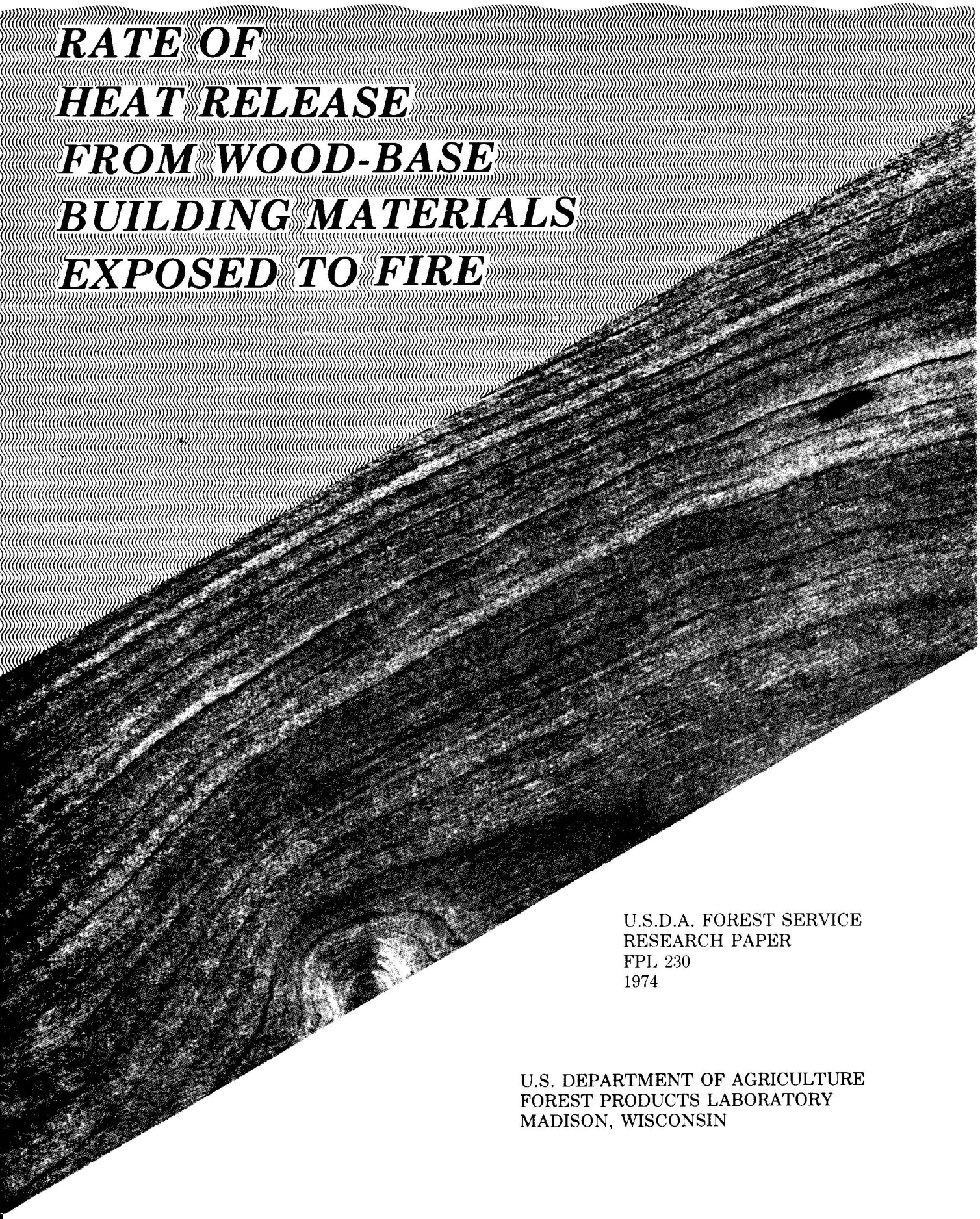
RATE OF HEAT RELEASE FROM WOOD-BASE BUILDING MATERIALS EXPOSED TO FIRE



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SUMMARY

Data on the "potential total heat release" or on the "rate of heat release" has been suggested as means of defining combustibility of materials in building code regulations, and would replace the present "noncombustibility" requirements. Rate of heat release data on several types of wood-base materials and constructions were determined under fire exposure in an FPL (Forest Products Laboratory)-developed, gas-fired, water-jacketed furnace. Materials evaluated include Douglas-fir plywood (untreated and fire retardant treated), high-density hardboard, red oak lumber, rigid insulation board, and particleboard. Among the constructions were a plywood-faced polyurethane foam sandwich panel and assemblies of both fire-retardant-treated and untreated Douglas-fir studs and gypsum wallboard facings. The results indicate that fire-retardant treatment of wood greatly reduced the maximum rate of heat release. Rate of heat release for treated wood studs compared to untreated was reduced when both were protected with a gypsum wallboard facing. This work provides both a potentially useful measurement of combustibility and additional information on fire performance of wood-base building materials.

RATE OF HEAT RELEASE FROM WOOD-BASE BUILDING MATERIALS EXPOSED TO FIRE

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INTRODUCTION

Code officials generally recognize that many materials will not pass the current three-part definition of "noncombustible" in the model codes *(1,4,7,12)*,[2] but the materials will release only limited amounts of heat during the initial and critical periods of fire exposure. There is also some criticism of using limited flammability to partially define "noncombustibility." Therefore, consideration has been given to define combustibility in terms of heat release based on the "potential heat" method suggested by the National Bureau of Standards (NBS) *(6)*, with the low levels used to define low combustibility or noncombustibility. This method serves as a measure of the total heat release. It is generally agreed that a better or a supplementary measure of the "combustibility" would be a determination of the rate of heat release. This would assess efficiently the relative potential heat contribution of materials - thick, thin, untreated, treated - under fire exposure.

Equipment developed at the FPL to measure the rate of heat release of building materials or assemblies exposed to fire on one face has been described *(3)*.[3] The research reported here is on the use of the FPL-developed equipment under one of several possible operating conditions to determine the rate of heat release of some typical wood-base building materials and assemblies and on methods of reducing the release rate. A significant reduction in rate of heat release would probably lead to possible significant reductions in fire hazards.

EQUIPMENT

The apparatus to determine the rate of heat release in this research *(3)* consists of a furnace in which one surface of the test materials is exposed to fire (fig. 1a), a fuel-air mixture supply system (fig. 1b) for a burner within the furnace, and instrumentation to control and record various responses of the furnace operation (fig. 1c).

The inside dimensions of the insulated furnace (figs. 2a-c) are about 30 inches wide by 43 inches high by 17 inches deep. The front of the furnace has an 18- by 18-inch opening to accommodate the test specimen. An exhaust (or flue) at the top of the furnace is equipped with a wire mesh screen to improve the gas flow patterns and attain better flue temperature measurements. The flue temperature is measured using three, 20-gage, chromel-alumel thermocouples. The furnace is water jacketed; the water circulating in the jacket in the furnace walls absorbs the heat that flows from the hot furnace interior through the internal insulation. These wall heat losses can be measured from the temperature rise of the water. The water jacket also serves to cool the insulation to prevent deterioration caused by high temperatures.

[1] *Maintained at Madison Wis., in cooperation with the University of Wisconsin.*

[2] *Italicized numbers in parentheses refer to literature cited at the end of this report.*

[3] *Since initiation of this research, several reports have been published on results of research at Ohio State University (9-11), and the National Bureau of Stand ards (8) on other equipment developed to measure rate of heat release.*

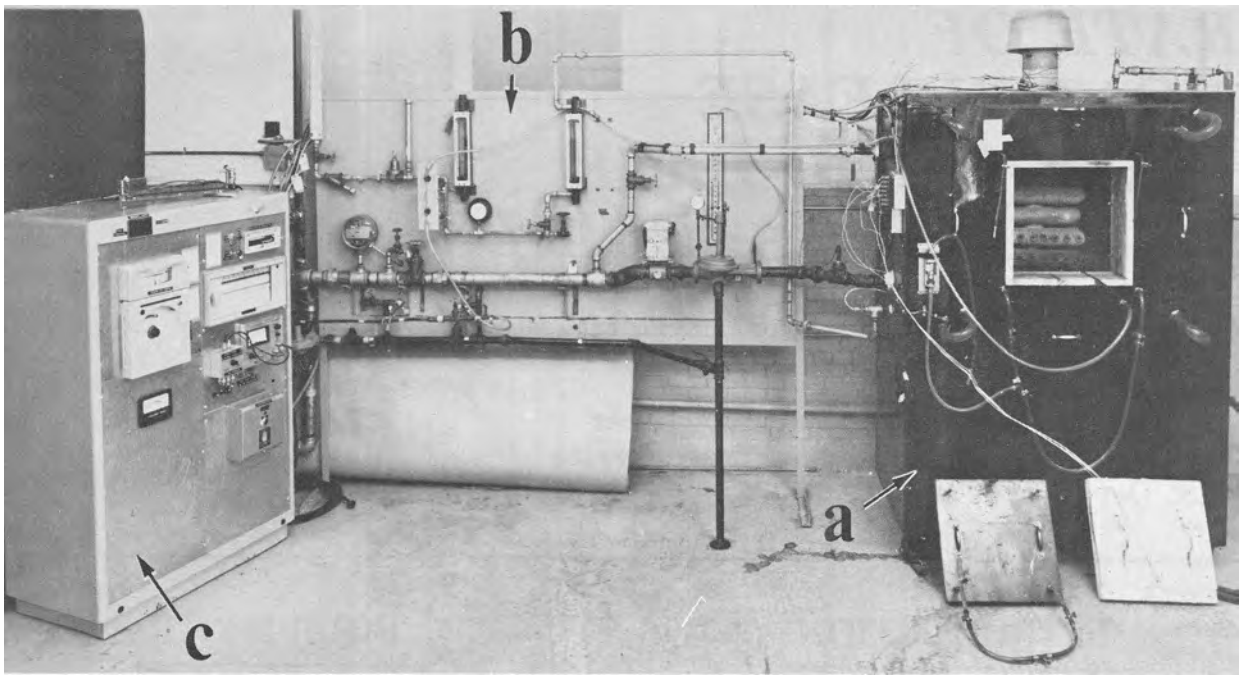

Figure 1. - Apparatus for measureing rate of heat release: Furnace, a; gas-air-water supply system, b; and electronic control cabinet, c.
(M 141 195)

A vertical exposure burner within the furnace (fig. 3a) was used to burn a premixed natural gas-air fuel mixture to provide the fire environment to which the test specimens were exposed. The burner consists of four horizontal ducts, or manifolds. made from 1-1/4-inch pipe; each manifold can provide eight 3/8-inch lava-tip burner nozzles. Originally the manifolds and the nozzles were so arranged that the nozzles were evenly distributed over an area 18 by 18 inches (the test specimen exposure area). However, preliminary measurements of the temperature distribution over the exposed specimen surface showed that the most uniform distribution was obtained if the nozzles in the top two horizontal manifolds were closed off. Further temperature improvements were obtained when the exposure burner was moved as far away from the exposed specimen surface as possible. The burner was equipped with an electronic device to detect throughout the test, presence or absence of flame.

