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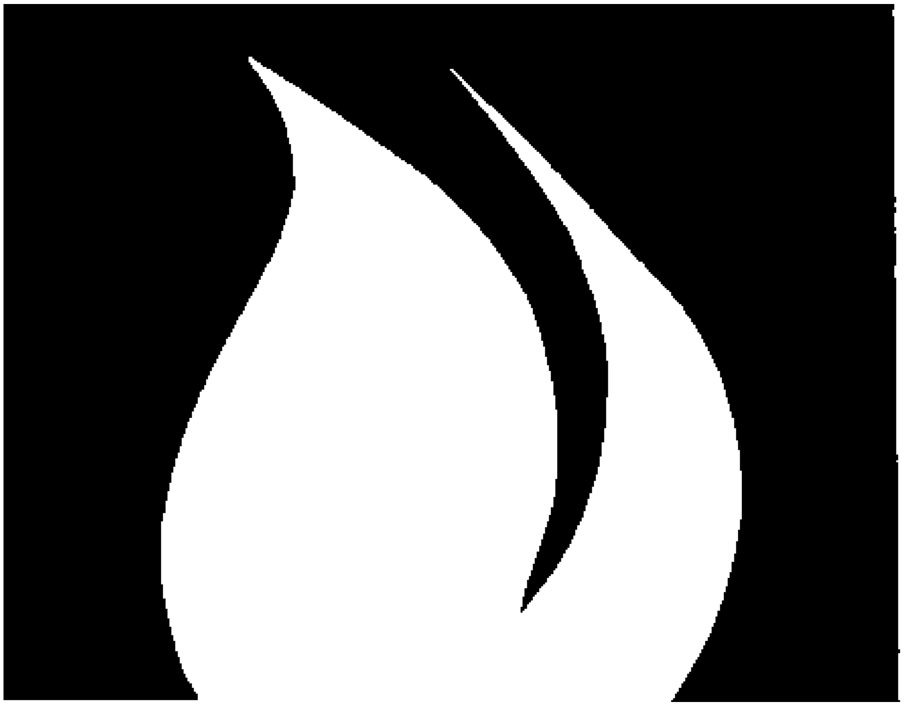
FPL 364

March 1980

Fire Development and Wall Endurance in Sandwich and Wood-Frame Structures



ABSTRACT

Large-scale fire tests were conducted on seven 16- by 24-foot structures. Four of these structures were of sandwich construction with cores of plastic or paper honeycomb and three wre of wood-fram construction. The wasss were loaded to a computer design loading, and the fire endurance determined under a fire exposure from a typical building contents loading of 4-1/2 lb/ft^2 floor area. The results in the large-scale tests henerally agreed with results of laboratory ASTM E 119 tests on the same wall constructions if the slower fire buildup time in the large-scale tests is considered. Thermal barrier protection (gypsum board) on the interior walls of the plywood sandwich construction provided the improved performance needed. The large-scale tests also showed a critical temperature associated with flashover under the fire conditions employed.

ACKNOWLEDGMENTS

The authors acknowledge the considerable cooperation and active participation in this study by many individuals of research work units and service groups at the Forest Products Laboratory. Particularly recognized are the contributions of Gunard Hans, who designed the structures; Roger Tuomi, who conceived and designed the system for structural loading of the walls; members at the FPL Engineering Mechanics Laboratory under the direction of Karl Kanvik, who built and instrumented the structures and obtained the test data; and E. L. Schaffer for his advice on analysis of some of the test results. The services provided by members of the Middleton, Wis., Volunteer Fire Department are also gratefully acknowledged.

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Fire Development and Wall Endurance in Sandwich and Wood-Frame Structures

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INTRODUCTION

Providing housing at reasonable cost challenges the Nation today. One means of reducing that cost is the introduction of new wall, floor, and roof assemblies that are both structurally and material efficient. The conventional light-frame stud-joist-rafter house is readily accepted as a standard, so it is logical to compare performance of any new construction designs with the conventional.

One of the key performance measures is fire safety, as reflected by the integrity of assemblies under exposure to fire. This paper discusses the results of fire safety research on load-bearing sandwich wall assemblies and compares results to those on the conventional stud wall. Structural sandwich panels with facings of plywood or wood-base panel products were evaluated for use in housing in cooperative research with the U.S. Department of Housing and Urban Development (HUD)(*5,6,8,16*).[2]

Initial research (*5*) with laboratory-scale fire endurance tests (ASTM E 119 (*2*)) as a part of the Forest Products Laboratory (FPL) program had indicated structural failure of unprotected sandwich walls under design load in 3 to 6 minutes. Interior protection with 1/2-inch type-X gypsum wallboard provided an additional 20 minutes of fire endurance. Endurance times for several types of wood-stud walls ranged from 16 to 34 minutes.

