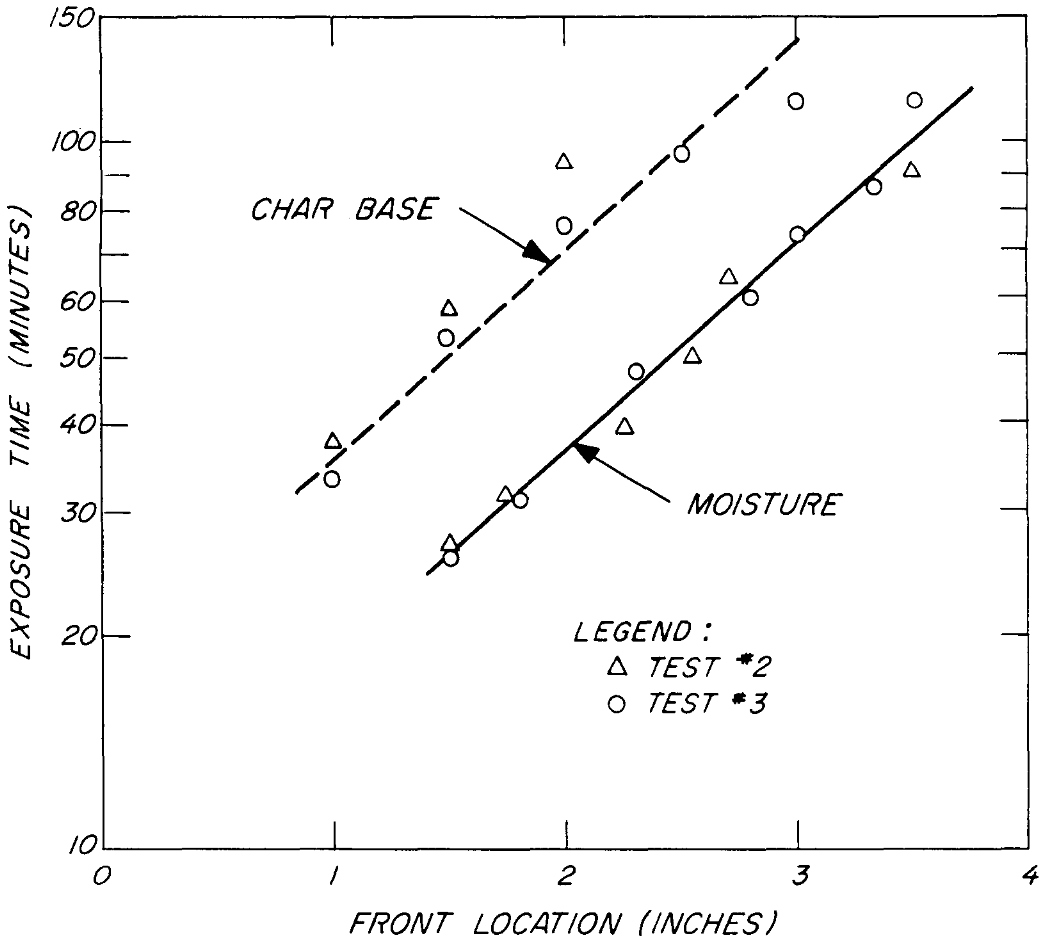

FIG. 21. Location of moisture peak and char base in a charring 190-mm (7.5-inch) Douglas-fir slab under ASTM E 119 fire exposure.
(M 145 185)

"structural fire resistance" so that generation of the analysis and collection of appropriate data may begin.

Also required is more care in reporting of test data so that estimates of property and results variability are presented. This has been a shortcoming in much past reporting.

THERMAL PROPERTIES

There is a continuing need for an improved data base on the thermal properties of wood and wood-based materials. Special attention should, again, be given to reporting both mean levels and measures of variability of such data.

COST EFFECTIVENESS

Providing the degree of "barrier" fire protection for a given building type consistent not only with life safety or property safety, but with "costs" of doing so requires further development. Ideally, maximum fire protection is desired. Realistically, a degree of risk must be assumed to keep cost of fire protection within reason. Methods are needed to optimize this balance. Baldwin (1975) discusses British efforts in this area.

No similar activity has been reported in North America.

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Appendix A

1972 Wisconsin Administrative Code Section Industrial 51.046 (WDLIHR 1972)

Ind. 51.046 Calculation Method. (1) The rational design of structural members for fire resistance shall be submitted to the department and shall be based on the type of span (simple or restrained), the magnitude of longitudinal restraint, accepted structural engineering principles and methods.

a. Appropriate research data and design criteria to substantiate the method, interpreting between known information, shall accompany the above material and shall include:

1. Time-temperature relationship ASTM E 119.
2. The temperature-strength characteristics of the structural components.
3. The time-temperature characteristics of the insulating material, at temperature range designated by ASTM E 119.
4. The expansion characteristics of the materials comprising the member, at the temperature range designated by ASTM E 119.

Note: 1. For ASTM E 119 standard adopted, see Ind. 51.25 (90).
2. The [Wisconsin] department [of Industry, Labor, and Human Relations] will accept published research data from Portland Cement Association, American Iron and Steel Institute, and American Institute of Steel Construction, Inc.

5. The safety factor of not less than 1.0 shall be maintained at the end of the time requirement for the full design live and dead load.

Appendix B

Nomenclature for "Charring of Wood" section

Term	*Wood value range*
β—char rate	(= 0.6 cm/min)
χ_c—char depth	
l—slab thickness	
t—time	
t_c or t^*—time to char through	
$\dot{q}_o$—heat input rate per unit area	(= 0.15 to 0.3 cal/cm^2 sec)
x—dimensional coordinate	
T_p—charring temperature	(= 290 C)
T—initial temperature	
ρ_w—dry specific gravity of wood	(= 0.5 to 0.7 g/cm^3)
ρ_c—dry specific gravity of char	(= 0.2ρ_w)
Q_p—heat of pyrolysis of wood	(= 75 to 100 cal/g of volatiles)
α—thermal diffusivity	(= 1.6 $\times$ 10^{-3} cm^2/sec)
ξ—($= x - \beta t$) point in wood referenced to char-wood interface	

Subscript w—wood
Subscript c—char