The fuel mixture delivery system consists of three subsystems: (1) An air supply subsystem, (2) a natural gas supply subsystem, and (3) a proportional mixer. The air and the natural gas supply subsystems supply air and natural gas to the mixer that proportionally mixes the two components for use by the exposure burner.

The ratio of air to natural gas is adjustable by the mixer over a wide range. There is also an adjustment for outlet pressure. By varying the ratio of air to natural gas and the pressure of the mixer outlet, it is possible to get a wide range of flame shapes, flame colors, and temperature exposure conditions in the furnace. To control the furnace operation and aid in making process calculations, the total air flow rate is measured with a pitot tube, and the natural gas flow rate is measured by a rotameter. The temperatures of both streams are measured with copper-constantan thermocouples and recorded by the recorder shown in the instrument console in figure 1c.

"Secondary air" to the furnace is supplied through a 1-inch pipe from the air supply subsystem. This secondary air is in excess of the air required for combustion of the fuel mixture. The secondary air can be contrasted to the "primary air." which is the air mixed with the natural gas fuel and burned by the exposure burner. The secondary air serves two purposes: (1) Supplies oxygen for combustion of the test specimen and (2) creates a turbulence in the furnace interior that improves the internal fur-

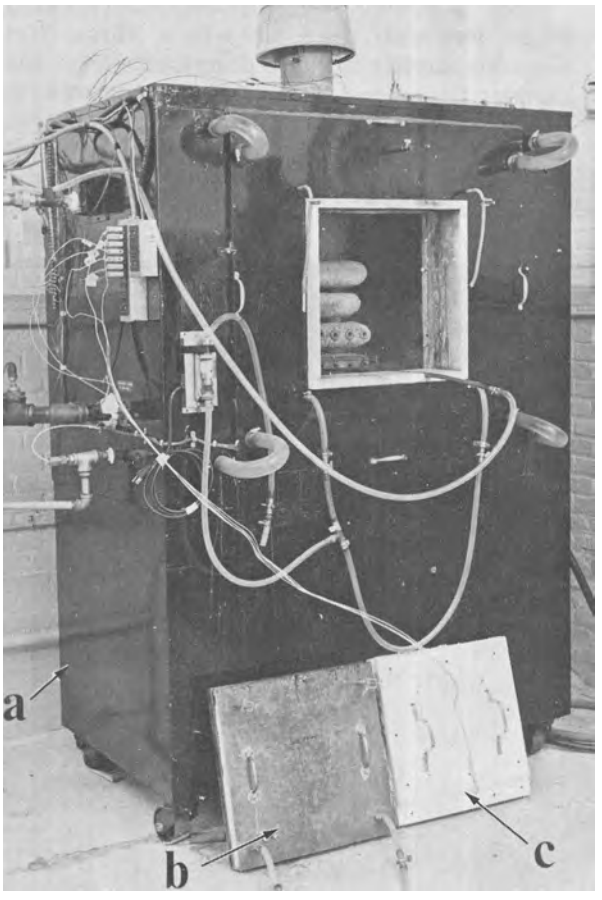

Figure 2. –Furnace to determine rate of heat release, a; water jacket for specimen,b; and noncombustible specimen, c.
(M 141 104-1)

nace temperature distribution.

To facilitate conducting the experiments, two additional items were designed and built: (1) A water jacket for the specimen and (2) a "noncombustible" blank specimen.

The water jacket for the specimen (fig. 2b). 18 by 18 inches by 1 inch, fits in the specimen opening snugly in back of the specimen. Its purpose is to collect the heat transmitted through the back of the sample that would otherwise be lost to the surrounding room. Water is circulated from the jacket of the furnace through the water jacket of the specimen and then back to the water jacket of the furnace.

The 18- by 18-inch noncombustible blank specimen (fig. 2c) used during furnace adjustment and as a substitute specimen consists of two sheets of 1/2-inch-thick asbestos millboard nailed together. Sandwiched between the two sheets is a 1/4-inch-thick layer of mineral wool insulation. Twenty-gage chromel-alumel ther-

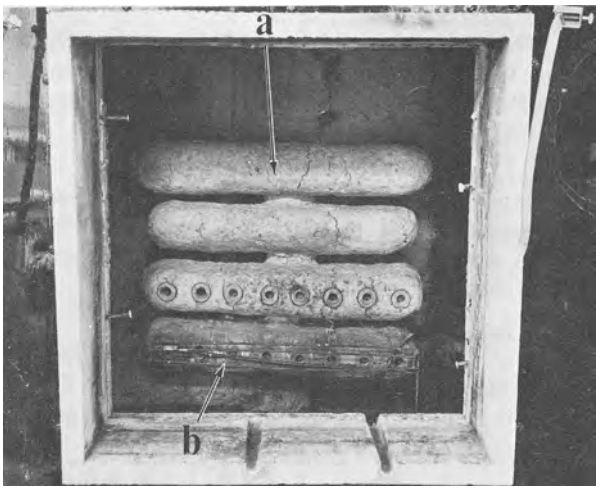

Figure 3. –Interior of furnace showing the four-bank exposure burner (two banks plugged and coated). a; and the electrode and grounding rods, b, for the flame detector. (M 141 101-12)

mocouples are located in each corner of the noncombustible specimen about 4-1/2 inches in from each of the sides that form the corner. There is also a thermocouple at the center of the fire-exposed specimen surface. The thermocouple junctions are 1/4 inch from the surface toward the hot furnace interior. These thermocouples are connected to the temperature recorder in the instrument console (fig. 1c).

MATERIAL SELECTION AND PREPARATION

In this study, seven types of building materials and three types of wall assemblies were selected to determine initial rates of heat release. Most of the test materials were cut into 18- by 18-inch test specimens from larger sheets of commercially available stock of a thickness typical for each material. Specimens were conditioned at 80°F and 30 percent relative humidity for at least 2 weeks prior to determining rate of heat release.

Douglas-Fir Plywood

Samples were cut from a 4- by 8-foot sheet of 3/4-inch-thick, exterior-grade, A-C quality plywood (29 lb/ft^3). For two determinations, four pieces, 18 by 18 inches by 3/4 inch, were glued together with phenol-resorcinol adhesive to make a laminated specimen 18 by 18 by 3 inches. The samples were glued, clamped, and cured under ambient conditions. For an additional determination, a single sheet (18 by 18 by 3/4 in.) was used.

Rigid Insulation Board

These samples were cut from a 4- by 8-foot sheet, 1/2-inch thick (regular density sheathing, 18 lb/ft^3). Rate of heat release was determined on a single thickness.

High-Density Hardboard

Samples were cut from a 4- by 8-foot sheet, 1/4 inch thick (tempered quality, 59 lb/ft^3). Only a single thickness was used to determine rate of heat release.

Red Oak

The material (44 lb/ft^3) was obtained from stock on hand that was 1 inch thick. Two replicate determinations were made on red oak.

Fire-Retardant-Treated Plywood

This material was 5/8-inch-thick exterior-grade Douglas-fir plywood that had been fire-retardant treated. The treated plywood (37.8 lb/ft^3) contained 3.6 pounds of water-soluble dry chemical salts per cubic foot of wood and was reported to have a flame spread classification of 25-28 *(2).* Rate of heat release was determined on a single thickness of this material.

Particleboard

This particleboard (40 lb/ft^3) was made in 1/2-inch-thick sheets at the Forest Products Laboratory from Douglas-fir heartwood using 6 percent resin solids (based on the ovendry weight of wood). The resin was a urea-formaldehyde solution containing 65 percent solids. The flakes for the board were 0.015 by 1 inch by random widths.

Polyurethane Sandwich Panel

Specimens were fabricated from rigid polyurethane foam (1.9 lb/ft^3) sandwiched between 1/4-inch-thick, exterior-grade, A-C quality Douglas-fir plywood used as facings. The plywood was glued to the urethane foam with a phenol-resorcinol adhesive. The foam thickness was 3 inches and resulted in an overall specimen thickness of 3-1/2 inches.

Gypsum Wallboard Wall Assemblies

Simulated wall assemblies (fig. 4) were fabricated from 3/8-inch-thick gypsum wallboard on one face and three vertical nominal 2- by 4-inch Douglas-fir studs. One stud was mounted with its centerline corresponding to the specimen centerline, whereas the two remaining were mounted with centerlines 8 inches either side of the first centerline. Three 1-1/4-inch-long gypsum wallboard nails, 8 inches on center, were used to apply the gypsum wallboard to each stud. There was not a facing on the back or unexposed side, but the usual 112-inch asbestos millboard was on this side during the test to insulate against heat losses.