However, these laboratory tests provide only relative performance, not actual endurance times, of complete structures where there are interactions of many building elements. In full-scale structural fires, the time from ignition to full involvement depends on several variables; therefore, the time for the structures to reach various temperature levels at the wall surfaces will differ from the time used in standard tests.

The principal objectives of this study were to obtain information on the actual endurance times of structural sandwich walls in one-story, 16- by 24-foot structures under design loads when exposed to interior fires: To determine the influence of interior thermal protection, to compare endurance times for similarly built wood-frame structures, and to correlate performances to laboratory-scale results.

Laboratory fire endurance evaluations exceeding 30 minutes for symmetrical interior walls are quite extensive. However, until recently, fire endurance data have not been available on conventional exterior wood-frame walls for one- or two-family housing or sandwich assemblies for use in walls for this type of housing (*5*). Nor are fire endurance data available from extensive full-scale fire tests of struc-

[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.

tural sandwich housing or even of conventional wood-frame housing while under design loads. This research was designed to provide these data

TEST STRUCTURES

The structures for these tests were one-story three-room, flat-roofed, 16 by 24 by 8 feet high and built on a concrete slab (figs. 1-2) The east room was approximately 12 by 16 feet, and the two west rooms were each 8 by 12 feet. Door openings were 3 feet by 6 feet 8 inches.

The primary interest was in the fire endurance of the long, load-bearing walls in the structure. Because the structural integrity of the end walls was necessary until all the loaded wall sections had failed members of the local volunteer fire department occasionally sprayed water on the end walls if it appeared that the fire would cause their prior failure

Construction Types

Construction of sandwich panels and stud-frame walls used in this research was generally the same as the 8- by 10-foot wall sections tested in the ASTM E 119 furnace at FPL (5) A summary of the wall and roof construction is given in table 1. Additional roof or ceiling protection was provided in the structures lo ensure that structural failure of all wall sections would occur before ceiling-roof failure caused abortion of the test

Combustible Contents Fuel Load

The combustible contents load in the structures was simulated by the use of 70-pound, 2- by 2-foot wood cribs, constructed of 2- by 2-inch and 2- by 4-inch western white woods (fig. 2)(*12*) All material was dried to constant weight at 80° F and 30 percent relative humidity — about 6 percent moisture content. The cribs were distributed on the floor of the structure (figs. 2-3), with four triple-type cribs included to represent large furniture items

The total combustible contents load from the cribs was about 1,550 pounds (ovendry weight) in each structure. The average fire load density was about 4.5 pounds per square foot (lb/ft^2) of floor area. This corresponded closely to the combustible contents fire load density (3.9 lb/ft^2 in living rooms and 5.0 lb/ft^2 in bedrooms including closets) which was indicated for residences in a 1942 survey of residences by the National Bureau of Standards (*9*) Other full-scale burnout tests (*4,14*) have used fire load densities from 2 3 to 3.8 lb/ft^2.

