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Effect of Fire-Retardant Treatments on Performance Properties of Wood

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The one million fires in buildings in the United States account for about two-thirds of the 12,000 people who die each year in fires. The property loss in building fires is about 85 percent of the total annual \$3 billion property loss in fires (1). Building contents are often a primary source of fire and are-usually responsible for fire-related deaths before structural members become involved. Nevertheless, wood and wood-base products, extensively used both as structural members and as interior finish in housing and buildings, can be contributors to fire destruction.

To reduce the contribution of wood to fire losses, much research through the years has gone into development of fire-retardant treatments for wood. A total of 21.3 million pounds of fire-retardant chemicals were reported used in 1974 to treat 5.7 million cubic feet of wood products (2). The amount of wood treated was about one tenth of 1 percent of the total domestic production of lumber and plywood and has increased ninefold in 20 years.

How does our research stand in rendering wood fire retardant? What is the effect of fire-retardant treatments on the fire performance properties of wood and on the physical and mechanical properties of wood that are important to its utility? Discussion will be limited to fire retardancy obtained by pressure Impregnation, which is currently the most effective method. Fire-retardant coatings, wood-plastic combinations, and chemical modifications of wood will not be considered.

Fire-Retardant Chemicals

Past research on fire retardants, including those for wood; from about 1900 to 1968 is reviewed in John W. Lyons' comprehensive reference book, "The Chemistry and Uses of Fire Retardants" (3). A more recent review by Goldstein (4) gives additional information on fire-retardant chemicals and treatment systems for wood and also discusses some of the topics of this

present paper more thoroughly. These two references, together with the older review by Browne (5), are recommended to the reader as basic reviews on selection and chemistry of fire retardants for wood. The chemistry of synergistic effects between chemicals in a fire-retardant system is presented by Lyons (3); it was also discussed more recently by Juneja (6,7) and recommended by him as an area of needed investigation.

Fire-retardant chemicals used by the commercial wood-treating industry are limited almost exclusively to mono- and diammonium phosphate, ammonium sulfate, borax, boric acid, and zinc chloride (4,8). It is believed that some use is also made of the liquid ammonium polyphosphates (9). Some additives such as sodium dichromate as a corrosion-inhibitor are also used. Aqueous fire-retardant treatment solutions are usually formulated from two or more of these chemicals to obtain the desired properties and cost advantages. For leach-resistant type treatments, the literature shows that some or all of the following are used: urea, melamine, dicyandiamide, phosphoric acid, and formaldehyde (10-12).

Effect of Fire-Retardant Treatment on Fire Performance Properties

What are the fire performance properties of untreated wood and how are these properties altered by fire-retardant treatments?

Ignition

Wood, like all organic materials, chemically decomposes--pyrolyzes--when subjected to high temperatures, and produces char and pyrolysis vapors or gases. When these gases escape to and from the wood surface and are mixed with air, they may ignite, with or without a pilot flame, depending on temperature. Ignition--the initiation of combustion--is evidenced by glowing on the wood surface or by presence of flames above the surface.

The temperature of ignition is influenced by many factors related to the wood under thermal exposure and the conditions of its environment (5,13,14). Factors include species, density, moisture content, thickness and surface area, surface absorptivity, pyrolysis characteristics, thermoconductivity, specific heat, and extractives content. Environmental conditions affecting temperature of ignition include duration and uniformity of exposure, heating rate, oxygen supply, air circulation and ventilation, degree of confinement or space geometry surrounding the exposed wood element or member, temperature and characteristics of an adjacent or contacting material, and amount of radiant energy present.

Reviews covering ignition of cellulosic solids by Kanury (13), Beall and Eickner (15), Browne (5), and Matson *et al.* (14) report a wide range of ignition temperatures obtained on wood, and dependence on radiant or convective nature of heat. For radiant

heating of cellulosic solids, Kanury (13) reports spontaneous transient ignition at a critical temperature of 600°C with piloted transient ignition at 300°C to 410°C. Persistent flaming ignition is reported at a temperature greater than about 320°C.

With convective heating of wood under laboratory conditions, spontaneous ignition is reported as low as 270°C and as high as 470°C (5,14,15). Spontaneous ignition of wood charcoal, which has excellent absorption of oxygen and radiant heat, occurs between 150°C and 250°C (5). In one experiment on ignition, oven-dried sticks of nine different species were ignited by pilot flame in 14.3 to 40 minutes when held at 180°C, in 4 to 9.5 minutes when held at 250°C and in 0.3 to 0.5 minutes when held at 430°C (16).

Many field reports collected by Underwriters' Laboratories, Inc. (UL) (14) show ignition occurring at or near 212°F (100°C) on wood next to steam pipes or other hot materials. Laboratory experiments have not been able to confirm these low ignition temperatures (5,14,16,17). To provide a margin of safety, Underwriters' Laboratories, Inc. suggests that wood not be exposed for long periods of time at temperatures greater than 90°F (32°C) above room temperature or 170°F (77°C). The National Fire Protection Association handbook (18) gives 200°C as the ignition temperature of wood most commonly quoted, but gives 66°C as the highest temperature to which wood can be continually exposed without risk of ignition. McGuire (17) of the National Research Council of Canada suggests that 100°C would be a satisfactory choice of an upper limiting temperature for wood exposure.