An assembly from fire-retardant-treated studs was also used. It was a three-stud assembly similar to those described except the Douglas-fir was commercially impregnated with a water-soluble combination of inorganic salts. Information supplied by the product label indicates the flame spread classification for the treated wood is 15 *(2).*

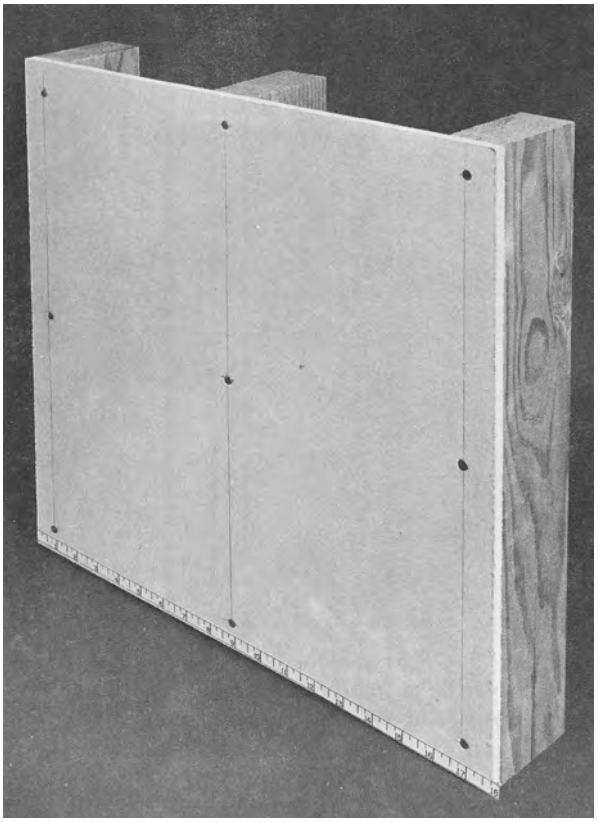

Figure 4 -Wall assembled from gypsum wallboard.
(M 142 215)

METHOD OF DETERMINING RATE OF HEAT RELEASE

Experimenta1Approach

The method of determining heat release used here can be looked on as constituting the "substitution method" of measuring rate of heat release. This method follows the general procedure used by the Factory Mutual Engineering Division with their materials calorimeter *(5).*

The substitution method involves making two determinations for each test material: The first determination is made with the test specimen in place while a record is kept of the effects that the specimen burning has on the

furnace flue temperature; and the second, with a noncombustible specimen and an additional "substitution burner" supplying heat in measured quantities to reproduce the first flue temperatures. The rate of heat release is then calculated as the rate at which heat is supplied by the substitution burner during the second determination.

Before describing the experimental procedures and calculations used in the determinations, it is necessary to discuss the conditions for operating the furnace because these conditions control the fire environment to which the test specimen (and noncombustible specimen) are exposed. The exposure conditions greatly influence the magnitude of the measured rates of heat release.

Conditions for Operating Furnace

The first decision to be made on the operating conditions of the apparatus was whether the furnace should be operated at constant temperature or at a constant exposure heat input. A constant temperature operation for exposing a combustible specimen would involve varying the heat input to the furnace dependent on the heat contribution by the test specimen. This would involve a need for continuous and accurate measurement and control of heat inputs to the furnace. It was judged that the present flow measurement equipment was not sufficiently versatile and precise for this purpose. The use of a constant heat input to the face of the specimen was judged the simpler of the two operations. This might also be more closely related to actual fires when there is an external heat source and each material influences its own exposure temperature. In this method, a stabilized heat input rate is established. It then is fairly simple to accurately control and measure the constant flow of air and gas to the furnace.

After deciding to use constant heat input, it was necessary to establish the values to use for other furnace-operation parameters. As has been mentioned and described in another publication *(3),* most of the furnace controls were capable of operating over a rather wide range. Therefore, some preliminary experiments were undertaken to determine appropriate process (test) settings for these controls. It was decided the following were the important considerations in the fire exposure environment: (1) Temperature distribution of specimen exposure (should be as even as possible) and (2) character of the flame from the exposure burner (should be a blue, oxidizing flame extending about 2 in. from the burner nozzles).

For this study, it was also determined that an average temperature of about 800° F (±20° F) at the corners of the noncombustible specimen (under steady-state conditions) was desirable. This was a temperature that would result in relatively short-time ignition of plywood, but was not excessive for convenient furnace operation. Selection of this operating condition resulted in a heat flux in the range of 1.5 to 3.0 watts per square centimeter (79.2-158.4 Btu/min/ft^2) being applied to the specimen surface with highest heat at the bottom of the specimen. The energy measurements were made by mounting an air-cooled, unguarded, Gardon-type radiometer (similar to that used in the NBS smoke chamber) in openings in several positions in an asbestos millboard specimen. The radiometer measures radiant energy plus some convective heat. Therefore, these heat flux measurements were only an approximation.

To achieve these exposure conditions, it was found that the proportional mixer should be set to mix the fuel for the exposure burner in the ratio of 10 volumes air to 1 volume natural gas and that the natural gas rate should be about 1.1 standard cubic feet per minute. This is equivalent to a constant heat input of 1,100 ± 50 Btu's per minute. In addition, it was found that the secondary air setting should be about 30 standard cubic feet per minute to supply oxygen for combustible specimens and to help distribute exposure heat more uniformly on the specimen. To give the desired pattern for the burner flame, the mixer was set to deliver the fuel mixture to the exposure burner at a pressure of 2.5 inches of water.

A flow rate to the furnace water jacket of 1.6 gallons per minute was found sufficient to absorb the wall heat flux encountered under most conditions with a temperature rise (outlet temperature minus inlet temperature) in the range of 20° to 30° F. Cool process water (in a range of 50° to 55° F) was available at the experimental site. During the course of the experimental work, however, maximum temperature increases of up to 45° F occasionally were encountered under conditions of high rate of heat release.

The substitution burner used here is a 3-foot length of copper pipe with an inside diameter of 3/8 inch. The outlet of the pipe is at the lower bottom edge of the noncombustible specimen when in place in the furnace. In reproducing the effects of the combustible specimens, the substitution burner was fed a controlled amount of propane-base fuel gas with a heat value of 2,516 Btu's per standard cubic foot. The flow rate of the fuel gas was measured with a rotameter that has an accuracy of ±2 percent of maximum scale.

Experimental Procedure

The objective of the first determination (run) was to learn how the furnace would behave when the test material was burned. The first step was warming the furnace with the noncombustible specimen in place and allowing the furnace operating variables to stabilize to a steady state. Using the flow rates and the operating conditions that have been given, the end of the warmup period was taken as the time when (1) the cooling water temperature rise was constant with time (usually at about 21 ± 1° F), (2) the furnace flue temperature was constant (usually at about 900 ±15° F), and (3) the temperatures at the corners of the exposed surface of the noncombustible specimen were relatively constant (usually at about 800 ± 20° F). These three parameters were measured with the water jacket of the specimen in place.

The second step was replacing the noncombustible specimen with the test specimen as quickly as possible and with a minimum of disturbance to the exposure conditions. In mounting the specimens, a 1/2-inch-thick sheet of asbestos millboard was placed on the back of the specimen. The purpose of this sheet was to reduce heat flow from the back of the specimen opening when the sample was consumed (under these exposure conditions most of the specimens were completely burned to ash). Specimens 1 inch thick or less were secured to the millboard backing by five brass screws (one at each corner and one in the geometric center of the exposed surface). To control the geometry of the exposure conditions, stops were placed in the specimen opening so that during the initial phases of the exposure the specimen surface was recessed 1/2 inch into the furnace wall on the hot side. As the test specimen burned, recorder chart records were kept of the response of the furnace to the released heat. The response consisted of the temperature rise of exhaust (flue) gases and of the cooling water.

The objective of the second run was to reproduce as closely as possible the conditions of the first, except, in place of the test specimen. propane-base fuel gas was fed into the furnace through the auxiliary (substitution) burner. When doing this, of course, the noncombustible specimen was in place, and care was taken that the propane-base fuel was completely burned.

The first step in the second run was warming the furnace to a steady state with conditions as similar as possible to those of the first run. When the steady state was reached, the flow of propane-base fuel was begun and regulated by an operator so that the flue temperature-time relationship would be the same for the second run as for the first. During the second run, a record was kept of the propane fuel flow rate (in cubic feet per minute) at 1-minute intervals. The time variation of the cooling water temperature rise was also observed and recorded.

Calculations

The calculations are relatively simple. The uncorrected rate of heat release (Btu's per minute) is arrived at by multiplying the propane-base fuel flow rate in standard cubic feet per minute by the fuel heat of combustion (2,516 Btu/stdft^3).

Although the flue-gas temperatures were regulated to be the same in the specimen and "substitution" runs, slight differences occurred in the heat lost through the furnace walls as measured by the data for the relationship of cooling water temperature rise to time. These losses are computed on the basis of water flow rate, specific heat, and temperature rise. Therefore, the values mentioned for rate of heat release have been corrected by using differences in losses in furnace wall heat between the first and the second runs.

The specimen area (2.25 ft^2) is taken into account so that the rate of heat release can be expressed in Btu's per minute per square foot of specimen surface area. Because the calculations are done using flow rates and temperature rises at the end of 1-minute intervals, the final results can be expressed as curves of rate of heat release (Btu's per minute per square foot) versus time (minute).

RESULTS AND DISCUSSION

The results of determinations of rate of heat release on seven types of building materials are given in figures 5 through 16 and are summarized in table 1. As indicated, these data were calculated from the heating value of additional propane gas controlled in a second. or "substitution." run with a noncombustible specimen to produce the same furnace flue-gas thermal response as with the test material. The data also include a minor correction for any variation between the water temperatures of the jacket in the two runs.