In addition to the crib loads, there

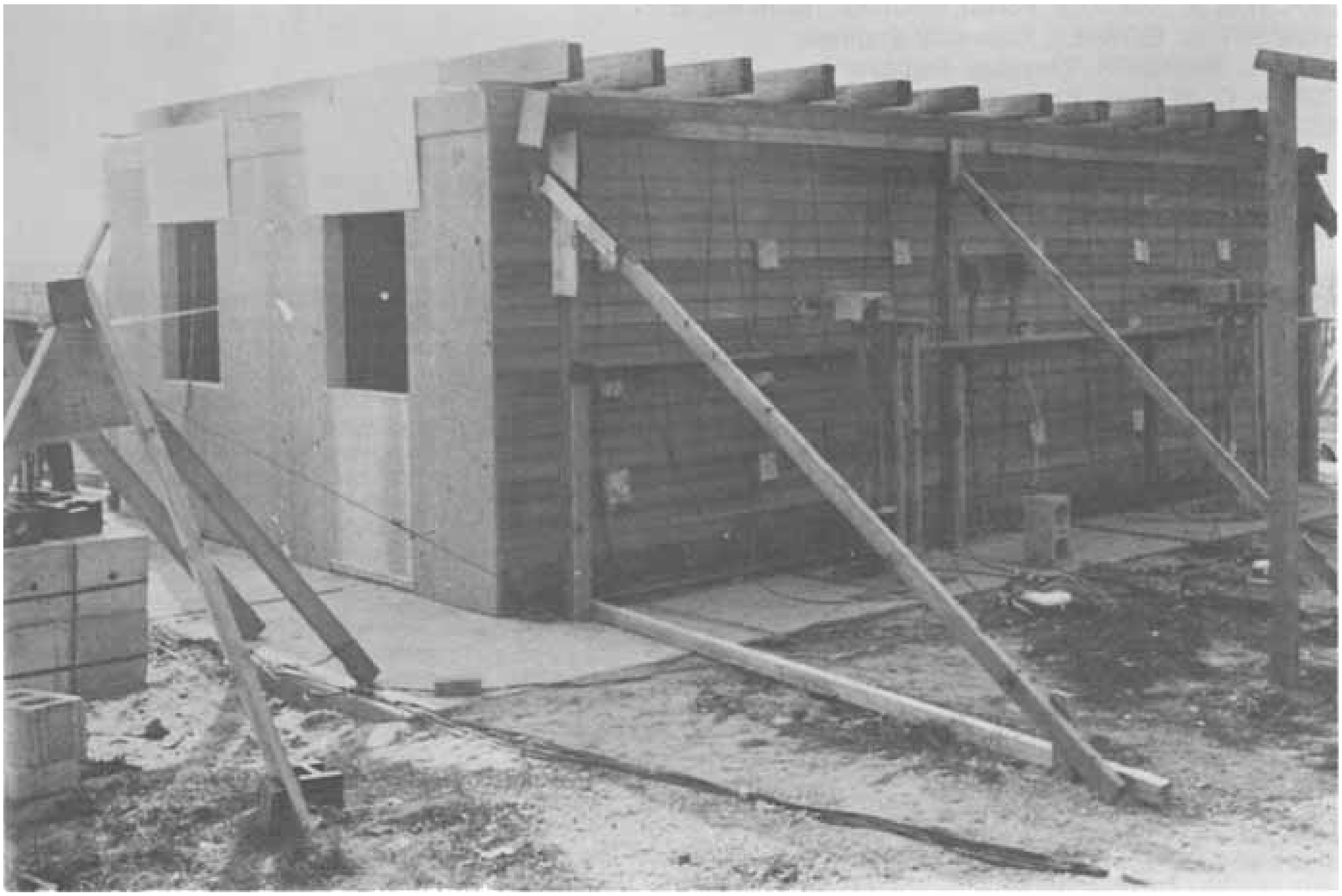

Figure 1. — Outside view of Structure 7 before start of the fire test
(M 143 767-6)

