FIRE-RESISTIVE STRUCTURAL DESIGN

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INTRODUCTION

To provide fire safety in any structure, many approaches are considered. This involves a combination of (1) preventing fire occurrence, (2) controlling fire growth, and (3) providing protection to life and property. All need systematic attention to provide a high degree of economical fire safety. The building design professional can control fire growth within the structure by generating plans that include features such as protecting occupants either confined or exiting the structure, confining fire in compartment areas, and incorporating fire suppression and smoke-heat venting devices at critical locations. For an expansion of this topic, the reader is directed to An Interim Guide for Goal-Oriented Systems Approach to Building Fire Safety [Ref. 1).

Controlling construction features to facilitate rapid egress, protecting of occupants in given areas, and preventing fire growth or spread are regulated by codes as a function of building occupancy. If the design professional rationally blends protection solutions for these items with the potential use of a fire-suppression system (sprinklers, for example), economical fire protection can be achieved.

Although attention could be given to all protection techniques available to the building design professional, the scope here is limited to the provisions that prevent fire growth and limit the fire to compartments of origin.

PLANNING

Generating the plans for a building of prescribed occupancy is a challenge because of the varying requirements of three major regional building codes: Building Officials Conference of America (BOCA) (basic), International Conference of Building Officials (ICBO) (uniform), and Southern Building Code Congress International, Inc. (SBCCI) (standard). Canada is regulated by a separate building code. As a first step, the local jurisdiction where a proposed building is to be constructed must be consulted for the requirements of the specific design project. This normally concerns the type of construction desired as well as allowable building areas and heights for each construction type.

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Buildings constructed using wood are generally classified into types such as wood frame, noncombustible wall-wood joist, heavy timber, and noncombustible.

Wood frame construction is defined as having exterior walls, bearing walls, partitions, floors, and roofs of wood stud and joist framing of 2-in. nominal dimension. (See Table 1 for metric conversion factors.) These are divided into two subclasses that are of protected or unprotected construction. Protected construction calls for having load-bearing assemblies of l-h fire endurance.

Noncombustible wall-wood joist types of construction have exterior walls of noncombustible materials and roofs, floors, and interior walls and partitions of wood frame. As in wood frame construction, these are divided into two subclasses that are either protected or unprotected.

Heavy timber construction includes exterior walls of noncombustible materials and columns, floors, roofs, and interior partitions of wood of a minimum size, as follows:

Material	Minimum size
Roof decking	
Lumber (thickness)	2 in. nominal
Plywood (thickness)	1-1/8 in. net
Floor decking (thickness)	3 in. nominal
Roof framing	4 by 6 in. nominal
Floor framing	6 by 10 in. nominal
Columns	8 by 8 in. nominal

Noncombustible construction is generally required to be of noncombustible materials having fire-endurance ratings of up to 4 h, depending on the size and location of the building. Some circumstances provide for the use of wood in the walls of noncombustible wall-wood joist and noncombustible types of construction. For example, the Uniform Building Code allows the use of fire-retardant-treated wood framing for nonbearing walls if such walls are more than 5 ft from the property line. Exceptions to the use of noncombustible materials in the noncombustible-type buildings are sometimes made for heavy timber

Table l--Factors for converting English units of measurement to SI units.

English unit	Conversion factor	SI unit
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
lb/ft^2	4.882	$kilogram/meter^2$
lb/ft^3	16.01	$kilogram/meter^3$

members. Heavy timber members can often be used for roof members more than 25 ft above the floor, balcony, or gallery in one-story noncombustible-type buildings.

Besides having protected and unprotected subclasses for each building type, increases in floor area and height of the building are allowed when sprinkler protection systems are included. For example, protected wood frame educational occupancies can be increased from two to three stories in height because of the presence of sprinklers. Also, the floor area in the first two stories may be doubled or even tripled under some conditions.

To assist the designer, allowable height and area information for eight occupancy classifications in each of the major building codes has been assembled by the National Forest Products Association. This information is clearly presented in Code Conforming Wood Design [Ref. 2]. Similar information for the Canadian building code is contained in Fire Protection Design Manual [Ref 3.).

FIRE-RATED ASSEMBLIES

The previous section explained that some occupancies require the use of fire-rated assemblies or members to prevent collapse or fire spread from one compartment of a building to another or from one building to another. Members and assemblies are rated for their ability either to continue to carry design loads during fire exposure or to prevent the passage of fire through them. Such ratings are arrived at either by calculation or experiment for both members and assemblies. The fire exposure is defined as that given in ASTM E119 [Ref. 4].