These data show widely varying rates of heat release among the different types of specimens. In all of the figures there is a period of time - from zero (the time when the specimen was inserted in the specimen opening) to the

Table 1.--Rate of heat release on seven types of building materials

Test material (one thickness unless otherwise noted)	Density	Maximum heat release rate	Time of maximum rate	Average rate (first 10 min)	Percent of total area under curve in first 10 minutes
	Lb/ft^3	Btu/min/ft^2	Min	Btu/min/ft^2	Pct
Douglas-fir plywood (3/4 in. thick) (four sheets) (first replicate)	29	616	3.0	330	(1)
Douglas-fir plywood (3/4 in. thick) (four sheets) (second replicate)	29	[2]476 [3]705	4.0 72.0	265	5.4
Douglas-fir plywood (3/4 in. thick) (one sheet)	29	611	3.0	308	27.8
Rigid insulation board (1/2 in. thick)	18	586	2.0	336	73.3
High-density hardboard (tempered quality) (1/4 in. thick)	59	[2]1,159 [3]928	6.0 8.0	425	73.2
Red oak (1 in. thick) (first replicate)	44	[2]569 [3]964	6.0 25.0	269	12.0
Red oak (1 in. thick) (second replicate)	44	932	24.0	389	16.8
Fire-retardant-treated plywood (5/8 in. thick)	37.8	132	42.0	16	2.6
Particleboard (1/2 in. thick)	40	[2]706 [3]935	5.0 15.0	465	44.4
Polyurethane sandwich panel (1/4-in.-thick plywood facings, 3-in.-thick foam core)	1.9 (foam)	[2]896 [3]775	5.0 17.0	482	42.3
Gypsum wallboard wall assembly (untreated Douglas-fir studs)	(4)	206	58.0	(5)	(5)
Gypsum wallboard wall assembly (fire-retardant-treated studs)	(4)	105	67.0	(5)	(5)

[1]1st replication using 4 sheets of 3/4-in.-thick Douglas-fir plywood was not carried to completion; thus total area under curve was not determined.

[2]1st peak.

[3]2d peak.

[4]Assemblies were composites of several materials; thus no overall densities were calculated.

[5]Assemblies did not begin to release heat until after 10 min of run elapsed.

time when measurable heat release rates begin to occur. This is the "induction" period during which the specimens absorb enough heat to raise their temperatures to the point at which active burning with exothermic chemical reactions can proceed. During this period, it is probable that negative rates of heat release can be observed; the physical significance of the

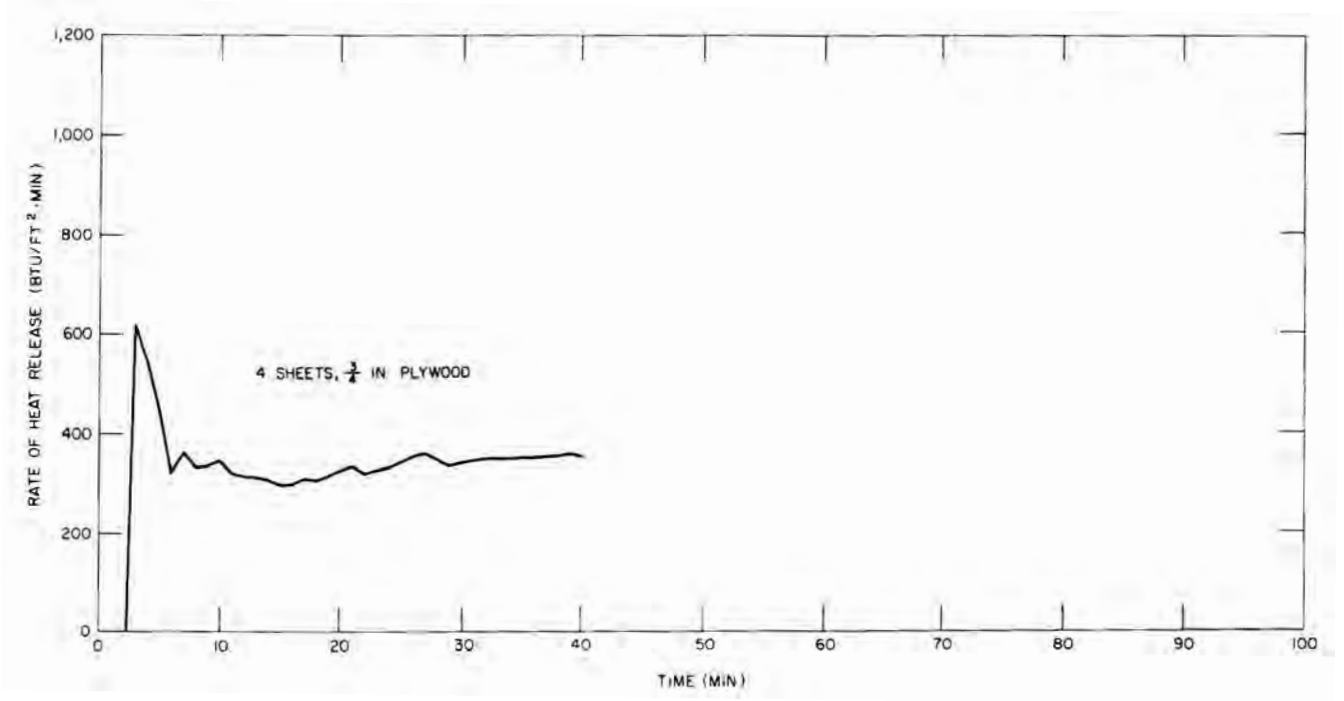

Figure 5. - Relationship of rate of heat release to time for four sheets of 3/4-inch-thick Douglas-fir plywood (laminated together with phenol-resorcinol adhesive, 40-min test).

(M 141 213)

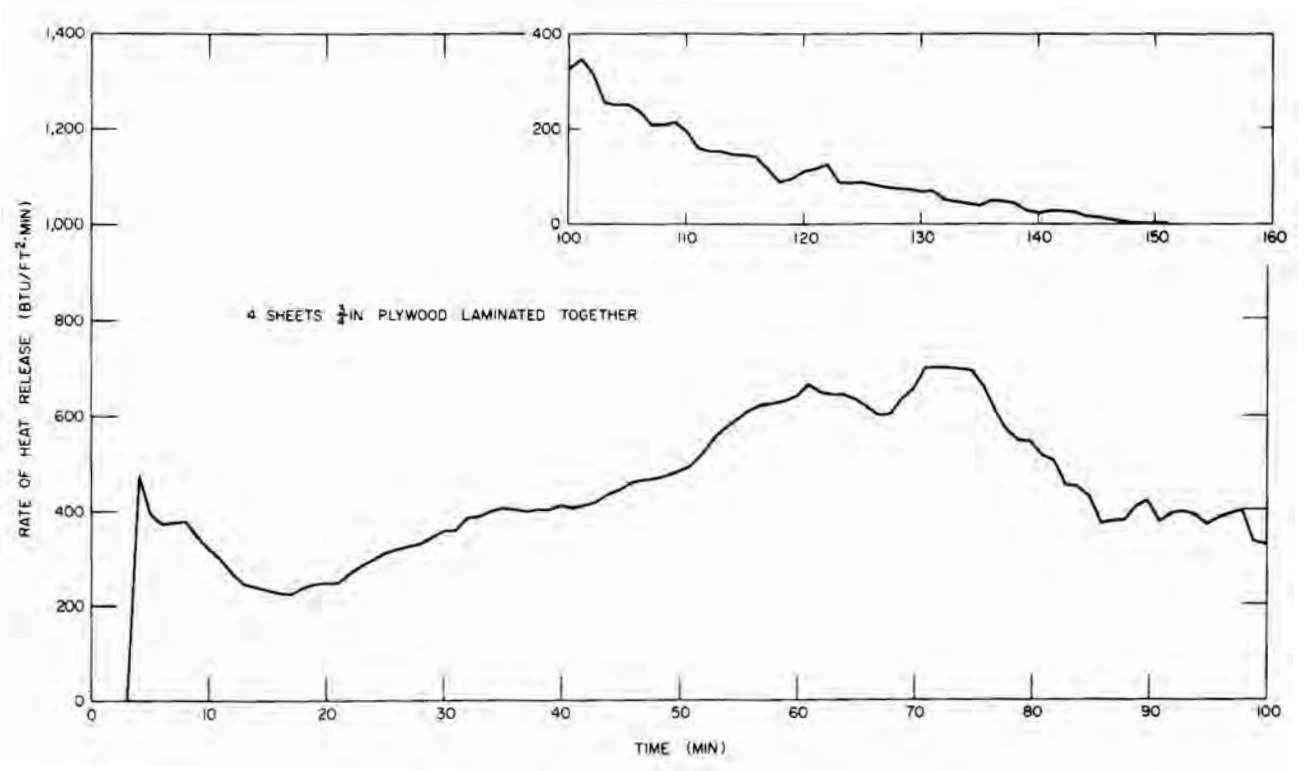

Figure 6.-Relationship of rate of heat release to time for four sheets of 3/4-inch-thick Douglas-fir plywood (laminated together with phenol-resorcinol adhesive. 151-min test)

(M 142 043)

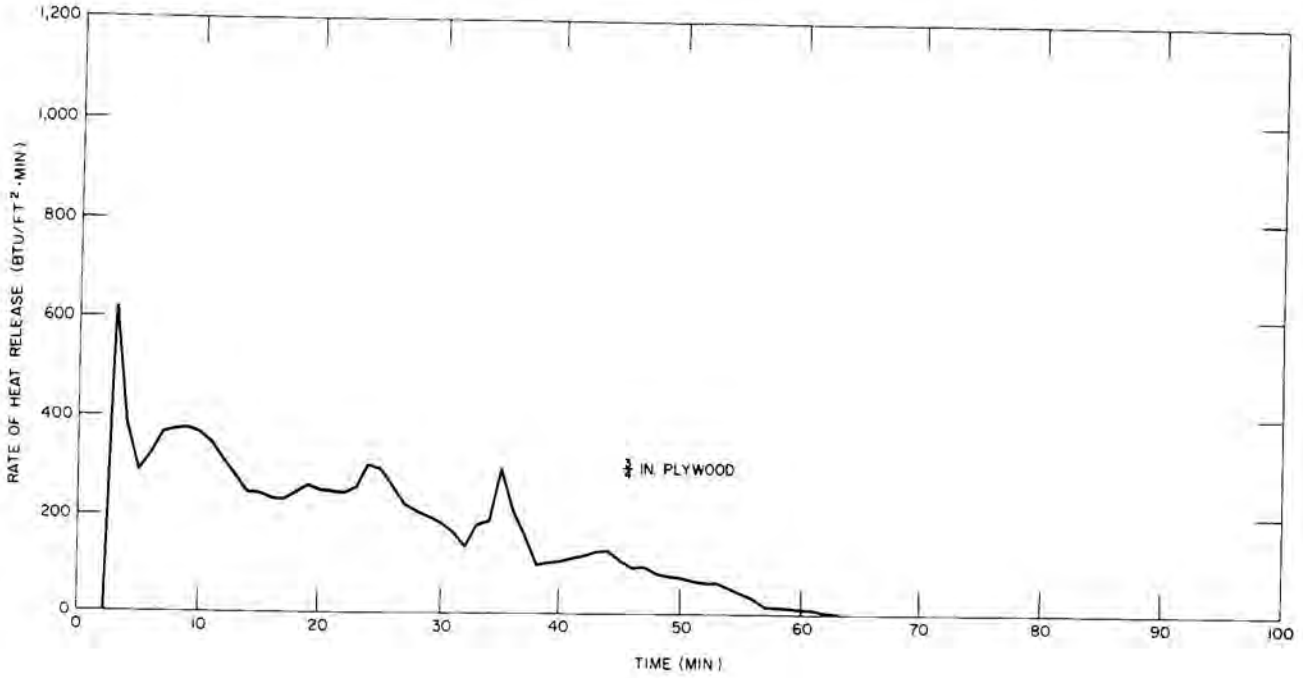

Figure 7.- Relationship of rate of heat release to time for one sheet of 3/4-inch-thick Douglas-fir plywood (Untreated).