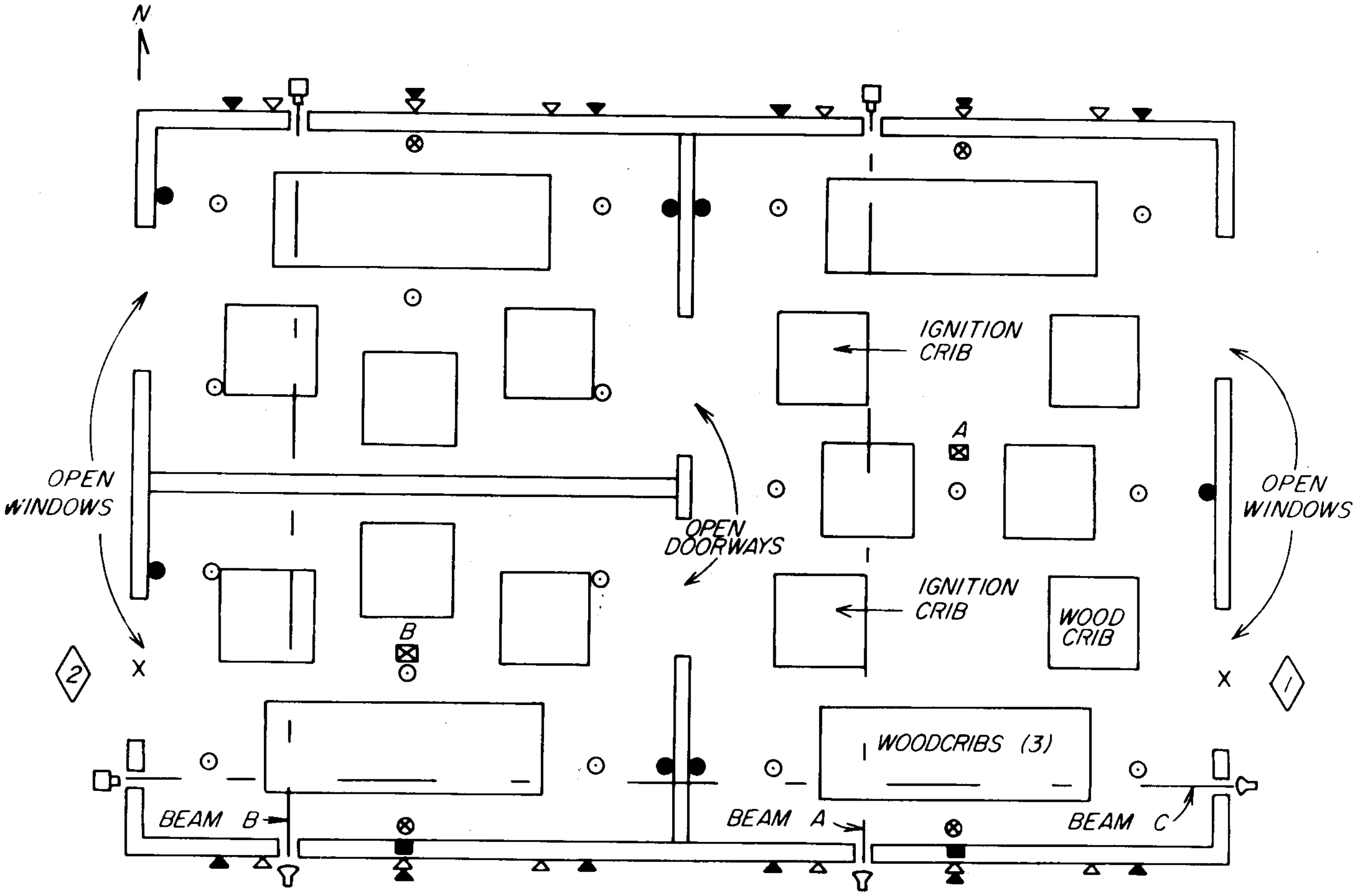

Figure 2.—Plan view of sandwich and wood-frame test structures showing locations of wood cribs, thermocouuples, gas sampling points, and smoke-measuring apparatus.

Symbols:

- △ *Thermocouples under 6- by 6-inch asbestos pads at 2-, 4-, and 6-foot heights.*
- ⊙ *Thermocouples in air at 1-, 3-, 5-, and 7-foot heights and at floor and ceiling.*
- ● *Thermocouples on surface at 1-, 4-, and 7-foot heights.*
- ■ *Thermocouples behind interior wall lining at 1-, 4-, and 7-foot heights.*
- × *Thermocouples at 4-inch intervals in southeast and southwest window openings.*
- ⊠ *Gas-sampling tubes at 5-foot height, A & B.*
- ⊲ *Light sources at 5-foot height for smoke measurements.*
- ⊏ *Light receptors at 5-foot height for smoke measurements.*
- ⊗ *Thermocouples in ½-inch capped iron pipe located 6 inches from interior wall at 1-, 4-, and 7-½-foot heights.*
- ◇1 *Radiometer, total hemispherical, 10 feet from east window.*
- ◇2 *Radiometer, circular foil, quartz window, 10 feet from west window.*
- ▲ *Deflection measurement locations on exterior wall at midheight.*

(M 148 000)

was the added combustible load from the plywood interior lining on the walls in Structures 1, 3, 4, and 7 of about 2 lb/ft^2. For Structures 1, 3, and 4 with plywood ceilings, there was an additional fuel load of 0.8 lb/ft^2.

Structural Loading

A vertical load of 1,250 pounds per linear foot was applied to both of the longer north and south walls of each structure. This load was the same as used in the laboratory ASTM E 119 wall tests (*5*), and was selected on the basis of maximum design load for a 28-foot-wide, two-story, frame house with a 2-foot overhang. The load was applied through four pulley and cable systems (two each side) attached between the concrete slab and wood beams across the roof, and terminating in a 1,250-pound dead weight (figs. 1 and 4).