A l-h fire-resistance rating for wall, floor, and floor-ceiling assemblies incorporating nominal 2-in. structural lumber can be accomplished through the use of noncombustible surfaces (such as gypsum wallboard). However, fastening of these surface materials is critical for ceiling membranes and is carefully specified. For some wood assemblies, 2-h ratings have been achieved.

Experimentally Rated

Experimentally rated members and assemblies are listed in the following publications:

- National Building Code of Canada, Part 9
- NBCC Supplement No. 2: Fire Performance Ratings Listings of Underwriters' Laboratories of Canada Ltd.
- Listings of Underwriters' Laboratories (UL) Incorporated (U.S.)
- Listings of the International Conference of Building Officials (ICBO)
- Listings of the Building Officials Conference of America (BOCA)
- Listings of the American Insurance Association
- Fire Resistance Design Manual [Ref. 5].
- Fire Protection Handbook [Ref. 6].

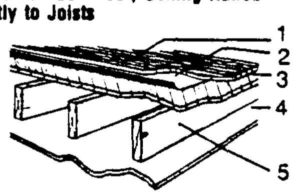
Experimental ratings are also obtained independently on assemblies and members by materials and structural member producers. For a given assembly type incorporating proprietary components, the company supplying the component can be contacted to obtain the fire rating of the assembly. Typically rated floor-ceiling assemblies are shown in Fig. 1.

Analytically Rated

In Lieu of experimentally rating the fire endurance of members and assemblies, major building codes will accept engineering calculations of the expected fire endurance, based upon engineering principles and material properties. This applies to the rating of previously untested members or assemblies, or in cases where it is desired to substitute one material or component for another.

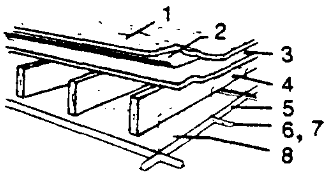
Typical One-Hour Fire-Resistive Floor-Ceiling Assemblies

Double Lumber Floor; Ceiling Nailed Directly to Joists



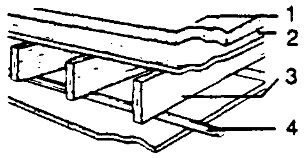
(1) 1" wood flooring; (2) building paper: (3) 1x6 T&G boards or ½" standard grade plywood with ext. glue; (4) 5/8" type X gypsum board ceiling or ½" special fire-resistive gypsum board ceiling (may be attached to resilient acoustical channels or nailed directly to joists); (5) joists 16" o.c.**

Double Plywood Floor; Ceiling Suspended in T-Bar Grid



(1) 5/8" T&G underlayment grade plywood; (2) building paper; (3) ½" standard grade plywood with ext. glue: (4) joists 16" o.c.**; (5) T-bar grid ceiling system: (6) main runners 48" o.c.; (7) cross-tees 24" o.c.; (6) ½"x48"x24" mineral acoustical ceiling panels (install with hold-down clips).

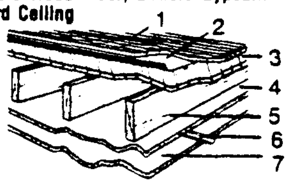
Gypsum Underlayment Compound on Plywood Subfloor; Ceiling Resilient Acoustical Channels



(1) gypsum underlayment compound; (2) ½" T&G underlayment grade plywood; (3) joists 16" o.c**; (4) 5/8" type X or ½" fire-resistive type gypsum board ceiling on resilient acoustical channels.

Two-Hour Fire-Resistive Floor-Ceiling Assembly

Double Wood Floor; Double Gypsum Board Ceiling



(1) 1" wood flooring; (2) building paper: (3) 1x6 T&G boards: (4) 5/8" type X gypsum board nailed directly to joists; (5) joists 16" o.c.**; (6) resilient acoustical channels; (7) 5/8" type X gypsum board, second layer applied on channels.

**Fire tests conducted with 2"x10" joists.

Figure l--Typical 1- and 2-h fire-resistive floor-ceiling assemblies. (Courtesy of Western Wood Products Association.)

Although calculation procedures may be conservative, they have the advantage of quickly rating an assembly or member and allowing interpolation or some extrapolation of expected performance.