(M 141 212)

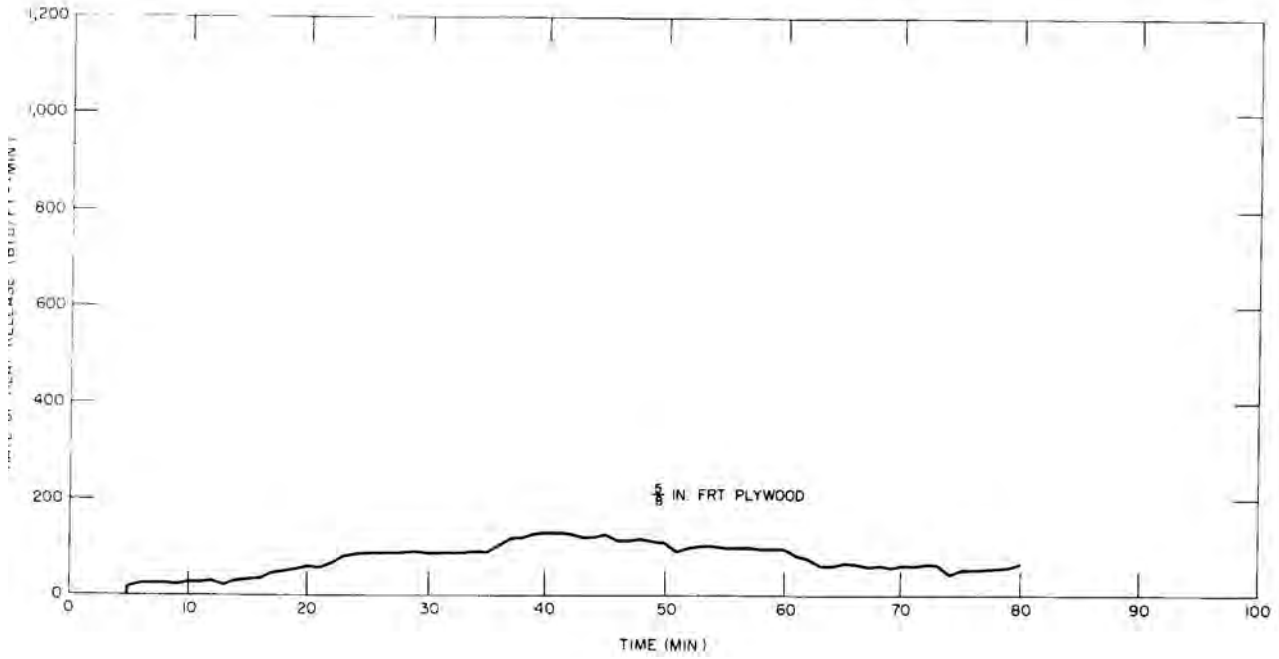

Figure 8.-Relationship of rate of heat release to time for one sheet of 5/8-inch-thick Douglas-fir plywood (fire-retardant treated (FRT)).

(M 141 215)

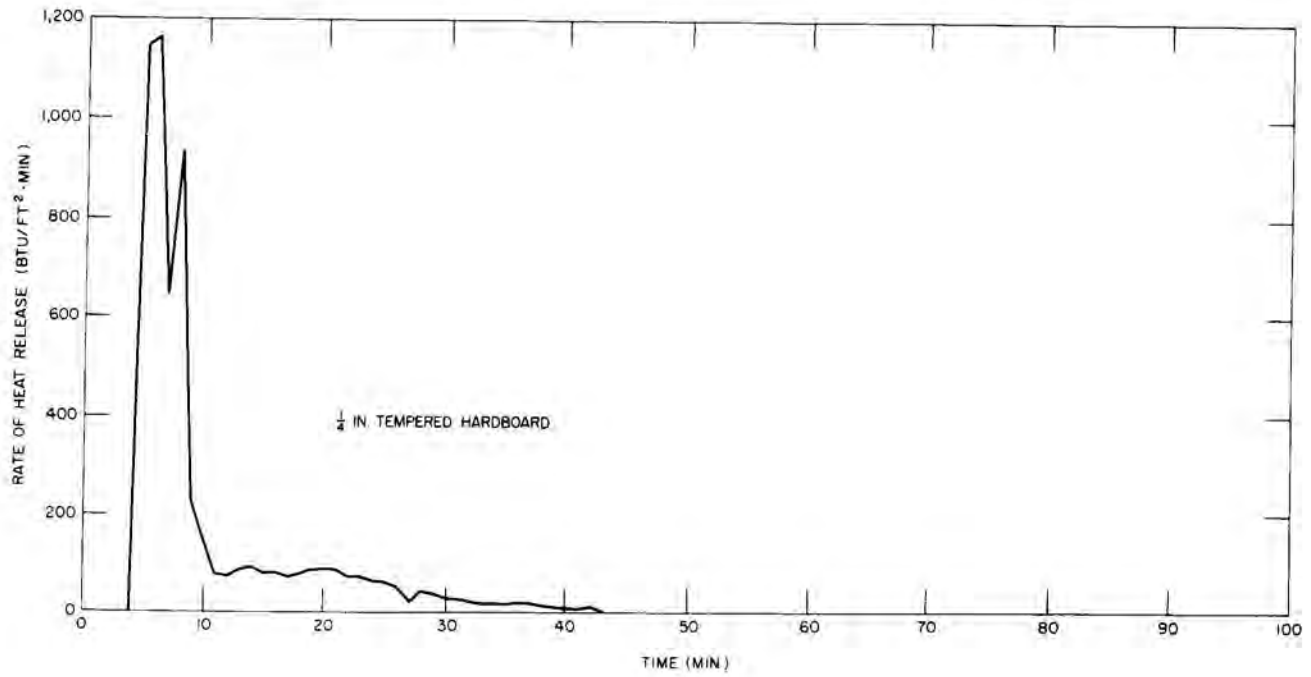

Figure 9.-Relationship of rate of heat release to time for one sheet of 1/4-inch-thick high-density hardboard (tempered quality).

(M 141 214)

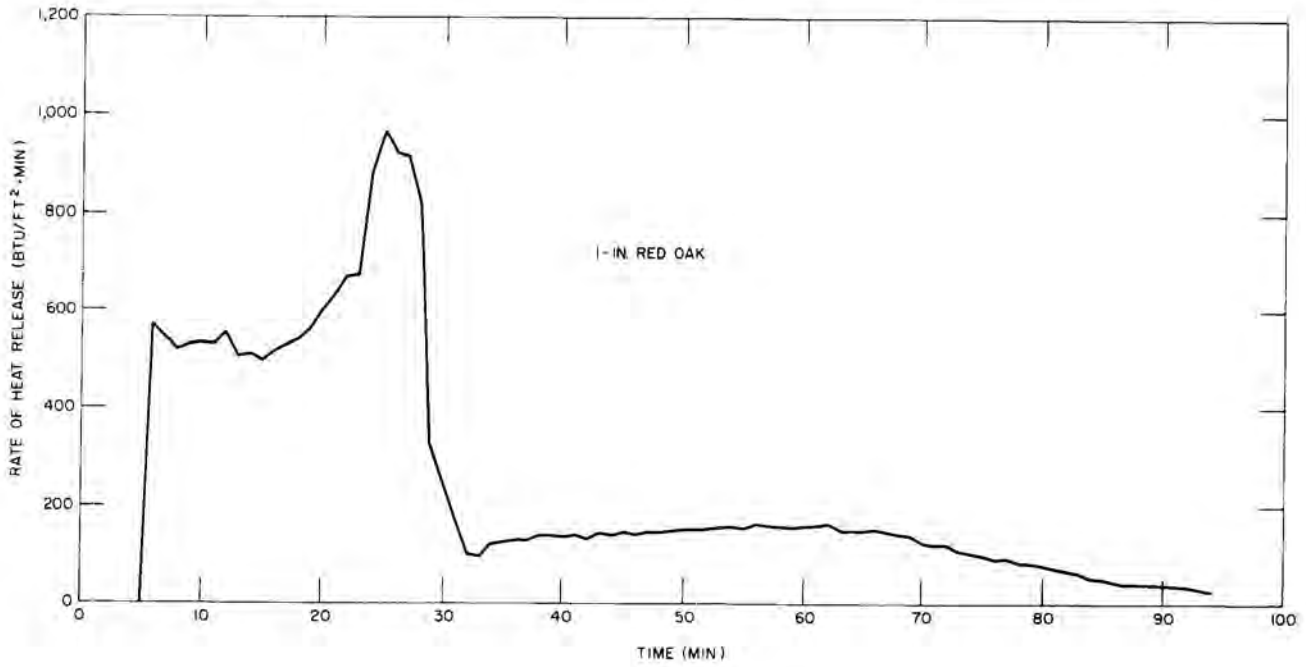

Figure 10.-Relationship of rate of heat release to time for one sheet of 1-inch-thick red oak.