ASTM E 119 (*2*), for load-bearing walls, requires the application of a "superimposed load to the construction in a manner calculated to develop theoretically, as near as practicable, the working stresses contemplated by the design." It also states that test specimen vertical edges shall not be restrained. The vertical loads as applied down through the roof members in this study reasonably simulated actual conditions. However, there was vertical edge restraint at the four outside corners and some restraint at the joining of the interior partitions. The time to structural failure, as measured in this study, was determined by total deflection (until weights struck the ground). Therefore, the failure of one 4- by 8-foot panel could result in structural failure. There was minimal vertical edge restraint lor the center panel in each wall section. Consequently, the ASTM E 119 requirements were partially met.

This design load is not the maximum design load based on maximum allowable stresses within the structural component. Maximum design loads and the ratios of applied load to maximum design loads are listed in table 2. The maximum design loads of the sandwich walls were computed according to the American Plywood Association (*1*). The maximum design load of the wood-frame walls is based on the allowable compression stress perpendicular to the grain of the plates.

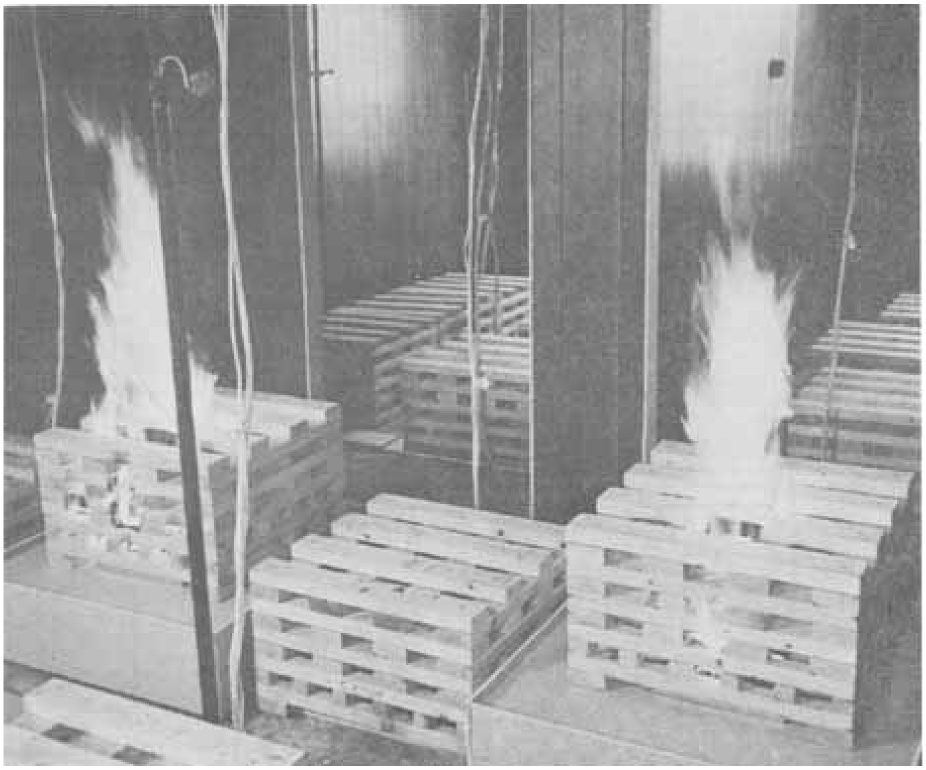

Figure 3.—Ignition cribs shortly after the start of the test—Structure 7. White, beaded wires are thermocouple "frees." Pipes at center of rear room and at the far left are for gas sampling.

(M 143 767-4)

Ventilation

Ventilation was provided by two window openings, 3 by 3-1/2 feet in both the east and west walls of the structure. No glazing was used in the openings.

Window openings were selected to obtain a fully developed fire condition that was controlled primarily by the ventilation. rather than a short-lived maximum-intensity fire controlled by the surface of the combustible contents. It was desired that the rate of burning and ventilation from the initial crib fire be sufficient to bring about a "flashover" to a fully developed fire. After the "flashover" and exposure of all crib contents, the fire intensity was then to be controlled by the ventilation over a time sufficient to determine fire endurance characteristics of the two 24-foot exterior walls. "Ventilation-controlled" and "fuel-surface-controlled" fires are described in the literature (*7, 11*).