Usually the fire-retardant treatment of wood slightly increases the temperature at which ignition will take place. There is evidence, however, that wood treated with some chemical retardants at low retention levels will ignite (flame) or start glowing combustion at slightly lower temperatures or irradiance levels than does untreated wood (19,20), though sustained combustion is usually prevented or hindered.

Thermal Degradation

An extensive review of the literature to 1958 on thermal degradation of wood is given by Browne (5). Beall and Eickner (15) and Goldstein (4) add additional review information on this complex subject. Shafizadeh's (21) review of the pyrolysis and combustion chemistry of cellulose gives a basis for understanding these processes in wood and the effect of fire-retardant treatment on these processes.

Browne (5) described the pyrolysis reactions and events which occur in each of four temperature zones or ranges when solid wood of appreciable thickness is exposed to heat in absence of air. Zone A is below 200°C; Zone B, 200° to 280°C; Zone C, 280° to 500°C; and Zone D, above 500°C. These zones may be present simultaneously. When wood is heated in air, events occurring in these

temperature zones include oxidation reactions and, after ignition, combustion of the pyrolysis and oxidation products.

Goldstein (4) more simply divided the thermal degradation processes into those occurring at low temperatures, below 200°C, and those at high temperatures, above 200°C. Decomposition of wood exposed to temperatures below 200°C is slow but measurable (22,23). For example, the average loss in weight of 11 species of wood was 2.7 percent in 1 year at 93°C and 21.4 percent in 102 hours at 167°C (22). Sound wood will not generally ignite below 200°C since products evolved are mostly carbon dioxide and water vapor.

High temperature degradation processes above 200°C include rapid pyrolysis of the wood components, combustion of flammable gases and tars, glowing of the char residue, and evolution of unburned gases, vapors, and smoke.

The most widely accepted theory of the mechanism of fire-retardant chemicals in reducing flaming combustion of wood is that the chemicals alter the pyrolysis reactions with formation of less flammable gases and tars and more char and water (4,5,8,21,24-29). Some fire retardants start and end the chemical decomposition at lower temperatures. Heat of combustion of the volatiles is reduced. Shafizadeh (21) suggests that a primary function of fire retardants is to promote dehydration and charring of cellulose. The normal degradation of cellulose to the flammable tar, levoglucosan, is reduced and the charring of this compound is promoted. Shafizadeh and coworkers used thermogravimetric (TG) and thermal evolution analysis (TEA) data, to confirm two different mechanisms involved in flameproofing cellulosic materials: 1) directing the pyrolysis reactions to produce char, water, and carbon dioxide in place of flammable volatiles, and 2) preventing the flaming combustion of these volatiles (27).

Fire Penetration

The property of a wood material or assembly to resist the penetration of fire or to continue to perform a given structural function, or both, is commonly termed fire resistance. The measure of elapsed time that a material or assembly will exhibit fire resistance under the specified conditions of test and performance is called fire endurance. Large furnaces are used to measure fire endurance of walls, floors, roofs, doors, columns, and beams under the standard ASTM E119 (30) time-temperature exposure conditions.

Wood has excellent natural resistance to fire penetration due to its low thermal conductivity and to the characteristic of forming an insulating layer of charcoal while burning. The wood beneath the char still retains most of its original strength properties.

In wood charring studies by Schaffer at the Forest Products Laboratory (FPL) (31), 3-inch-thick pieces of wood were vertically

exposed to fire on one surface. Rate of char development at three constant fire exposure temperatures, 1,000°F (538°C), 1,500°F (816°C), and 1,700°F (927°C), was described by an equation with an Arrhenius temperature-dependent rate constant. When specimens were exposed to the uniformly increasing fire temperatures of ASTM E119 (earlier linear portion of time-temperature curve) (30), the rate of char development was constant, after the more rapidly developed first 1/4 inch of char. Under the standard ASTM fire exposure, temperatures 1/4 inch from the specimen surface reached 1,400°F (760°C) at 15 minutes, 1,700°F (927°C) at 1 hour, and 1,850°F (1,010°C) at 2 hours (31). When wood is exposed to these conditions, the first visual effect of thermal degradation (Figure 1) is indicated by browning of the wood at about 350°F to 400°F (175°C to 200°C). The temperature which characterized the base of the char layer was 550°F (288°C). After the first 1/4 inch of char development, the rate that this char layer moved into the solid wood--the rate of fire penetration--was about 38 millimeters per hour (1-1/2 in/hr).

Schaffer (31) found some differences in char development rate in the three species studied, Douglas-fir, southern pine, and white oak. Charring rate decreased with increase in dry specific gravity and with increase in moisture content. He also found that growth-ring orientation parallel to the exposed face resulted in higher charring rates than when orientation was perpendicular to the exposed face. In studies at the Joint Fire Research Organization in Great Britain (32) on rate of burning, increased permeability along the grain was found to increase rate of char.

Schaffer (33) found that impregnations of southern pine with certain fire-retardant and other chemicals did not significantly change the rate of charring. Boric acid, borax, ammonium sulfate, monosodium phosphate, potassium carbonate, and sodium hydroxide variously reduced the rate of charring after 20 minutes of fire exposure by about 20 percent over untreated wood. Only polyethylene glycol 1,000 reduced the rate of charring over the entire period of fire exposure by about 25 percent over untreated wood. Tetrakis (hydroxymethyl) phosphonium chloride with urea, dicyandiamide with phosphoric acid, monoammonium phosphate, zinc chloride, and sodium chloride had no effect on charring rate.