(M 141 211)

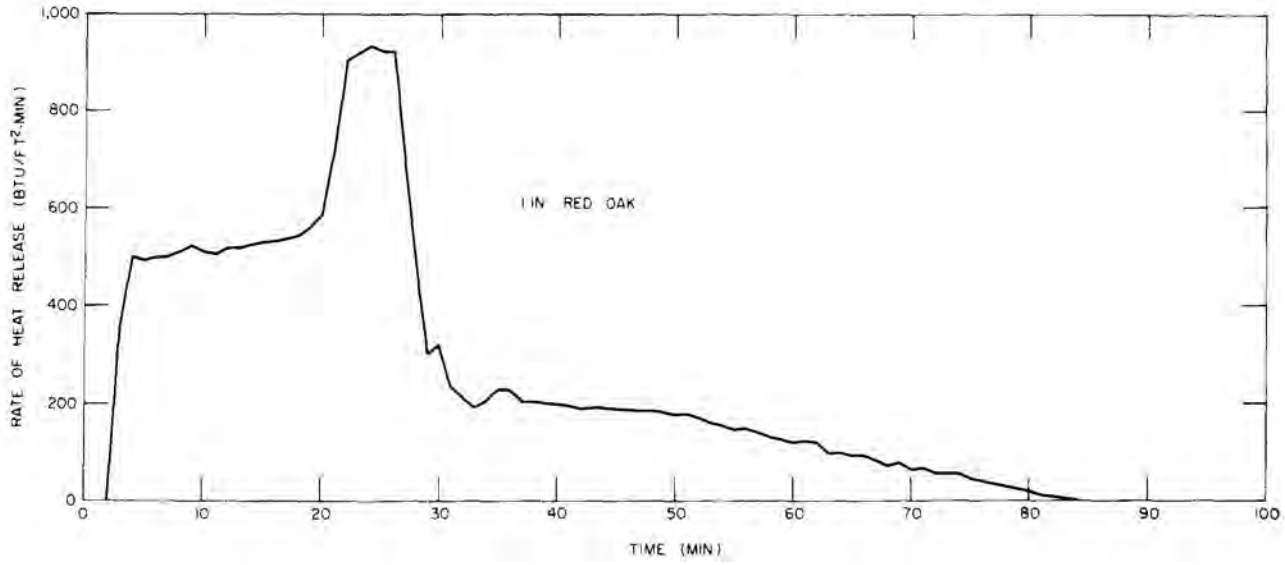

Figure 11.-Relationship of rate of heat release to time for one sheet of 1-inch-thick red oak (replicate of determination corresponding to fig. 9).

(M 142 039)

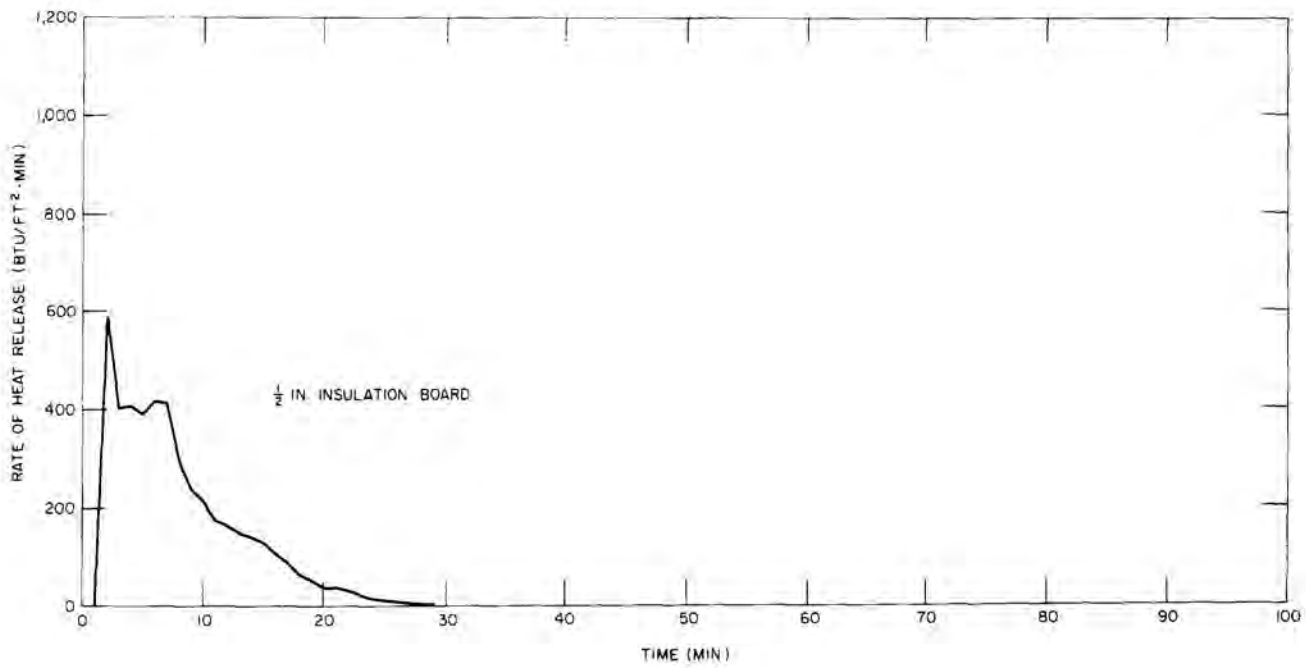

Figure 12.-Relationship of rate of heat release to time for one sheet of 1/2-inch-thick rigid insulation board.

(M 141 210)

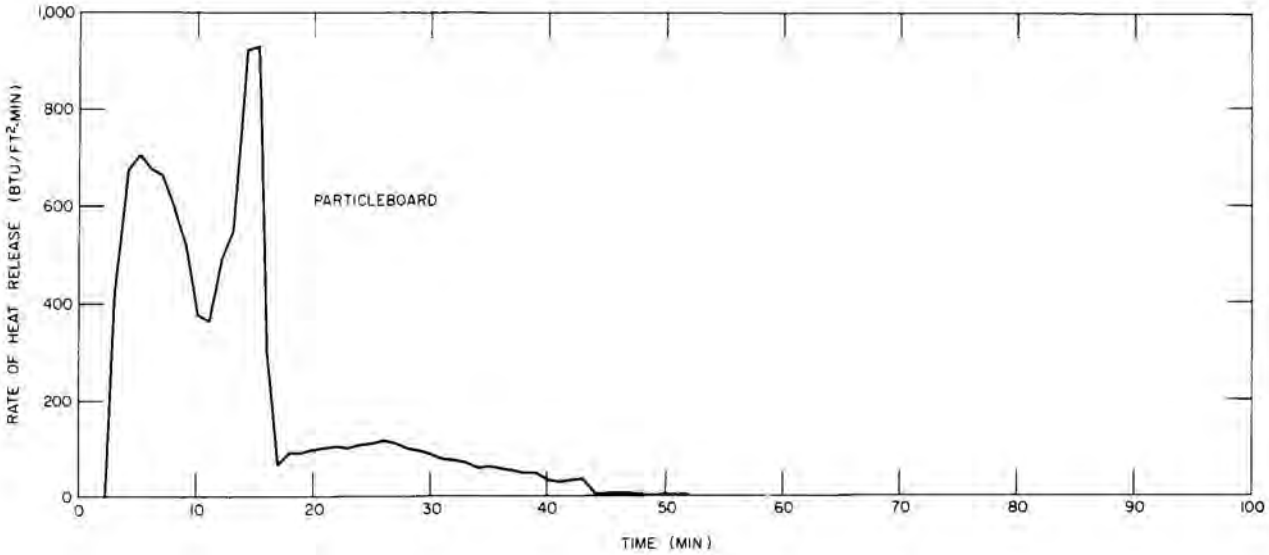

Figure 13.-Relationship of rated of heat release to time for one sheet of 1/2-inch-thick particleboard.
(M 142 041)

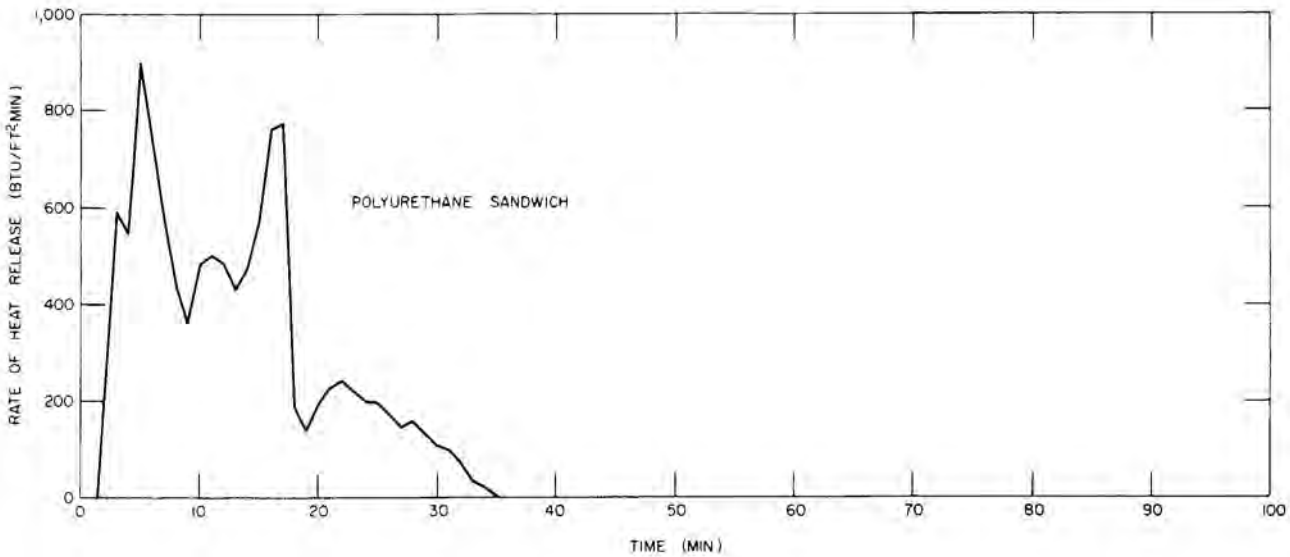

Figure 14.-Relationship of rate of heat release to time for 1/4-inch-thick Douglas-fir plywood-faced polyurethane sandwich panel.
(M 142 044)