Walls and Floors

An additive protection calculation procedure for both load-bearing and nonload-bearing wall-wood stud frame assemblies has been advanced and is accepted by the Southern Building Code and the Canadian Standards Association. The 2-by 4-in. nominal studs spaced 16 in. on center are assigned a minimum incremental 20-min fire endurance with any surface on both sides. The incremental times assigned to other interior wallboard membranes are given in Table 2. Additional constraints when using this information include the following:

1. Gypsum wallboard shall be installed with its long dimension parallel to framing members, and joints shall be finished.
2. Where the fire endurance is expected to occur only on one side of a wall, as on the interior side of an exterior wall, the wall is assigned a rating based upon the interior membrane materials. The membrane on the outside or nonfire exposed side may include sheathing, sheathing paper, and siding assigned an incremental time for fire endurance of 15 min or more. Possible combinations of membranes on the exterior face of wood stud walls are listed in Table 3.
3. Calculations can only be used to determine ratings up to 1-1/2 h.
4. Add 15 min to the rating of wood stud walls if the spaces between the studs are filled with rock wool or slag mineral wool batts weighing not less than 1/4 lb/ft^2 of wall surface.

Table 2--Incremental time assigned to wallboard membranes.

Description of finish	Time (min)
1/2-in. fiberboard	5
3/8-in. Douglas fir plywood, phenolic bonded	5
1/2-in. Douglas fir plywood, phenolic bonded	10
5/8-in. Douglas fir plywood, phenolic bonded	15
3/8-in. gypsum wallboard	10
1/2-in. gypsum wallboard	15
5/8-in. gypsum wallboard	20
1/2-in. type X gypsum wallboard	25
5/8-in. type X gypsum wallboard	40
Double 3/8-in. gypsum wallboard	25
1/2- + 3/8-in. gypsum wallboard	35
Double 1/2-in. gypsum wallboard	40

Table 3--Membrane of exterior face of wood study walls.

Sheathing	Paper	Exterior Finish
5/8-in. tongue and groove lumber		Lumber siding
5/16-in. exterior grade plywood	Sheathing paper	Wood shingles and shakes
1/2-in. gypsum wallboard		1/4-in. plywood exterior grade
5/8-in. gypsum wallboard		1/4-in. hardboard
		Metal siding
		Stucco on metal lath
		Masonry veneer
None		3/8-in. exterior grade plywood

This example shows how to calculate the fire endurance of a stud wall with the following construction:

2- by 4-in. studs, 16 in. on center
Interior membrane: 1/2-in. gypsum wallboard
Exterior membrane: 1/2-in. fiberboard and 5/8-in. exterior sheathing siding plywood

Insulation: Rock wool of 1/4 lb/ft^2 of wall surface

Rating calculation:

2 by 4 studs	20 min
Insulation	15 min
1/2-in. gypsum	15 min
Total	50 min

Check exterior membrane:

1/2-in. fiberboard	5 min
5/8-in. exterior plywood	15 min
Total	20 min > 15 min OK

The calculated fire-endurance rating is SO min.

In a similar fashion, the additive procedure is acceptable for wood-floor and roof-joist assemblies exposed to fire from below and having joists or rafters spaced 16 in. on center and nominal thickness dimension of 2 in. In this case, the joists or rafters are assigned an incremental rating of 10 min. The flooring or roofing material shall be at least that given in Table 4. This coincides with the rating assigned to unprotected joist-floor assemblies found in one- and two-family dwellings.

Incremental rating times for the protective ceiling membrane may be taken from Table 2. Therefore, to achieve a 1-h protected joist-floor fire-endurance rating, at least two layers of 1/2-in. type X gypsum wallboard (2 x 25 min - 50 min) would need to be attached to joists 16 in. on center (10-min increment). Experimentally tested assemblies using specific improved fastening means can achieve l-h ratings with one layer of 5/8-in. type X wallboard. This illustrates both the conservative nature of the calculation procedure and the

Table 4--Flooring or roofing over wood framing.

