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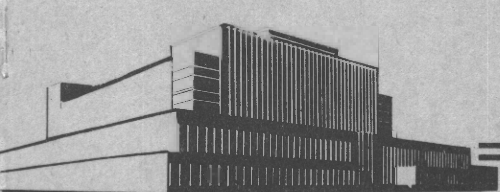

FOREST PRODUCTS LABORATORY
MADISON 5, WISCONSIN

UNITED STATES DEPARTMENT OF AGRICULTURE
FOREST SERVICE
In Cooperation with the University of Wisconsin

THE PERFORMANCE OF WOOD IN FIRE[1]

By

H. O. FLEISCHER, Chief
Division of Timber Processing

Forest Products Laboratory,[2] Forest Service
U.S. Department of Agriculture

Introduction

About 60 miles west of Portland, Oreg., in what was once a fine timbered area, lies the small city of Tillamook. During World War II, several large dirigible hangars were built there, which have since been used for factory purposes. One of these hangars is 1,000 feet long, 170 feet high at the crown, and 296 feet wide. It consists of a wood arched roof shell. The arch ribs are of the truss type, 18-1/2 feet deep, spaced on 20-foot centers. Wood purlin trusses, rafters, and roof sheathing of 2-inch wood planking complete the construction. All wood parts in this building were pressure treated with fire-retardant chemicals. In the summer of 1955, a fire started in an exhaust duct, at a considerable height on the roof. The fire swept both up and downward over the roofing material on the outside of the building, stimulated by a strong wind. Firemen called to the scene were able to reach only about one-third the height of the building with their hose streams. After the fire had burned for about an hour, firemen working on the roof were able to reach the flames with their hose lines, and the blaze was controlled. For 6 additional hours, the fire continued to smoulder in hidden spots until finally extinguished.

Altogether this fire had burned over 40,000 square feet of roofing, or about one-tenth of the roof area. About 3,000 square feet of 2-inch roof planking was charred through, and eventually about 15,000 square feet of the planking, covering less than 4 percent of the roof area, was replaced. No structural damage had occurred to the rafters, purlins, bracing, and other parts, despite the fact that the flames had swept through a charred hole in the roof.

By contrast, only 2 years before the Tillamook fire, a flash fire in the General Motors Transmission Plant at Livonia, Mich., had swept with lightning speed through the entire factory. In only a few minutes, this 34-acre building, made entirely of noncombustible materials, collapsed completely, destroying both the building and all of its contents. It had to be completely razed and rebuilt during a period of months, whereas the original wood building at Tillamook was used almost without interruption and still today houses a large plywood manufacturing plant.

The property of wood which enables it to burn at a moderate rate, through a slow process of pyrolytic decomposition, followed by charring and flaming, is one of its important characteristics. It is intimately related with man's oldest uses for nature's versatile material: On the one hand, for shelter and protection, and on the other, for fuel.

The development of sound scientific information about the performance of wood in fire will enhance the usefulness of wood to mankind in the future. Because the greatest volume of wood is used in building construction, and because of the life hazard involved,

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building fires are of particular interest. Research in this field is aimed at learning about the performance of wood in fire and at improving its resistance to fire.

How Wood Performs in Fire

Wood rarely burns directly. In common with other organic materials, it decomposes when subjected to heat and gives off flammable gas and tars, leaving behind a charcoal residue. This process is known as pyrolysis. Pyrolysis of wood occurs very slowly at low temperatures and requires the external application of heat. At about 270° C., the reaction becomes rapid and heat is released. Flaming may then occur in the combustible gases after they have left the wood surface and become mixed with air. A pilot flame may be used to ignite these flammable gases or, under heating rates about twice as great as required for pilot ignition, spontaneous ignition may occur. The poor thermal conductivity and high specific heat of wood and of charcoal formed on its surface keep the pyrolysis reaction from penetrating wood rapidly. Under high temperature exposure, when the pyrolysis gases have been sufficiently spent so that oxygen can reach the remaining charcoal surface, the charcoal will burn by glowing. Flaming and glowing are independent processes (3).[3]

Basic studies of the pyrolysis and combustion of wood are essential to the development of improved fire retardants. Yet it is equally important that the conditions that normally exist in fires be analyzed and that all aspects of the fire performance of wood under these external conditions be studied. To determine what transpires in a going fire requires that large-scale tests be made.