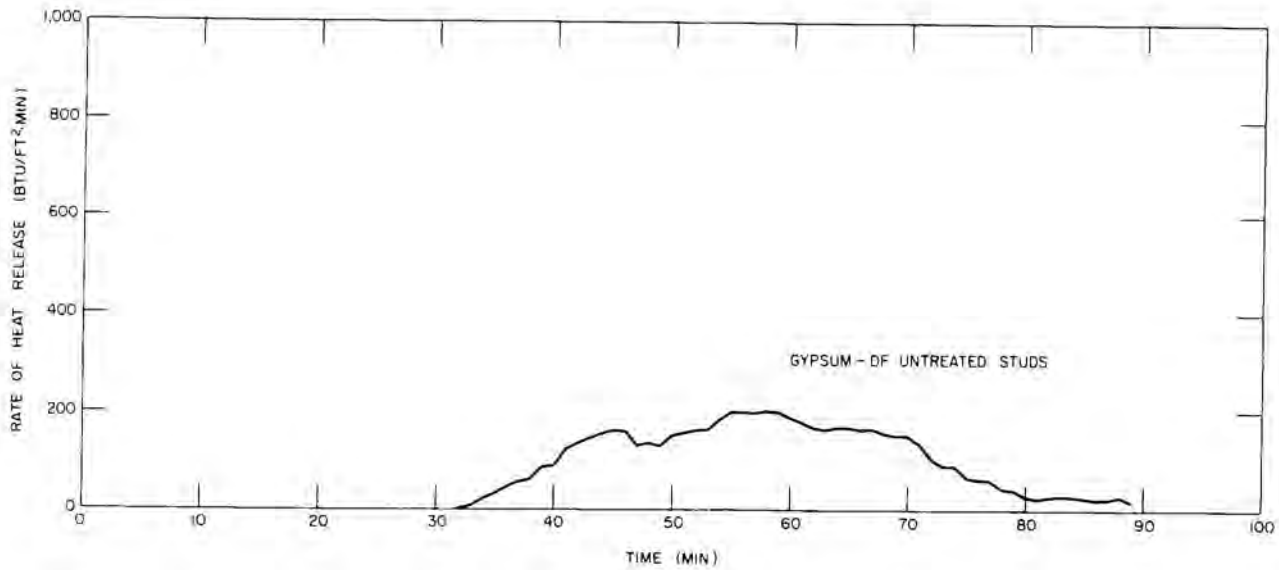

Figure 15.-Relationship of rate of heate release to time for gypsum wall-board-Douglas-fir (DF) stud wall assembly (three untreated studs.)

(M 142 042)

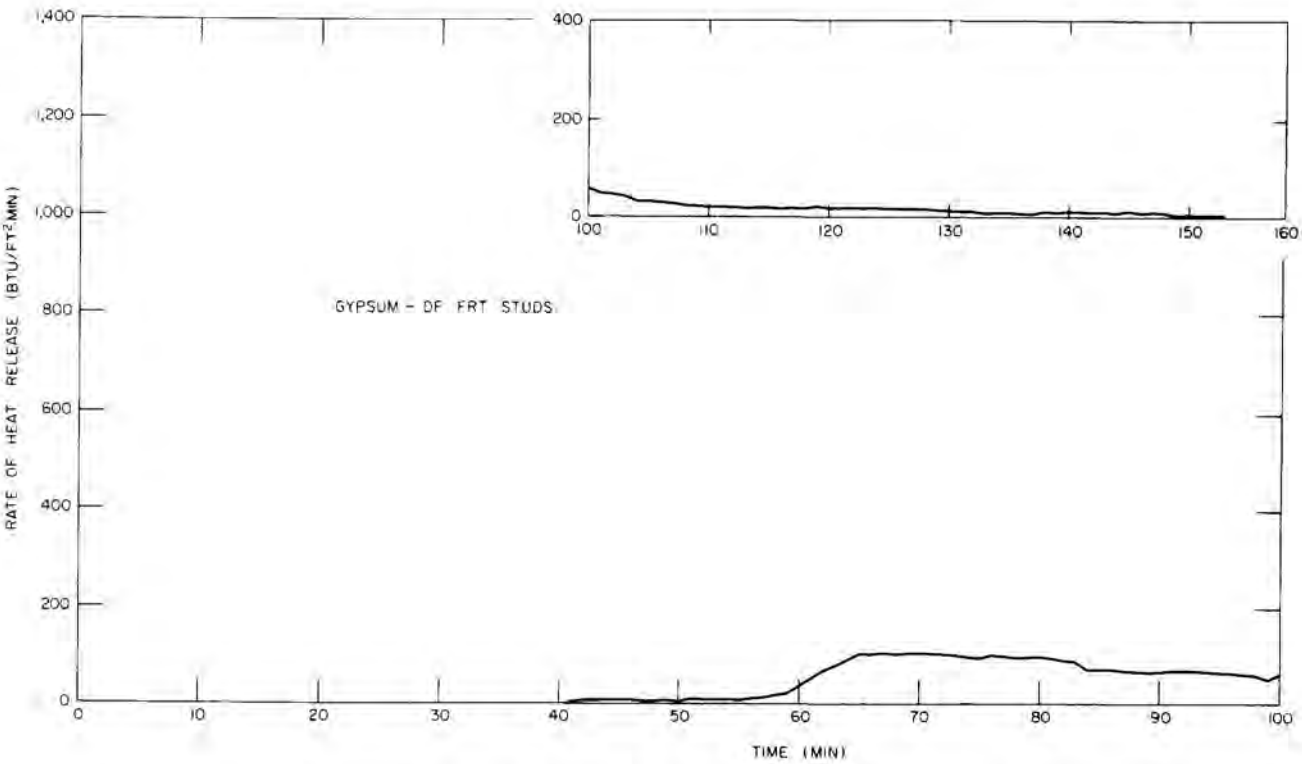

Figure 16..-Relationship of rate of heat release to time for gypsum wall-board-Douglas-fir (DF) stud wall assembly (three fire-retardant-treated (FRT) studs).

(M 142 040)

negative rates is that in this case heat flows from the furnace to the specimen rather than vice versa.

Three-Inch Douglas-Fir Plywood Laminate

Figure 5 shows that after the initial induction period the rate of heat release rises rapidly to 616 Btu's per minute per square foot at the end of 3 minutes. After this peak is reached, the rate falls off to the range of 300 to 350 Btu's per minute per square foot. The decline is steepest during approximately 3 minutes after the maximum value is reached. The average rate of heat release during the first 10 minutes of the test was 330 Btu's per minute per square foot. During a period from 20 to 40 minutes, the rate of heat release attains what is apparently a more or less steady state in the range of about 320 to 355 Btu's per minute per square foot, and the test was stopped.

The first period of rapid heat release is associated with flaming combustion of the pyrolysis products generated by the specimen. The period from about 6 minutes to about 20 minutes is characterized as combustion by both flaming and glowing during which a char layer is accumulated, and the zone of active pyrolysis penetrates more deeply into the specimen. After ahout 20 minutes, a more or less steady state apparently has been achieved in which the reaction zone progresses into the specimen at an approximately uniform rate. During this later period. combustion is almost exclusively by glowing.

Figure 6 was obtained from a specimen identical to that used for figure 5, except the test exposure was continued for a longer period. Figure 6 shows a lower initial peak of 476 Btu's per square foot per minute at 4 minutes, a slower rate of decline from that peak, and virtually no steady-state period such as that suggested by figure 5. During the first 10 minutes of the determination, the average rate of heat release is 265 Btu's per square foot per minute and 5.6 percent of the total area under the curve occurs during this time. Beginning at 17 minutes, the rate of heat release steadily increases to a peak of 705 Btu's per square foot per minute at 72 minutes. After the peak, there is a more or less steady decline to zero. In figure 6, apparently there is an initial flaming combustion period of about 15 minutes, followed by a period from about 15 minutes to about 75 minutes when the specimen becomes almost completely involved in a combination of flaming plus glowing combustion. The period after ahout 75 minutes probably represents a time of mostly glowing combustion.

Differences between figures 5 and 6 are probably due to slight differences in the samples and to unexplained differences in the runs. Also, it is possible that if the first test (fig. 5) had been continued, it would have indicated a second heat release peak similar to that noted in figure 6.

Three-Fourths-Inch Douglas-Fir Plywood

Examination of figure 7 and comparison of figure 7 with figures 5 and 6 are useful because the same material was used for all three determinations except that four thicknesses were used for figures 5 and 6, whereas one thickness was used for figure 7. Thus many differences between figure 7 and either figures 5 or 6 can be attributed mainly to differences in sample thickness (sample mass).

First to be noticed when these curves are compared is that they are remarkably alike during 0 to 6 minutes. Since this is the time during which combustion is largely by flaming, it can be concluded that the initial flaming reactions leading to flaming combustion are probably not dependent on the sample thickness for plywood 3/4 inch thick or greater. The first peak of 611 Btu's per square foot per minute occurs at 3 minutes. During the period from 6 minutes onward, figure 7 shows a generally declining rate of heat release with several peaks until the sample was consumed at the end of about 63 minutes. One explanation of the peaks is that they are associated with delamination of some of the plywood plies: thereby some fresh. unpyrolyzed wood is exposed that is then subject to flaming combustion in a manner similar to the mechanism that prevails during the first few minutes of exposure. If this is indeed the explanation, however, it is unclear why these peaks are not observed more distinctly in the other two figures. The average rate of heat release during the first 10 minutes of the run was 308 Btu's per square foot per minute. Calculations also show that 27.8 percent of the total area under the curve is under the first 10 minutes.