Commercial fire-retardant treatments generally do not add significantly to the fire endurance of assemblies. It is often more advantageous from the cost standpoint, either to use thicker wood members or to select species with lower charring rates, than to add the cost of the fire-retardant treatment. In some assemblies, however, it has been found worthwhile to use some fire-retardant-treated components in order to gain the extra time which will bring the fire endurance time up to the goal desired. For example, treated wood studs in walls and treated rails, stiles, and cross bands in solid wood doors have been used.

Flame Spread

In the ASTM E84 25-foot tunnel furnace test (34) for measuring flame spread of building materials, an igniting pilot flame is applied to the underside of a horizontally mounted specimen. The flame heats the combustible material to pyrolysis, and the flammable gases given off are ignited by the pilot flame. If the pyrolysis-combustion process becomes exothermic, the flaming on the specimen becomes self-propagating. A flame-spread classification or rating number is calculated from the time-distance progress of the flame along the length of the specimen surface.

The flame-spread number is derived relative to red oak (with an arbitrary flame-spread rating of 100) and to asbestos-cement board (rated zero). Natural wood products (1-inch lumber) usually have flame-spread ratings of 100 to 150 in the test furnace of Underwriters' Laboratories, Inc. (35). Some exceptions are poplar (170-185), western hemlock (60-75), redwood (70), and northern spruce (65).

Wood well treated with current commercial fire-retardant impregnation treatments will have flame-spread ratings of 25 or less. Many treated wood products have obtained a special marking or designation "FR-S" from UL (36) for having a flame-spread, fuel-contributed, and smoke-developed classification of not over 25 and no evidence of significant progressive combustion in an extended 30-minute ASTM E84 (34) test procedure. The fuel-contributed and smoke-developed classifications are also calculated relative to performance of red oak and asbestos-cement board.

Eickner and Schaffer (10) found that monoammonium phosphate (Figure 2) was the most effective of different fire-retardant chemicals in reducing the flame-spread index of Douglas-fir plywood. They used the 8-foot tunnel furnace of ASTM E286 (37). The untreated plywood had a flame-spread index of 115. This was reduced to about 55 at a chemical retention of 2 pounds per cubic foot, to 35 at 3 pounds, 20 at 4 pounds, and to about 15 at retentions of 4.5 pounds and higher. Zinc chloride was next in effectiveness but required higher retention levels to reduce the flame-spread index values equivalent to monoammonium phosphate. It required 5.5 pounds of zinc chloride to reduce flame spread to 35, and 7 pounds to reduce flame spread to 25. Ammonium sulfate and borates were as effective as zinc chloride at retentions of about 4.5 pounds per cubic foot and lower but not as effective at higher retention levels. Boric acid had some effectiveness in reducing flame spread. It was equivalent to zinc chloride, ammonium sulfate, and the borates at a retention of about 2 pounds per cubic foot, but much less effective at high retention levels. A retention of 6 pounds per cubic foot reduced the flame-spread index of the plywood to only 60.

In many laboratories, flame-spread tests of different types have consistently shown that the current acceptable treatments will

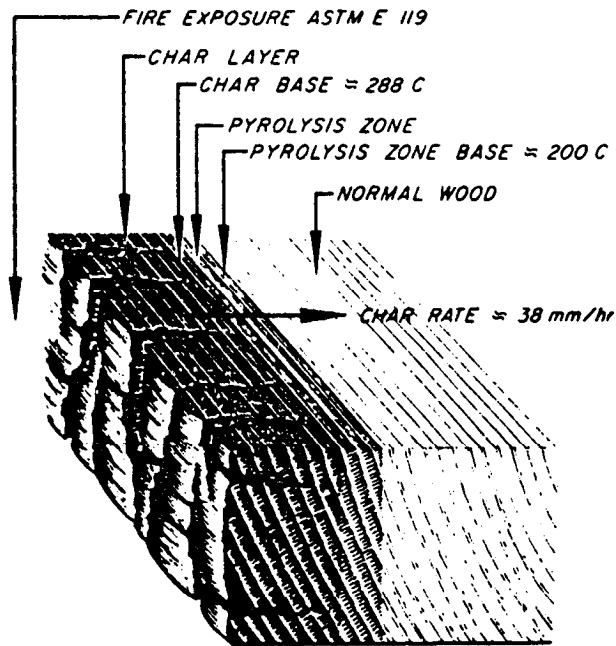


Figure 1. Fire penetration into wood and formation of char layer under the fire exposure conditions of ASTM E119