One such series of tests was completed at the Forest Products Laboratory in 1953, involving the complete burnout of the furnishings and interior walls of a test room 8 by 12 feet in size (4). In these tests, it was found that the rate of temperature rise in the room during the early stages of the fire was relatively slow. However, a critical period, known as the flash-over stage, was reached, during which the rate of temperature rise was exceedingly fast. Radiation from fire in the center of the room raised the temperature of combustible materials near the wall to the ignition point. The nature of the wall material, whether plaster, fiber insulation board, or plywood, had little or no effect on the time or temperature of the critical point and only a small effect on the flash-over. In every case, the flash-over occurred at a wall temperature which was too high for the survival of human life. The intense heat produced by the burning of the combustible contents would have made the burning room unbearable by a human occupant, even before the concentration of toxic gases became excessive. These tests led to the conclusion that the customary furnishings of most dwelling rooms provide enough fuel to create a serious fire regardless of whether the walls and ceilings are combustible or noncombustible. Once a fire is started, it spreads not only by direct contact of the flames and by movement of hot air and combustible gases through channels not provided with fire stops, but also by elevating the surface temperature of combustible materials to their ignition point by direct radiation.

A series of large-scale tests conducted in 1959 in a condemned schoolhouse in Los Angeles has to a certain extent confirmed these conclusions (10). It demonstrated the importance of the early temperature rise in a fire and the fact that smoke and heat may make a building uninhabitable by humans very early during the development of a fire, even though the type of construction and the wall lining material may be fire resistant.

Wide variations in the conditions that govern fires in different types of buildings produce different fire effects. Important factors affecting combustion are the density of the wood, its moisture content, the dimensions of the pieces, their arrangement, the amount of draft, and the element of time, all in relation to the amount of heat available for producing ignition.

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[3] Underlined numbers in parentheses refer to literature cited at the end of report.

A number of different laboratory test methods are used to get information on specific aspects of fire performance. Most of them serve to classify materials as to (1) ignitability, (2) tendency to spread flame, or (3) to evaluate the resistance to fire penetration, usually as applied to various structural elements or construction systems. A number of common and widely used tests in the classifications mentioned above are discussed in a paper published in the proceedings of the Third FAO Conference on Wood Technology (7). Only a very short discussion of this subject can be given here.

Ignitability

Ignitability is simply the tendency to begin to burn by flaming or glowing. The less the ignitability, the higher will be the "ignition temperature," that is, the greater the external heat must be before the material concerned will contribute to the fire. Therefore, the ignition temperature is important in classifying material. One is reminded here of the difficulties which our early ancestors had in developing sufficient heat to kindle a fire. Charles Darwin describes such an incident observed in a visit with the aborigines of Tahiti as follows (6):

"They then proceeded to make a fire, and cook our evening meal. A light was procured, by rubbing a blunt-pointed stick in a groove made in another, as if with intention of deepening it, until by the friction the dust became ignited. A peculiarly white and very light wood (the *Hibiscus tiliaceus*) is alone used for this purpose; it is the same which serves for poles to carry any burden, and for the floating out-riggers to their canoes. The fire was produced in a few seconds; but to a person who does not understand the art, it requires, as I found, the greatest exertion; but at last, to my great pride, I succeeded in igniting the dust."

Methods used for measuring ignition conditions include exposure of the material to high temperature in a muffle furnace, heating by radiation, heating by controlled flow of hot air, and contact with electrically heated wire.

The establishment of ignition temperatures for wood is complicated because it is affected by many factors including the rate of heating, size and state of subdivision of specimen, moisture content, rate of air flow, duration of exposure, and presence or absence of an igniting flame.

Values generally determined for the spontaneous ignition of small wood samples are 650° to 800° F. A somewhat different value is obtained if one measures the temperature at which exothermic heating develops in wood and from which heating logically progresses to the ignition point. In one series of test, southern yellow pine, untreated and impregnated with several retentions of fire retardants, was used. A sample of small chips was exposed in an air stream of constant flow rate and uniform temperature increase, without a pilot flame. By progressively recording the time and the temperature in the air stream and within the sample, the point at which exothermic heating began was determined. For the untreated wood this was between about 445° and 465° F. For zinc chloride-treated wood, exothermic heating began at a slightly lower temperature than for untreated wood (12).