It was determined that the ventilation should be selected near, but below. the "critical airflow" as given by Harmathy (*7*). The critical airflow is that at which any increased air flow would cause the fire to become controlled by the surface area of the fuel rather than by the amount of ventilation.

At the selected 4.5 lb/ft^2 fire load density (combustible contents), the critical airflow rate (7) is about 7.5 pounds per second (lb/sec). It was desired that the total window opening area of the structure be selected so that the airflow rate would be below 7.5 lb/sec and the fire be ventilation controlled. The airflow with natural ventilation, U_a (lb/sec), is given by the equation:[3]

$$U_a = \frac{A_w \sqrt{h}}{15} \qquad (1)$$

where

A_w is the total area of windows (ft^2), and

h is the height of windows (ft).

If 3½ feet is selected as a conve-

[3] Hamathy's equation is based on a room 25 ft by 12 ft by 9 ft 5 in. or 2,825 ft^3. The interior dimensions of the structures used in this study were 22 ft 10 in. by 15 ft 1 in by 8 ft or 2,775 ft^3. The equation is assumed to be applicable to this structure.

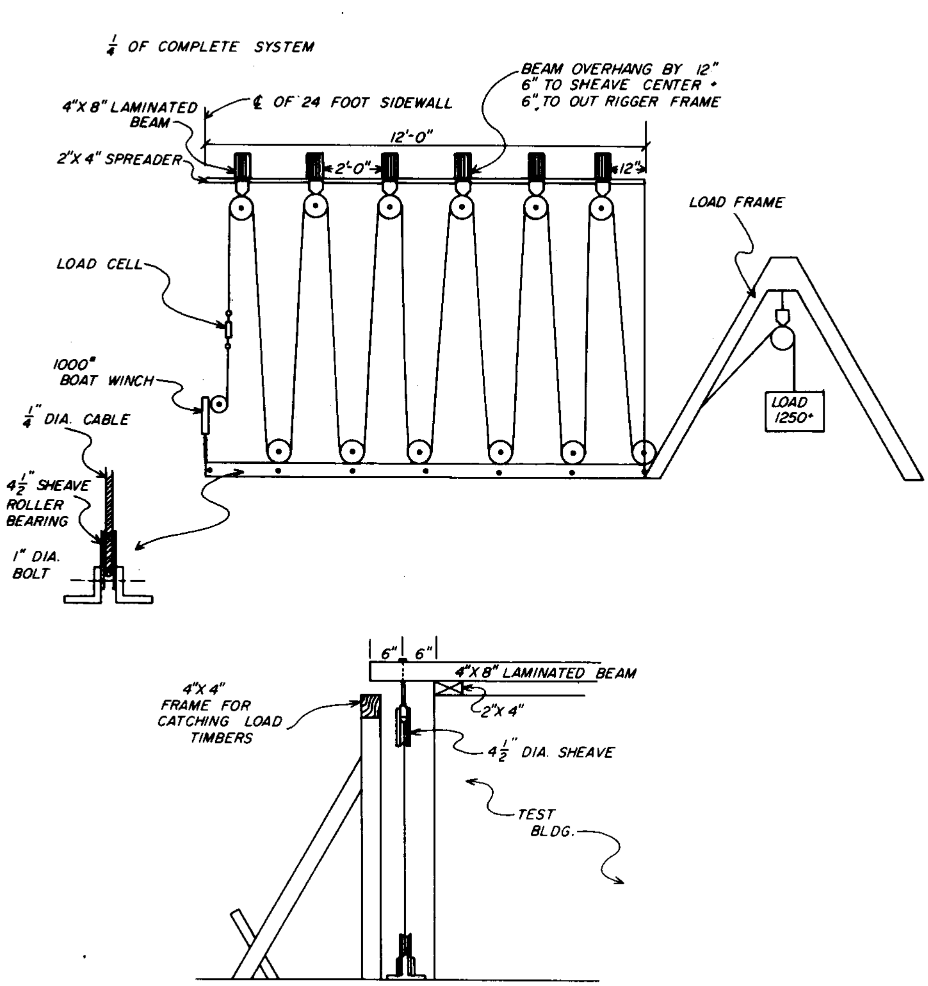

Figure 4.—Schematic for applying design load to north and south walls of test structures.