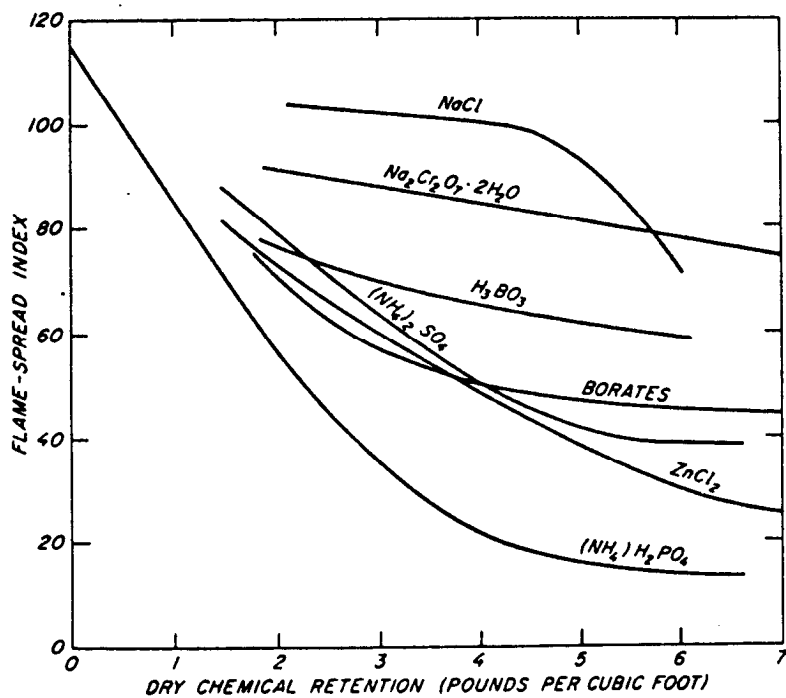


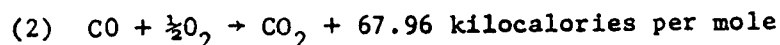
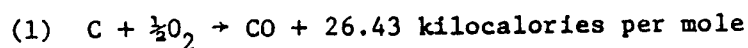
Figure 2. Relationship of flame spread to level of chemical retention in 3/8-in. Douglas-fir plywood evaluated by the 8-ft tunnel furnace method

prevent flaming combustion of the wood and prevent spread of fire over the surface. Wood, properly treated, will be self-extinguishing of both flaming and glowing once the primary source of heat and fire is removed or exhausted.

Glowing

Glowing is the visual evidence of combustion of the carbon in the char layer of the burning wood. If flaming of the released combustible gases has ceased, the glowing of the char is usually termed afterglow.

Of the several possible oxidation reactions in glowing combustion, both Browne (5) and Lyons (3) in their reviews show one possibility to be a two-stage reaction:



The first reaction occurs on the surface of the char and the second is a gas-phase reaction.

Wood that has been effectively treated should not exhibit any afterglowing. Reviews (3,5) covering the Subject of glowing point out that the mechanism involved in glow retardance is not clear. Both physical and chemical theories have been suggested. Physical methods include the exclusion of oxygen from the carbonaceous char by formation of coatings of the fire retardant during the combustion process or by a cooling effect due to the fire retardant. The chemical theory with the most supporting evidence indicates that effective glow retardance increases the ratio of CO to CO₂.

If the reaction can be directed mostly to the monoxide, step (1) above, the heat liberated is only 28 percent of that given off when the reaction continues to the dioxide. Thus glowing may be eliminated by an insufficient amount of heat to continue combustion.

Effective glow retardants for wood are the ammonium phosphates, ammonium borates, boric acid, phosphoric acid, and compounds that yield phosphoric acid during pyrolysis (3,5). Some chemicals that are reported to stimulate glowing are chromates, molybdates, halides of chromium, manganese, cobalt and copper, and ferric and stannic oxides (5,10). Chemicals found to be ineffective in retarding afterglow in a limited study were ammonium sulfate and sodium borates (10).

Combustion Products

The combustion products of burning wood--smoke and gases--are becoming of increased importance. Code and building officials, builders, producers of building materials and furnishings, and all

engaged in fire research are being directed by public interest and scrutiny toward a greater concern for the real hazard to life safety of building materials in a fire situation. A study conducted by the National Fire Protection Association (18) of 311 fatal fires in one- and two-family dwellings, including mobile homes and recreational vehicles, revealed that 73.6 percent of the deaths were caused by products of combustion resulting in asphyxiation or anoxia. In a study of fire fatalities that occurred in the state of Maryland, a Johns Hopkins University group (38) found that carbon monoxide was not only the predominant factor in hindering escape from the fire scene but was also the primary agent in the cause of death in 50 percent of the 129 cases. It was also a major contributor to death in another 30 percent of the cases in combination with heart disease, alcohol in the blood, and burns.

Visibility in a burning building is extremely important. Smoke can obscure vision and exits, thereby retarding escape and resulting in panic. It also hinders the work of firefighters. The particular fraction of smoke, exclusive of any combustion gases, acts as an irritant to the respiratory system and may also result in hypoxia and collapse (39).

Smoke from untreated wood.--or research purposes, there are several methods used for measuring smoke developed by burning building materials (40). These tests generally measure the visible smoke products. One method of smoke determination being used for building code purposes is the 25-foot tunnel furnace method of ASTM E84 which yields a smoke-developed rating relative to red oak. Because the test is conducted under a strong flame, the results are not always indicative of performance in a building fire where materials may have some high-temperature exposure without the presence of flames.

During the last decade, the National Bureau of Standards (NBS) and other laboratories worked to develop a meaningful test method for measuring the smoke development potential of burning wood and other building materials. The method developed at NBS is now extensively used (41,42). This method thermally exposes a small sample in a closed chamber and supplies a specific optical density based on light transmission, light path length, burning area, and volume of enclosure. It is intended to relate to light obscuration and the hindrance in finding exits. This method has been accepted as a standard by the National Fire Protection Association (43) and is expected to be accepted by others and more widely used for rating building materials for regulatory purposes.

The chemical makeup of the combustion products, including aerosols and particulates, will change with burning conditions and the complex processes result in complex mixtures of products (28). More smoke is produced under nonflaming combustion than under flaming combustion. The complexity of the smoke is indicated by the fact that over 200 compounds have been found in the destructive distillation of wood by Goos (45).