Tests in the presence of a pilot flame were made on nine species of untreated wood and one species treated with nine different fire-retardant chemicals. The wood was tested both ovendry and air-dry. For air-dried blocks, the temperatures at which the specimens could be heated for 40 minutes without ignition varied from about 315° to 385° F. for untreated wood, and from about 290° to 500° F. for the one species of wood treated with fire retardants. In another series using the same test procedure on 34 untreated softwood and hardwood species, but igniting the specimens within 4 to 6-1/2 minutes, the temperatures varied from 608° to 660° F. for the softwoods and from 595° to 740° F. for the hardwoods. The results of these tests, when plotted, show a fairly close relation between specific gravity and ignition temperature. In general, low-density species ignite at lower temperatures than high-density species. This relationship was more consistent for hardwoods than for softwoods (12).

Flame Spread

The tendency for flame to spread on a material is important in determining the passage of fire from one area of a structure to another and thus in exposing additional fuel to the fire. Perhaps more important is the fact that the time for personnel to extinguish a fire or to evacuate a building is in some cases dependent on flame spread. Many of the fire test methods proposed or standardized, particularly for panel materials which may be used as wall or ceiling surfaces, measure this characteristic.

Flame spread is commonly measured by observing the rate of spread of fire over a surface, such as the wall or ceiling of a room, or over a specimen or panel exposed in an artificially controlled apparatus, such as a tunnel, tube, or assembly.

Rates of flame spread can vary greatly depending upon the arrangement of the fuels, the manner in which the heat and the flame are applied, and other external conditions. A common method of expressing rates of flame spread is to relate them to a scale in which red oak flooring is arbitrarily assigned a rating of 100, and asbestos millboard a rating of 0. On this scale, many common species in lumber or plywood form, with surfaces uncoated or untreated and tested in an 8-foot tunnel furnace, received a flame spread rating lying between about 75 and 135 (5). Structural insulating boards received flame spread ratings of between 46 and 170, the latter high value being obtained with an asphalt-impregnated fiberboard. Medium-density building fiberboards received flame spread ratings of between 97 and 144; hardboard, 87 to 119; and particle boards, 83 to 106.

By chemical impregnation treatments and by the application of fire-retardant coatings, it has been possible in some cases to obtain ratings for wood and wood-base materials of less than 25. These have been termed "noncombustible." Ratings of 50 or less have been called "fire retardants," and 75 or less have been called "slow burning" by some authorities, such as the Basic Building Code (2).

Fire Penetration

In addition to combustibility and tendency to spread flame, the resistance of a material or structural assembly to the penetration of flame is important in determining whether the material or assembly will perform satisfactorily in resisting fire. Tests in this category are usually made with one side exposed to a heat source controlled to a standard time-temperature curve, such as that described in ASTM Standard E-119 (1).

Furnaces of various sizes and types are commonly used for measuring fire resistance. Some of these are very large, being suitable for exposure of entire building assemblies such as walls and partitions, columns, floors, roofs, and ceilings. For example, the minimum size wall panel test under ASTM Standard E-119 is 100 square feet, with a minimum dimension of 9 feet in width or height.

Untreated wood construction generally has shown favorable results under the conditions of this test. The charring rate for wood is 1/30 to 1/50 inch per minute or about 1-1/2 inches per hour. As the heat penetrates slowly ahead of the char, the temperature 1/4 inch ahead of the charring is only about 360° F. As a result, sizeable wood members generally maintain a high percentage of their strength under fire conditions (12).

The Underwriters Laboratories report that timber columns, when given adequate end protection, sustained fire and load tests for 78 to 112 minutes before failure (14). Tests on laminated members glued with casein glue have shown only a very slight reduction in strength immediately adjacent to the charred area. Glued members made with phenolic, resorcinol, and melamine adhesives have been found to perform similarly to solid wood (15). The glue joints hold the charred wood in place. Fire-retardant treatments do not increase the resistance to charring as greatly as they reduce the surface flaming. Such treatments have been found to increase the time to failure for nonbearing fire walls about 30 percent, and load-bearing walls 20 to 24 percent.

Tests of stress-covered type of prefabricated plywood wall panels showed that it is possible to vary their fire resistance from about 10 minutes to more than an hour. Four elements of construction were found to be important: (1) The plywood used for the faces, (2) the insulation used between the faces, (3) the width of stud or separation of the faces, and (4) the manner of joining the wall units. In assemblies of panels heavily insulated with mineral wool insulation, high fire resistance was obtained when strict attention was given to the treatment of the joints between wall units (8).