Assembly	Structural members	Subfloor or roof deck	Finish flooring or roofing
Floor	Wood	1/2-in. plywood or 11/16-in. tongue and groove softwood	Hardwood or softwood flooring on building paper; Resilient flooring, parquet floor, felted-synthetic-fiber floor coverings, carpeting, or ceramic tile on 3/8-in.-thick panel-type underlay; Ceramic tile on 1 1/4-in. mortar bed
Roof	Wood	1/2-in. plywood or 11/16-in. tongue and groove softwood	Finish roofing material with or without insulation

benefit achieved by giving attention to the manner and type of fastening used to attach the ceiling membrane to the joists. No benefit is assigned to the presence of insulation in the cavity between joists or rafters.

Beams and Columns

Heavy timber construction has traditionally been recognized to provide a fire-resistant building. This is primarily due to the large size of the members, the connection details, and the lack of concealed spaces. Such a construction type has often satisfied the fire-resistive requirement in all building codes by simple prescription. Although heavy timber construction has not been "rated" in the United States, Canada has assigned it a 45-min fire-endurance rating.

Some local building codes in the United States have accepted the heavy timber type as having a l-h rating if the minimum timber or lumber depth and thickness sizes, given in the first section of this paper, are increased to the next nominal dimension.

Using calculations, glulam timber columns and beams can be designed for desired fire-endurance ratings in the United States and Canada. The fire-endurance rating R, in minutes, is determined for beams or columns exposed to fire on either three or four sides by

$$R = 2.54(ZbG) \quad (1)$$

where

Z - factor dependent on load applied and member type (Fig. 2),
b - width (inch) dimension of cross section of beam or of larger dimension of a column before exposure to fire, and
G - beam or column cross-sectional factor (Table 5).

The allowable load on a beam or column is determined by employing the allowable stresses and the procedures given in the National Design Specifications (NDS) [Ref. 7,8].

Applying Eq. (1). the following example is given. What is the fire-endurance rating for a glulam beam of cross section 8.75 in. wide by 16.5 in. deep, carrying a uniform load that develops 100 percent of its allowable design stress in bending and subjected to fire exposure on two sides and at the bottom? (A deck covers the top.)

Z - 1.0 (Fig. 2)
b/d - 8.75/16.5 - 0.530
G - 4 - b/d - 3.47
R - 2.54Zb(4 - b/d) - 2.54(1.0) (8.75) (3.47) - 77 min
R - 77-min fire-endurance rating

More precise procedures are under development that allow glulam beams and columns to be designed to achieve given fire-endurance ratings, as a function of laminate grade ordering and placement.

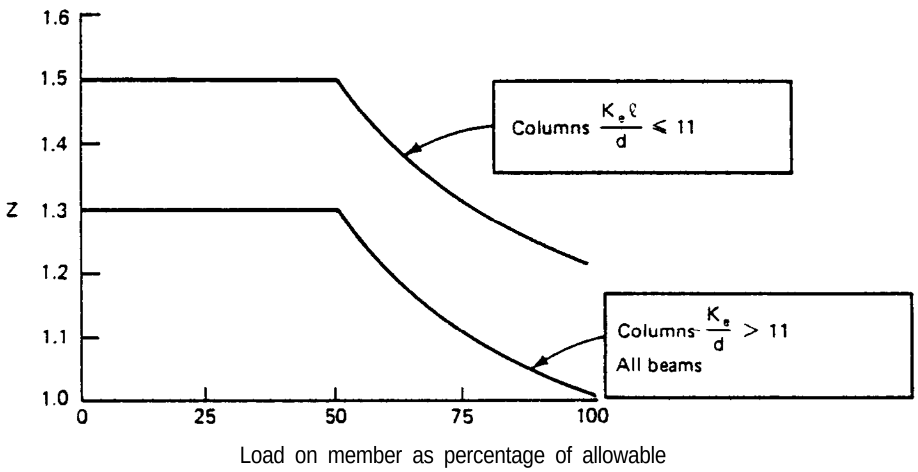
FIRE AND DRAFT STOPPING

In all construction types, no greater emphasis can be placed on the control of construction to reduce the fire growth hazard than the emplacement of fire and draft stops in concealed spaces. The spread of fire and smoke through these concealed openings within large rooms or between rooms is a continuous cause of major life and property loss. As a result, most building codes enforce detailing of fire and draft stops within building plans.

Table 5--Cross-sectional factor G for beams or columns exposed to fire on three and four sides.[a]

	Three sides	Four sides
Beam	4 - b/d	4 - 2b/d
Column	3 - b/2d	3 - b/d

[a] b = width (in.) of beam or larger side of column before exposure to fire; d = depth (in.) of beam or smaller side of column before exposure to fire.