In complete combustion, the products from burning wood are carbon dioxide, water, and ash. Other gases and vapors that may be present due to incomplete combustion include carbon monoxide, methane, formic acid, acetic acid, glyoxal, and saturated and unsaturated hydrocarbons (46). The aerosols can also contain various liquids such as levoglucosan and complex mixtures. The solids can consist of unburned carbon particles and high-molecular-weight tars.

There is no standardized test method for determining the combustion products given off from wood or other materials during a real fire situation. The gases and products obtained and their estimated hazard to life will depend on the experimental conditions of any test method selected. Most studies on the toxicity of combustion products show that the dominant hazardous gas from burning wood is carbon monoxide followed by carbon dioxide and the resulting oxygen depletion (46-50).

Considerable research is underway by various institutions and agencies and by industry on the physiological and toxicological effects of smoke and gaseous products. Of particular note are the extensive research programs at the University of Utah under the direction on I. N. Einhorn (44,48), at Johns Hopkins University under R. M. Fristrom (38,50), and at the National Bureau of Standards under M. M. Birky (51).

Smoke from treated wood. --Fire-retardant-treated wood also produces smoke and gaseous combustion products when burned. Many commercial fire-retardant-treated wood products showed greatly reduced smoke development when tested in the 25-foot tunnel furnace used for rating purposes by UL (36). This test, however, does involve flaming exposure, regardless of the flammability of the specimen. In a recent study at the FPL (52), results of tests with the NBS smoke chamber show that plywood treated with specific fire-retardant chemicals may give off more or less smoke than untreated wood depending on the chemicals employed and the conditions of burning.

Eickner and Schaffer (10) examined the effects of various individual fire-retardant chemicals on fire performance of Douglas-fir plywood (Figure 3). Using the 8-foot tunnel furnace test method (37), they found that monoammonium phosphate and zinc chloride greatly increased the smoke density index values for the plywood when treatment levels were above 2.0 pounds per cubic foot. Boric acid, at retentions above 5 pounds per cubic foot, also increased smoke development. Sodium borates and sodium dichromate considerably reduced smoke development. At low retention levels of about 1 to 3-1/2 pounds per cubic foot, ammonium sulfate was also found effective in reducing smoke. In the 8-foot furnace, effective fire retardants produced a low-flaming combustion and this condition generally resulted in more smoke development than in the flaming combustion of untreated wood.

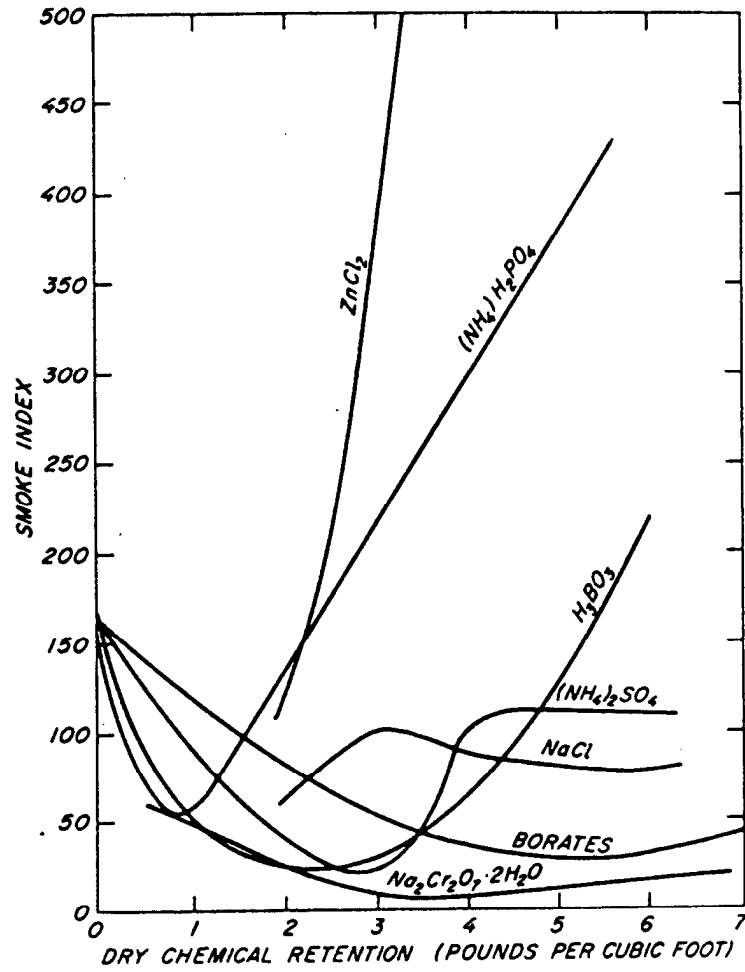


Figure 3. Relationship of smoke density to level of chemical retention in 3/8-in. Douglas-fir plywood evaluated by the 8-ft tunnel furnace method

Satonaka and Ito (53) obtained reduced smoke from fir and oak treated with either-ammonium sulfate or diammonium phosphate, or with the commercially used formulations pyresote or minalith. (Pyresote consists of zinc chloride 35 percent, ammonium sulfate 35 percent, boric acid 25 percent, and sodium dichromate 5 percent. Minalith consists of ammonium sulfate 60 percent, diammonium phosphate 10 percent, boric acid 20 percent, and borax 10 percent.) They also obtained reductions in carbon monoxide and carbon dioxide levels compared to the untreated wood with each of the four treatments at the two pyrolysis temperatures employed, 400°C and 700°C.