Doors can be used effectively to block the progress of fires in buildings. Fire-resistance tests of doors are usually made on the complete assembly, consisting of the door, the door frame, the hinges, and the lock. Flush doors with solid cores of untreated wood 1-3/4 inches thick have withstood 30 to 40 minutes of exposure (9). In some cases, however, failure occurs earlier, particularly around such metal parts as the lock and the hinges. Many wood doors incorporate the use of core materials treated with fire-retardant chemicals, or include layers of mineral insulating material in order to improve the overall fire resistance and obtain ratings up to 1 hour.

General Considerations

To summarize, it may be said that the information available indicates that the ignition temperature of wood, while informative, is not useful for predicting the actual performance of wood under fire conditions, nor in evaluating the significance of fire-retardant treatments and coatings. Fire spread, on the other hand, is a characteristic of wood that is most affected by fire-retarding treatments and coatings. Size, form, density, moisture content, and arrangement of members are other factors that have an important effect on the fire-spread characteristics of wood. Resistance of wood to destruction by fire, such as rate of penetration of fire and maintenance of structural properties under standard time-temperature conditions, is affected by its physical properties and structural details but not greatly increased by fire-retardant treatments.

Other properties that are of importance in connection with the performance of wood in fire are the amount of fuel contributed, the smoke developed, the unique property of wood to stand up in a fire so that the structural integrity of the building may be retained, the relative ease and safety with which firemen can combat fire in a wooden building, and the ease of repair of a wood building that has suffered limited damage. Unfortunately, the favorable properties are not often taken into account by those who seek to promote other competitive materials in place of wood.

Using Wood to Best Advantage From the Fire Standpoint

Good performance of wood construction under fire conditions is obtained by taking advantage of the self-insulating qualities of wood, employing good structural details, using fire-retardant treatments and coatings, and other protective measures where circumstances warrant.

Heavy Timber Construction

One method of obtaining acceptable fire resistance of wood in construction is to take advantage of its self-insulating qualities. Heavy timber construction has been widely accepted and used for industrial and commercial buildings, and in recent years the fire advantages obtained thereby have been used to advantage in the design of laminated structural members.

In heavy timber construction, wood columns are not less than the nominal 8 inches thick, with rounded or chamfered corners. Beams and girders are not less than the nominal 6 inches thick and not less than the nominal 10 inches deep. Built-up beams are permitted, when closely jointed by gluing or bolting. Other structural details, such as floor design and thickness, roof deck construction, roof girders, and the like, must also be of heavy timber design (15). The resistance of heavy timber construction to fire has been recognized for many years. Favorable consideration is given to such construction in most building codes, in that it is considered as being approximately equal to construction of protected noncombustible materials with respect to building height and area limitations. Insurance authorities in many localities still tend to penalize the heavy timber construction when quoting insurance rates on buildings but, when occupancy is also considered, the differential in rates between noncombustible and heavy timber construction may disappear.

Good Building Design

Light-frame wood buildings do not have the fire resistance of the heavier wood frames. Therefore attention to good construction details is important to retard the spread of fire. Important elements are the so-called "fire stops," or obstructions provided in concealed air spaces, so designed as to interfere with the passage of flames up or across a building. Around chimneys and fireplaces, wood members should be separated from smoke pipes and masonry by air spaces, metal thimbles, asbestos papers, and noncombustible insulating materials. Walls, ceilings, floors, roofs, stairways, and doors should be so designed as to restrict the spread of fire to limited spaces, resist the penetration of fire for reasonable times, and to carry the necessary loads under fire conditions. Finishing or covering materials, such as paint, should not promote the rapid spread of flame or give off toxic gases.

Impregnation Treatments

For new wood construction and for the repair of existing structures with new parts, pressure impregnation with effective fire-retarding chemicals offers the best possibility of obtaining lasting fire-retarding effects in high degree. Lumber, timbers, and plywood impregnated with fire-retarding chemicals now find many uses in a great variety of buildings, and have been used for the construction of dirigible hangars and for shoring aboard ships.

It is known that the fire-retarding effect of impregnation treatments is closely related to the quantity of chemical injected into the wood as well as to the chemical used (11). For a high degree of effectiveness, 5 to 6 pounds of the more effective chemicals per cubic foot of wood in thicknesses less than 2 inches are required, or approximately 400 to 500 pounds per thousand board feet. Wood in greater dimensions is often given a heavy treatment to a depth of only about 3/8 inch.