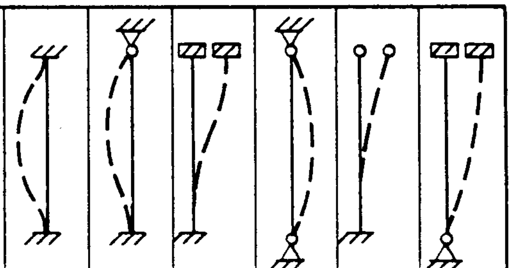
Buckling modes						
Theoretical K_e value	0.5	0.7	1.0	1.0	2.0	2.0
Recommended design K_e when ideal conditions approximated	0.65	0.80	1.2	1.0	2.10	2.4
End condition code		Rotation fixed, translation fixed Rotation free, translation fixed Rotation fixed, translation free Rotation free, translation free				

Figure 2--Determination of Z factor.

Recommendations for fire and draft stopping in wood construction have been developed by the National Forest Products Association. Refer to their brochure "Improved Fire Safety: Design of Firestopping and Draft-Stopping for Concealed Spaces." Fire stops considered acceptable are (1) 2-in. nominal lumber, (2) two thicknesses of l-in. nominal lumber, and (3) one thickness of 3/4-in. plywood with joints backed with 3/4-in. plywood.

Draft stops do not require the fire resistance of fire stops. Therefore, draft-stop material is not required to be as thick. Typical draft-stop material and their minimum thicknesses are (1) 1/2-in. gypsum wallboard and (2) 3/8-in. plywood.

Building codes consider an area between draft stops of 1.000 ft^2 as reasonable. Concealed spaces consisting of open-web floor truss components in protected floor-ceiling assemblies are an important location to draft-stop parallel to the component. Areas of 500 ft^2 in single-family dwellings and 1,000 ft^2 in other buildings are recommended, and areas between family compartments are absolutely necessary.

Critical draft-stop locations are in the following concealed spaces:

1. Floor-ceiling assemblies
2. Attics of multifamily dwellings when separation walls do not extend to the roof sheathing above

Other important locations to fire-stop in wood frame construction are in the following concealed spaces:

1. Stud walls and partitions at ceiling and floor levels
2. Intersections between concealed horizontal and vertical spaces such as soffits
3. Top and bottom of stairs between stair stringers
4. Openings around vents, pipes, ducts, chimneys (and fireplaces at ceiling and floor levels) with noncombustible fire stops

Draft stopping is not required where approved sprinklers are provided.

FLAME SPREAD

Regulation of materials used on the interior building surfaces (and sometimes exterior surfaces) of other than one- and two-family structures is provided to minimize the danger of rapid flame spread. ASTM E84 [Ref. 9] gives the method used to obtain the flame-spread property for regulatory purposes of paneling materials. Materials are classified as having a flame spread of more or less than that of red oak, which has a base of 100. A noncombustible inorganic reinforced cement board has a base of zero. A list of accredited flame-spread ratings for various commercial woods and wood products is given in

Table 6. Note that most wood products have a fame-spread rate from 75 to 250.

FIRE-RETARDANT TREATMENTS

It is possible to make wood highly resistant to the spread of fire by pressure impregnating it with an approved chemical formulation. Wood will char if exposed to fire or fire temperatures, even if it is treated with a fire-retardant solution, but the rate of its destruction and the transmission of heat can be retarded by chemicals. However, the most significant contribution of chemicals is reducing the spread of the fire. Wood that has absorbed adequate amounts of a fire-retardant solution will not support combustion or contribute fuel and will cease to burn as soon as the source of ignition is removed.

The two general methods of improving the resistance of wood to fire are (1) impregnation with an effective chemical and (2) coating the surface with a layer of noncombustible paint. The first method is more effective. For interiors or locations protected from the weather, impregnation treatments can be considered permanent and have considerable value in preventing ignition. These surface applications offer the principal means of increasing the fire-retardant properties of existing structures. However, these coatings may require periodic renewal if their effectiveness is to be maintained.

In the past, the only effective chemicals were water soluble, making fire-retardant treatments unadaptable to weather exposure. Impregnated fire retardants that are resistant to both high humidity and exterior exposures are becoming increasingly available on the market for treated lumber and plywood products, The chemicals are bound to the wood structure and cross linked to enhance their durability. The majority of these treatments are patented and trademarked.