The possibility of toxic gas formation can occasionally be predicted from the chemical composition of fire-retardant formulations. Chemicals containing chlorine may produce chlorine gas, hydrogen chloride, or other chlorinated products. Ammonia gas may also be a noxious gas from ammonia-containing compounds. The trend in recent years has been toward increased investigation and use of organic compounds as fire retardants for wood. The thermal decomposition products from wood treated with these compounds is not clearly understood, particularly in regard to their toxicological and physiological effects. Information on research in this area is lacking.

Heat Contribution

At Some time after the initial exposure of wood to heat and flames in a fire situation, the burning process becomes exothermic and heat is contributed to the surroundings. The total heat of combustion of wood varies with species and is affected by resin content. It varies from about 7,000 to 9,000 Btu per pound, but not all of this potential heat is released during a fire. The degree to which the total available heat is released depends on the type of fire exposure and the completeness of combustion.

During the initial stages of a fire, fire-retardant-treated wood contributes less heat than does untreated wood, especially from the flammable volatiles (8,26). This means that the spread of fire to nearby combustibles is slow. The fire tends to be confined to the primary source. In the ASTM E84 test for building materials, treated specimens produce about 75 percent less heat than untreated red oak. In a total combustion test, however, such as the National Bureau of Standards "potential heat" method (54), both treated and untreated wood release about the same total heat.

Heat release rate is another relevant measure of the combustibility of a material along with ease of ignition and flame spread. Smith (55) points out that the release rate data, obtained under different test exposures, will be useful in predicting the performance in actual fires under different fuel loading. Release rate data can thus be used--along with other

fire performance characteristics--for specifying materials and products in a particular location in an occupancy with a given fuel load rating.

The rate of heat release during the initial stages of fire exposure is considerably less, however, for treated wood than for untreated wood. Brenden (56), using the FPL rate of heat release method, obtained a maximum heat release rate of 611 Btu per square foot per minute for untreated 3/4-inch Douglas-fir plywood, with an average release rate of 308 Btu per square foot per minute for the first 10 minutes. Fire-retardant-treated Douglas-fir plywood, with 3.6 pounds per cubic foot dry chemical and a reported flame spread of 25 to 28, had a maximum heat release rate of 132 Btu per square foot per minute at 42 minutes and an average rate of 16 Btu per square foot per minute for the first 10 minutes.

Treatment-Related Properties of Fire-Retardant-Treated Wood

Strength

Gerhards (57) reviewed the results of 12 separate studies on strength properties of fire-retardant-treated wood conducted at the FPL and other laboratories. He concluded that modulus of rupture (MOR) is consistently lower and modulus of elasticity (MOE) and work to maximum load are generally lower for fire-retardant-treated wood than for untreated wood if fire-retardant treatment is followed by kiln drying. The effect may be less or negligible if the fire-retardant-treated wood is air dried instead of kiln dried. The most significant loss was in work to maximum load, a measure of shock resistance or brashness, which averaged 34 percent reduction.

The losses from treating and kiln drying for small clear specimens averaged about 13 percent for MOR and 5 percent for MOE. Losses in structural sizes were about 14 percent for MOR and 1 percent for MOE (57). Losses due to high temperature kiln drying, above 65°C may be considerably greater (58).

The National Forest Products Association recommends that the allowable stresses for fire-retardant-treated wood for design purposes be reduced by 10 percent as compared to untreated wood; the allowable loads for fasteners are also reduced 10 percent (59). The 10 percent reduction in design stresses was confirmed providing the swelling of the wood resulting from treatment is taken into account (57,60). Treated wood is slightly more hygroscopic than untreated, therefore the density of equivalent cross sections of the treated test samples was slightly lower.

Brazier and Laidlaw (58) at the Princes Risborough Laboratory have written that, until more research is done in this area, it is wise to assume a loss in bending strength of 15 to 20 percent for treated wood dried at 65°C.

In addition to strength loss due to kiln drying at high temperatures (above 65°C), progressive loss of strength in treated wood members can be caused by acidic degradation of the wood by some treatment chemicals (58). There is evidence that phosphate and sulfate salts may be broken down to acidic residues within the wood. The degradation and resultant loss in strength may continue at a slower rate under use at normal temperatures.

The fire-retardant treatment of large structural members for applications where strength is a predominant factor is usually not recommended. The adverse effects of treatment chemicals on strength and other properties such as hygroscopicity outweigh any benefit obtained by the treatment. Large wood members have good fire resistance and if treatment is required for reducing flame spread, it would be better to use fire-retardant coatings or other protection.

Hygroscopicity

Wood that has not been treated will absorb moisture from the surrounding air until its moisture content reaches an equilibrium condition. The hygroscopicity of wood treated with inorganic fire-retardant chemicals is usually greater than that of the untreated wood and is dependent on size and species of wood, temperature, relative humidity, and type and amount of chemicals used (8,60). The increase in equilibrium moisture content is negligible at 27°C and 30 to 50 percent relative humidity. A 2 to 8 percent increase in moisture content occurs in the treated wood at 27°C and 65 percent relative humidity, and at 80 percent relative humidity the moisture content may increase 5 to 15 percent and cause exudation of the chemical solution from the wood.