Effectively treated wood can be charred or disintegrated by continuous exposure to intense heat from an outside source, but when the heating is discontinued, the burning ceases. The principal effects of fire-retardant impregnation treatments are to retard the normal increase in temperature under fire conditions, to decrease the rate of flame spread, to lessen the rate of flame penetration or destruction of wood in contact with fire, and to make fires more easily extinguishable.

Many chemicals have a fire-retardant effect when wood is impregnated with them but, because of cost limitations or various objectionable characteristics, comparatively few are considered commercially practical (13). Among the most commonly used chemicals are monoammonium phosphate, diammonium phosphate, ammonium sulfate, sodium tetraborate (borax), boric acid, and zinc chloride. The ammonium phosphates are effective in checking both flaming and glowing. Borax, although effective in checking flaming, is not a good glow retardant. Boric acid, on the other hand, is exceptionally effective in stopping glow but is not so effective for retarding flaming. Because of the different charactertistics of the compounds and because of cost considerations, fire-retardant treating formulations usually are mixtures of fire-retardant chemicals.

Many chemicals that might be used as fire retardants may have undesirable effects on the wood or may be otherwise objectionable for specific uses. Among use characteristics of importance are permanence of the fire resistance imparted to wood, effect on strength of wood, tendency to corrode metals, effects on paint and glue, hygroscopicity, and toxicity to occupants of buildings.

In recent years, about 9 million board feet of lumber and plywood have been treated annually with fire-retardant chemicals in the United States.

Fire-Retardant Coatings

Many coating materials partially protect wood against fire. The amount of protection provided by a fire-retardant coating is related to the amount and thoroughness of application, and to the severity of the fire exposure.

Fire-retardant coatings are particularly useful in controlling or reducing the rapid spread of fire through a building. They may be used to advantage on older buildings where additional protection is needed, which cannot be applied in any other way. One type of coating incorporates low-melting fluxing materials which glaze the surface, thus preventing oxygen from reaching the underlying material. The more common type of fire-retardant paints incorporate materials which decompose under heat to release gases which puff or swell the paint film to form an intumescent cellular insulating layer.

Fire-retarding coatings are of varying composition and properties. Most available preparations are of value primarily for interior use and are not durable when exposed to the weather. They usually owe their effectiveness to one of the following water-soluble fire-retardant chemicals: Ammonium phosphate, borax, or sodium silicate. Newly developed synthetic materials are also used. These fire retardants are combined with other constituents to provide other properties required or desirable in a paint, such as adherence to wood, appearance, and brushability. Some good proprietary fire-retarding coatings based on these chemicals are on the market.

Sprinkler Protection

Recent large-scale tests already referred to have emphasized the importance of quick action, applied early during the development of the fire, regardless of the type of construction and type of occupancy. Such early protective action can be provided effectively by the use of automatic sprinkler systems. Improvements in sprinkler system dependability are reported to eliminate some of the objections previously raised to such systems. When approved sprinkler systems are used, the type of construction material used is of little consequence.

Manufacturers of wood building components are giving considerations to the incorporation of sprinkling equipment directly into the design of the components. This can probably be done advantageously where such components as box beams or sizeable structural sandwich roof or ceiling components are used. Developments in this field are closely linked to the development of new wood building designs.

Conclusion: The Need for More Basic Research

A recent survey of the progress of research on the pyrolysis and combustion of wood leads only to the conclusion that too much of the research has been of the empirical type. Very little basic information has been learned about the mechanism of combustion of wood and other cellulosic materials, and of methods of imparting resistance against combustion (3).

Many theories exist about how wood may be flameproofed. The theories of greatest interest are those that give promise of leading to effective flameproofing with much smaller amounts of treating material than are now found necessary. This may be accomplished by (1) use of coatings or treatments that release catalysts to interrupt one of the many reactions that form the chain of chemical events known as burning; or (2) by impregnating with a material that modifies the burning process so that less of the flammable tars and gases are formed, but more charcoal, water, and other nonflammable gases are produced.

Strong acids or bases, or substances that generate strong acids or bases when heated, have the desired chemical action to satisfy the second theory. They act by attaching themselves to the hydroxyl groups of cellulose and upon decomposition result in the release of the hydrogen and oxygen of cellulose as water, leaving only carbon behind.

To one who is acquainted with the wonderful accomplishments of modern chemical research, it should be obvious that the ultimate solution to the problem of making wood more acceptable from the fire standpoint lies in the field of basic chemical research along the lines indicated by these theories.

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