Fire-retardant chemicals are injected into wood by the same pressure processes used in treatments to prevent decay. However, considerably heavier absorptions of preservatives are necessary for fire retardance than for protection from decay. Table 7 lists recommended retentions of fire-retardant salt preservatives such as Minalith,[2] Pyresote, and chromated zinc chloride (FR). each described in AWPA P10.

FIRE RETARDANTS

Salts such as sodium tetraborate, diammonium phosphate, trisodium phosphate, diammonium sulfate, and salts of boric acid have been used as fire retardants for several years.

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[2]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Table 6-ASTM E 84 flame-spread classifications for wood and wood products.

	Flame spread rate
Lumber, 1-in. nominal thickness	
Yellow birch	105 to 110
Eastern redcedar (1/2 in.)	110
Pacific Coast yellow cedar	78
Western redcedar	73,70
Cottonwood	115
Cypress	145 to 150
Douglas fir	70 to 100
Douglas fir (1/2 in.)	100
Red gum	140 to 155
West Coast hemlock	60 to 75
Maple flooring	104
Red or white oak	100
White pine	73
Eastern white pine	85
Idaho white pine	72
Lodgepole pine	93
Northern white pine	120 to 215
Ponderosa pine	105 to 230
Ponderosa pine (1/2 in.)	105 to 200
Red pine	142
Southern yellow pine	130 to 195
Southern yellow pine (1/2 in.)	130 to 190
Western white pine	75
Poplar	170 to 185
Redwood	70
Redwood (3/8 nominal)	95
Redwood (1/2 in.)	70 to 95
Northern spruce	65
Western spruce	100
White spruce	65
Spruce (1/2 in.)	75 to 110
Teak	76
Walnut	130 to 140
Composite products	
Fiberboard, 16 lb/ft^3, 1/2 in.	200 to 350
Fiberboard, 18 lb/ft^3, 1/2 in.	54
Flakeboard, 42-47 lb/ft^3, 1/2 in., four types	71,127,147,189
Flakeboard, red oak, 40 lb/ft^3, 1-1/16 in.	108
Hardboard, 60 lb/ft^3, 1/4 in.	130 to 200
Hardboard, 60 lb/ft^3, 0.2 in.	153
Particleboard, phenolic or urea binder, 3/8-3/4 in.	145 to 200
Plywood, phenolic or urea glue, 3/8 in. or thicker	75 to 200
Plywood, 0.1 in.	228
Plywood, 0.2 in.	205
Plywood, lauan, three-ply, 11/64 in.	167
Plywood, lauan, three-ply, 3/16 in.	69 to 271
Plywood, lauan, three-ply, urea glue, 1/4 in.	110
Plywood, Douglas fir, 1/4 in.	118
Plywood, redwood, 5/8 in.	75
Plywood, redwood, 3/8 in.	95
Plywood, walnut, 3/4 in.	130
Plywood, western species, 1-1/8 in.	56

Table 7--Recommended minimum retention of fire-retardant salts

Lumber thickness (in.)	Moderate fire retardance (lb/ft^3)	High fire retardance (lb/ft^3)
≤2	2.5	5.0
>2 to 4	2.0	4.0
>4 to 6	1.75	3.5
>6 to 8	1.5	3.0
>8 to 12	1.25	2.5
>12 to 16	0.75	1.5
>16	0.5	1.0

Many fire-retardant salt treatments are very hygroscopic. Accordingly, most formulations are not recommended for use where relative humidity is more than 80 percent. Recently, fire-retardant resin treatments have been developed that largely overcome hygroscopic and corrosion problems, but because they are proprietary, little is known of their nature.

Several studies have investigated the relationships between strength properties and fire-retardant salt treatments. The NDS [Ref. 7] recommends procedures for assigning design values for lumber pressure impregnated with fire-retardant chemicals, including both sampling and testing procedures. It also recommends procedures for qualifying fire-retardant-treated lumber and the requirements for identifying qualifying materials.

Fire-retardant treatments or coatings are used to obtain wood products with flame-spread ratings less than 75. Treated products with a special UL designation FR-5 have a flame-spread classification of not more than 25 in an extended 30-min ASTM E85 test, and no evidence of significant progressive combustion was indicated. Flame-spread ratings for other proprietary products are listed by UL.

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