In an unpublished study at the U.S. Forest Products Laboratory, the moisture content of wood treated with two commercial formulations reached 48 to 58 percent (based on oven-dry weight of treated sample) in 4 weeks' exposure at 27°C and 90 percent relative humidity. Continuous exposure of wood treated with water-soluble salts to conditions above 80 percent relative humidity can result in loss of chemicals and in adverse effects on dimensional stability and paint coatings. Corrosion of some metals in contact with the wood will also occur.

Zinc chloride will add considerably to the equilibrium moisture content of wood in the range of 30 to 80 percent relative humidity (8). Ammonium sulfate will add at relative humidities exceeding 65 percent, and borax and boric acid will attract water at lower humidities. Phosphate salts affect hygroscopicity mostly when relative humidity exceeds 80 percent (58).

Most commercial treatment formulations are developed for use under conditions not greater than 80 percent relative humidity. An exterior type, leach-resistant treatment that is not hygroscopic is available (61).

Gluing

Generally, the bonding obtainable with fire-retardant-treated wood is satisfactory for decorative purposes. Treated wood members can be bonded into structural assemblies with specially formulated adhesives under optimum bonding conditions (8). However, the quality of bonds is not usually equal to that obtainable with untreated wood, particularly in evaluation after exposure to cyclic wetting and drying (62).

Corrosivity

Current treatment solutions containing corrosive inorganic salts usually also contain corrosion inhibitors such as sodium dichromate or ammonium thiocyanate or are formulated to a more neutral pH (60). However, soluble-salt-treated wood in contact with metals should not be exposed to high relative humidities for prolonged periods. The treatment chemicals can attack and deteriorate metal fasteners. The corrosion products in turn deteriorate the wood. For example, under humid conditions, ammonium sulfate will attack the zinc and iron of galvanized punched-steel nail plates used in trusses (58). Alkaline and acidic areas are developed in the wood next to the attacked metal fastener, and cause degradation of the wood (58,63).

Paintability

Paintability is generally not a problem under dry normal conditions. Unusually high relative humidity conditions can affect adhesion of the paint film or cause chemical crystal blooming on the paint surface due to the increased moisture content of the wood. Natural or clear finishes are generally not used for treated wood because the chemicals may cause darkening or irregular staining.

Machining

The abrasive effect of treatments with inorganic salt crystals can reduce tool life. Where machining is necessary, this can be minimized by using tools of abrasive-resistant alloys.

Durability

Fire-retardant-treated wood is durable and stable under normal exposure conditions. Treatments using inorganic water-soluble salts, however, are not recommended for exterior exposures to rain and weathering unless the treatment can be adequately protected by water-repellent coating. Exterior-type treatments in which the chemicals are "fixed" in the wood in some manner are leach resistant and nonhygroscopic.

Current Research

The latest "Directory of Fire Research in the United States 1971 to 1973," by the National Research Council (64), shows that only a few of the listed federal, university, private, and industrial laboratories are doing research involving fire-retardant impregnation treatments for wood. Published research indicates that the current effort is in the development of leach-resistant types of fire-retardant treatments for both exterior and interior uses. Major emphasis is on reduction of flame spread as determined by ASTM E84 (34), and reduction of flaming and fire penetration as determined by ASTM E108 (65). Development is also directed toward enhanced properties of the treated wood in non-hygroscopicity, gluability, paintability, strength, and preservation against biodegradation. Some attention--but not enough--is being given to reduction of smoke and noxious gases. The current research emphasis on the toxicological and physiological effects from the combustion products of natural and synthetic polymers is expected to eventually include fire-retardant-treated wood.

FPL Research

At the U.S. Forest Products Laboratory, many of the research programs involve fire-retardant-treated wood. This has included extensive basic study of pyrolysis and combustion reactions of wood and its components and the effects of chemical additives on these reactions (15,24-26,28,29,66). A cooperative study (9) with the Division of Chemical Development of the Tennessee Valley Authority, showed the effectiveness of liquid ammonium polyphosphate fertilizers as fire retardants for wood. The commercial use of these products, made from electric furnace superphosphoric acid, has been shown to be economically feasible. Work has been completed by Schaffer (33) on the rate of fire penetration in wood treated with different types of chemicals. Some results of this study are reported elsewhere in this paper.

Studies are currently being conducted on smoke development and heat release rate from treated and untreated wood and wood products (52,56). An evaluation of the available treatment systems for wood shingles and shakes was completed using artificial weathering (11). A further development from this work was a new ASTM Standard Method D2898 (67,68) for testing durability of fire-retardant treatment of wood.

Other Institutions

Using full-scale fire test facilities of the Illinois Institute of Technology-Research Institute (IITRI), Christian and Waterman (69) studied fire and smoke behavior of interior finish materials including fire-retardant-treated wood products. The authors found that the materials performed according to a

"relative hazard" position, but that the tunnel test flame-spread number does not quite place them in the proper order. They state that "attempts to distinguish between hazards of materials whose tunnel test flame-spread numbers differ by 25 or less do not seem justified." These same IITRI researchers (70) also found that in some situations a significant amount of material with a flame spread of 90 can be safely used on walls of corridors wider than 6 feet when the ceiling material has a rating of 0 to 25.

Effective fire-retardant treatments for wood for exterior uses under conditions of leaching and weathering have been needed for many years. For wood shingle or shake roofing, a commercial treatment system has been developed (61) in the United States that meets acceptance requirements of Underwriters' Laboratories, Inc. Lumber and plywood are also available with this exterior-type treatment.