Five - Eighths-Inch Fire-Retardant Douglas- Fir Plywood

Examination of figure 8 and comparison with figure 7 are especially interesting. Although the material used to obtain figure 8 was slightly thinner than that used for figure 7, it is likely that differences in results are due mainly to fire-retardant treatment. Indeed, the slightly smaller weight of the sample used to obtain figure 8 might be expected to result in a slightly shorter induction time and faster rate of initial heat release. It thus appears that fire-retardant treatment eliminates the high portion of the

rate of heat release curve associated with flaming combustion, and reduces the rate of heat release from plywood for the first 35 minutes or so of exposure. The average rate of heat release during the first 10 minutes was 16 Btu's per square foot per minute, and 2.6 percent of the total area under the curve occurs during this time. The maximum rate of heat release observed was 132 Btu's per square foot per minute at 42 minutes for the treated plywood sample; whereas in figure 7 for the untreated plywood the initial heat release rate was 611 Btu's per square foot per minute at 3 minutes. The heat release rate for the untreated plywood also continued at more than 200 Btu's per square foot per minute for up to 30 minutes.

When there is a high external heat source and combustion is complete, fire-retardant-treated and untreated woods have approximately the same total heat release. Therefore, under the conditions of this research in which the exposure temperature was sufficiently high to result in continued burning of the fire-retardant-treated wood, there was a time period after 45 minutes when the untreated wood was almost consumed and the treated wood sample continued to release heat. However, under less severe external fire-exposure conditions, self-extinguishment of flaming and glowing of treated wood is possible with unburned residue. Self-extinguishment will result in the heating rate diminishing to almost zero sooner than for the untreated wood, less total heat release, and the heat release rate will then never exceed that for the untreated wood.

One-Fourth-Inch High-Density Hardboard

The data for 1/4-inch hardboard in figure 9 show a relatively long induction period followed by a high rate of heat release, probably by flaming combustion, that in turn is followed by a period of relatively low rate of heat release. The relatively long induction period may be explained on the basis that high temperatures are necessary to cause flaming combustion of the pyrolysis products from high-density hardboard. At any rate, more heat must be absorbed by the hardboard than by untreated plywood before active heat release begins. After burning begins, however, very high rates of heat release are observed until most of the specimen is consumed at the end of 10 to 12 minutes. The maximums are 1,159 and 928 Btu's per square foot per minute at 6.0 and 8.0 minutes, respectively. The period of 0 to 10 minutes has 73.2 percent of the total area under the curve: the average rate of heat release during this period is 425 Btu's per square foot per minute. The period after the first 12 minutes of the run probably represents glowing combustion of the portion of the specimen left after the initial period of high rates of heat release. Careful examination of the run data gives no clues to explain the dip and the recovery occurring at 27 minutes. Similarly, there is no readily discernible cause for the behavior of the data between 6 and 8 minutes into the run.

One-Inch Red Oak Lumber

Examination of figures 10 and 11 shows that red oak lumber gave comparatively high sustained rates of heat release. A conceptual model explaining this curve might be constructed as given in the following: First, there is a relatively long induction period that can be accounted for by the high sample mass. After the induction period, the sample is partly consumed by flaming combustion accompanied by heat release rates almost as great as those observed for Douglas-fir plywood. The average rates of heat release during the first 10 minutes in figures 10 and 11 were 269 and 389 Btu's per square foot per minute, respectively. During the first 10 minutes, in figure 10, 12.0 percent of the total area occurs while the corresponding proportion for figure 11 is 16.8 percent. Figure 10 shows peaks of 569 and 964 Btu's per square foot per minute at 6.0 and 5.0 minutes, respectively; whereas figure 11 shows a peak at 24.0 minutes of 932 Btu's per square foot per minute. For some unknown reason, in the red oak, the fire (in terms of the specimen consumption rate or heat release rate) tends to intensify during the period of 20 to 30 minutes until very high rates of heat release are observed. After about 30 to 32 minutes the flaming portion of decomposition is completed and the remainder of the sample is consumed by glowing. Thus the two replicate specimens of figures 10 and 11 behaved quite similarly to about 30 minutes, but finished their respective determinations by glowing that yielded slightly different shaped curves. There is no readily apparent explanation for the differences in the curves in the area usually characterized by glowing combustion.

One-Half-Inch Wood Fiber Insulation Board

Examination of figure 12 shows less clear-cut division between different sections of the curve. The initial induction period for this sample is relatively short, probably reflecting the small sample mass compared to the other

test materials. It is likely that the material is consumed by a combination of flaming and glowing combustion with flaming predominating at the start of the run and glowing predominating at the end. The maximum rate of 586 Btu's per square foot per minute at 2.0 minutes is similar to that obtained for the plywood tests and the initial part of the oak lumber tests. For this specimen, the average rate of heat release during the initial 10 minutes was 336 Btu's per square foot per minute. During that period 73.3 percent of the total area is found under the curve. The specimen is completely consumed in about 30 minutes.

One-Half-Inch Particleboard

Examination of figure 13 shows two distinct areas of interest in the behavior of particleboard when measured for rate of heat release. For about 15 minutes, cornbustion is, presumably, almost entirely by flaming with relatively little glowing. The two peaks in this period, 706 Btu's per square foot per minute at 5.0 minutes and 935 Btu's per square foot per minute at 15.0 minutes, may be due to an initial surface decomposition and flaming (first peak) followed by involvement of the whole specimen (second peak). The second peak value shown on this curve (935 Btu/min/ft) is one of the highest observed during this series of tests. Following this period of active flaming combustion there is a much longer period (from 15 min on) of glowing combustion characterized by relatively low rates of heat release during which the specimen is totally consumed. The average rate of heat release during the first 10 minutes is 465 Btu's per square foot per minute while 44.4 percent of the total area under the curve is found during this interval.

Three-and-One-Half-Inch Plywood-Faced Polyurethane Sandwich

Examination of figure 14 also shows two rather distinct areas: The period up to about 19 minutes and the period from 19 minutes to the completion of the test at 35 minutes. In the first period, the two peaks, 896 Btu's per square foot per minute at 5.0 minutes and 775 Btu's per square foot per minute at 17.0 minutes, may represent the flaming combustion associated with the two plywood facings of the sandwich panel. The area between the two peaks probably represents the thermal decomposition and burning of the polyurethane foam core of the panel. The average rate of heat release during the initial 10 minutes was 482 Btu's per square foot per minute while 42.3 percent of the total area under the curve is found in this interval. The second period probably represents glowing combustion of the remnants of the specimen left after active flaming combustion is no longer present.

Gypsum Wallboard Assembly With Untreated and Treated Wood Studs

Figures 15 and 16 represent data from testing simulated wall assemblies. Both of these curves are characterized by relatively long induction periods during which no measurable heat release occurs. These periods represent the time when heat is flowing through the gypsum wallboard to heat the wood studs to a temperature at which active burning can occur. As a result, there is no heat released during the first 10 minutes of these determinations. It is notable that figure 16 contains no sharp. distinct peaks such as those observed in some of the previously discussed figures although the maximum rate of heat release is 10.5 Btu's per square foot per minute at 67 minutes. The maximum rate of heat release in figure 15 is 206 Btu's per square foot per minute at 58 minutes. One interpretation of the lack of peaks is that after an extended period of mild pyrolysis, the studs finally burn by glowing rather than by flaming. If figure 15 is compared to figure 16, the effect of the fire-retardant treatment of the Douglas-fir studs is shown to markedly reduce the rate of heat release observed for the assembly. In addition, the treatment increases the time period from the start of the run to when measurable rates of heat release can be detected. It should be noted. however, that under the fire exposure of this research the heat is released from the treated assembly up to 153 minutes, whereas the untreated assembly is completely consumed in about 90 minutes. This is a similar trend to results observed for untreated and fire-retardant-treated plywood.

To summarize the discussion of experimental results as shown in table 1, these data show that there are differences in the behavior of the different specimen types when they are subjected to exposure in the rate of heat release apparatus. Thus the rate of heat release at any time after fire exposure is begun shows effects due to the test material itself (its composition), as well as its thickness, density, finish, and other factors. From another viewpoint, if it is considered that the total area under each curve is related to the total heat released by the specimen, table 1 shows that for materials of the type included in this study, the proportion of total heat released during the first 10 minutes varied from 2.6 to 73.3 percent. The data in table 1 also indicate that fire-retardant treatment of wood causes the treated wood to

have a much lower rate of heat release and a lower proportion of total heat released in the early stages of exposure than the untreated wood.

It is interesting to compare the values for rate of heat release obtained in this work with values obtained by others as reported in the literature *(5,9)*. The results given for the construction materials calorimeter *(5)*, using a substitution procedure similar to the one reported here, show for example, that 3/4-inch red oak gave values somewhat lower than those reported here. Those results (5) show a value of 394 Btu's per minute per square foot at 4 minutes, a decrease to 320 Btu's per minute per square foot at 5.5 minutes followed by a generally steady increase to around 440 Btu's per minute per square foot at 12 minutes (the end of the test). The data *(5)* generally are similar to the data shown in figures 10 and 11 of this report; the differences probably are due to variations in fire exposure and equipment construction.

Data in the literature for fire-retardant-treated plywood 3/4 inch thick (5) give a value of 88 to 103 Btu's per minute per square foot for the 2- to 10-minute range. The results in figure 8 are lower than these for the same time period. Again, the variation is probably due to differences in equipment and fire exposure as well as differences in fire-retardant treatment. The Construction Materials Calorimeter *(5)* also gives "no heat contribution" for 1/2-inch-thick gypsum wallboard. Figures 15 and 16 show long induction periods with no heat release being measured that probably represent the time for fire penetration of the gypsum wallboard in these assemblies.

Smith (9) has also given curves of rate of heat release versus time for several materials including particleboard and red oak. His data apparently are in the same order of magnitude as the results of this study, but the shape of the curves is somewhat different than those presented here. It is very likely that the lack of agreement can be attributed to differences in fire exposure environment between the two sets of apparatus.

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