The success of this treatment system indicated a breakthrough in the development of a commercially successful system whereby fire-retardant chemicals are pressure impregnated into the wood and fixed or converted to a leach-resistant state without serious impairment of the desirable natural wood properties. This development has stimulated research with leach-resistant type treatments. Chemicals employed usually involve organic phosphates and compounds that can react with phosphorous-containing chemicals or with the wood cellulose structure to give permanence of treatment.

The Eastern Forest Products Laboratory (12,71) at Ottawa, Ontario, has been active in development of leach-resistant treatments using melamine or urea with dicyandiamide, formaldehyde, and phosphoric acid. Decay resistance is also shown for a urea-based treatment (72). One system has met the requirements for Class C wood roofing under ASTM E108 by Underwriters' Laboratories of Canada (12,73). This treatment, or one similar, is expected to be introduced into the United States within the year as an approved exterior-type leach-resistant treatment.

McCarthy and coworkers (74) at the Australian Forest Products Laboratory reported that a pressure treatment for pine posts with zinc-copper-chromium-arsenic-phosphorus preservative produced a leach-resistant treatment having both fire retardancy and preservation against decay. This treatment system is reported to have commercial application in Australia.

Basic research on the chemistry of cellulosic fires is being studied by Shafizadeh at the University of Montana (75,76). Working with model compounds, he has shown how thermal reactions affect the cleavage of the glycosidic bond with breakdown of the sugar units through a transglycosylation mechanism which eventually results in formation of combustible tar and volatile pyrolysis products. Interference of the transglycosylation process by acidic additions, amino groups, and phosphate and halogen derivatives has been demonstrated to retard combustion by producing more water and char.

One area of continuing research at the Stanford Research Institute (SRI) is concerned with the effects of flame retardants on thermal degradation of cellulose (77,78). The results of a recent study (78) for treating wood showed that existing wood roofs can be given a self-help fire-retardant treatment equivalent to a Class C (65) rating for a 5-year period. To obtain adequate depth of penetration, the treatment is effective only on weathered shingle or shake roofs at least 5 years old. The treatment consists of a spray application of a 20 percent aqueous solution of diammonium phosphate, followed by a 20 percent aqueous solution of magnesium sulfate to form the water-insoluble magnesium ammonium phosphate.

Of particular interest is the application of the Parker-Lipska model for selecting fire retardants (77). This model of pyrolysis processes predicts the efficiency of candidate chemical fire retardants based on increased char yield and elimination of flaming. Efficient retardants will be those that have high oxygen content per molecule and contain phosphorus or boron to prevent afterglow. In addition, the studies at SRI have shown that the optimal add-on weight of a chemical retardant is about 10^{-4} mole per gram of cellulose.

Areas of Needed Research

From the viewpoint of life safety, the most urgent area of fire-retardant research is the development of treatments for wood that will reduce not only flame spread but also smoke and noxious gases. The treatments should not add or create new noxious gases. Basic research on the combustion of wood being conducted in many laboratories should be studied and carefully gleaned for clues on treatment chemicals or other means to alter the cellulose and lignin structure to reduce smoke and harmful gases. Because combustion products have been shown to be the primary cause of death in fires, research on the reduction of smoke and gases should take precedence over reduction of flame spread.

Another area of necessary research is development of treatments that will increase resistance of wood to fire penetration. The work done by Schaffer (31,33) and others in this field should be carried further. The slow rate of fire penetration in thick wood members is one of the basic assets of wood and has been accepted and utilized for many years in heavy timber construction. But thin wood members and paneling have a considerably higher fire penetration rate than thick wood members under severe fire conditions. A fire-retardant system that will give slower fire penetration means more available safety time for fire fighting personnel and for evacuation of occupants from a burning building.

Continuing basic research is needed in the pyrolysis, combustion, and fire chemistry of wood leading toward the

selection of fire-retardant chemicals and their more efficient application to wood.

The high loading required (2 to 6 pounds of dry chemical per cubic foot of wood) for chemicals in present use puts a severe limitation on cost of usable treatments. A higher cost treatment could be tolerated if it proved more efficient. A large part of the cost of treated wood to the consumer is the full-cell pressure process required by present-day formulations. A less costly method of getting the chemical into the wood is needed. We need not limit the choice of chemical candidates only to those that can be used in a water-treating solution. Application with hydrocarbon solvents or liquified gases with subsequent recovery of the carrier may prove practicable.

Further research should be directed toward the development of test methods to properly evaluate fire-retardant-treated wood. Current methods have been criticized (79) for not giving a true hazard evaluation of materials on their potential performance in a real fire. The limitations of small-scale test methods should be understood as adequate only for products research and development. Even the 25-foot rating furnace of ASTM E84 (34) has been criticized regarding its correlation with full-scale fires and the meaning of the numbers it produces for flame spread and smoke density (40,69,80). There is a trend toward more full-scale fire testing with the objective of relating the results of smaller scale tests including the 25-foot furnace to performance in real fires. Full-scale tests are too expensive, of course, to prove out building products on a routine basis. Perhaps the corner-wall test (80-82) is adequately realistic and could be used in conjunction with small-scale tests for determining product performance and fire hazard.

As new criteria are developed for defining combustibility, a method is needed to realistically indicate heat release rate of wood products exposed to building fires instead of dependence on "total heat values."

Continuing research must yield information on the treatment-related properties of fire-retardant-treated wood and methods for their improvement. The properties of the conventional salt treatments which need improvement especially are hygroscopicity, strength properties, gluing, and finishing.

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