(M 148 004)

nient window height for the structure, the total window area which would give the critical airflow rate (from eq. (1)) is 60 2 ft^2. Designing the test building with four windows, 3 feet wide sy 3½ feet high, gives a total window area of 42 ft^2. This should provide an air flow below the critical rate for the fire loading selected and thus give a ventilation-controlled fire.

INSTRUMENTATION AND MEASUREMENTS

The test structures were instrumented with a total of 220 sensors automatically read by a multiple-point digitizing data system controlled by 3 programmable calculator. The scanning rate was five data points per second with a scan interval of 1 minute, repeated during the entire duration of test. The data thus obtained were recorded by a high-speed paper tape punch system and subsequently transferred to the University of Wisconsin computer for processing.

A total of 198 thermocouples for temperature measurement were arranged inside and outside each structure (fig, 2). All thermocouples were of type K, chromel-alumel, 20-gage, polyvinyl-covered thermocouple wire. Air and surface temperatures were taken throughout the structure using vertical thermocouple "trees" (fig. 3), with the wires protected with ceramic beads. Smaller thermocouple trees were located at the center of the southwest and southeast window openings to record temperatures at 4-inch vertical increments.

In addition, thermocouples were located inside ½-inch-diameter capped iron pipes, facing and 6 inches from the interior of the side walls, at four locations. Thermocouples were also located underneath standard (ASTM E 119) 6- by 6-inch asbestos pads at the 2-, 4-, and 6-foot levels on the exterior of the two side walls (fig. 2).

For some of the tests, three additional thermocouples were located at the 1-, 4-, and 7-foot heights at the center of the south wall in the large and small rooms. These thermocouples were located in the back of the interior lining material.

During each fire test, the light transmission properties of the accumulated smoke were measured over three "light paths" in the structure (fig. 2). The light source was a sealed-beam bulb supplied with a regulaled 6-volt direct current power supply; the receiving unit included a silicon phototransistor driving a single-stage amplifier.

A limited number of composition measurements on the atmosphere in the structure were made during the fire tests. In the first test, the fire gases at one point were sampled for carbon monoxide (CO) and hydrogen cyanide (HCN). During the subsequent tests, two sample points were used (fig. 2), and in some cases data were obtained for carbon dioxide (CO_2) concentrations as well as CO and HCN. The gas analyses were made by pumping a known volume of gas sample through a glass tube packed with analytical reagent crystals.

Thermal radiation was monitored from the center of the southwest window opening and from the center of the southeast window opening. The radiometers had to be removed shortly before flashover occurred to protect them from destruction. Wind direction and speed were continuously monitored throughout the testing period.

The two ignition cribs were weighed during each test, using ringtype strain gage load cells. The lateral deflection of the geometrical center of each 4- by 8-foot wall panel was measured during the fire tests. The interior fires were allowed to continue until each of the four 8- by 12-foot exterior load-bearing wall sections had lost its structural integrity. Structural wall failure was considered to have occurred when the dead weight at the end of the loading cable of each wall section was lowered to the ground. Time to structural failure was recorded manually. Observations were also made of any fire penetration through the walls.

RESULTS AND DISCUSSION

Interior Fire Exposure

Ambient Conditions During Tests

The structures were tested in order as numbered. The first test was conducted on May 28, and the others at about 3-week intervals.

Some variation in ambient weather conditions between tests was unavoidable (table 3). Wind speed, direction, and character—steady or gusty—affected the burning intensity and most probably had some effect on time of flashover. In particular, during the test of Structure 6, the westerly wind entered the west facing windows and exited through the east facing windows of the large room. The early flashover time of 14:30 (minutes:seconds) was influenced by this wind condition. The wind condition may also have influenced flashover in Structure 5.

Fire Growth Stage

Within 2 to 6 minutes after the two ignition cribs were ignited (fig. 3) and (table 4), flames from the cribs reached the gypsum wallboard ceiling, but did not immediately spread across the ceiling. Cribs adjacent to the ignition cribs ignited as early as 3:45 and as late as 14:40 into the test. Flames and increasing radiant flux brought on ignition of other cribs. AS temperature increased, the wood decomposition products accumulated in the room. Before all cribs ignited in the large room, the flames from the individual cribs appeared to blend together and began to fill the room. These flames then usually extended or spread upward along the walls. across the ceiling, and out the east windows of the large room. The time of flame emission from the east windows was reported as the flashover time (table 4). Within 45 seconds, and usually before any cribs were ignited in the small west room, the flashover in the large room extended into the small rooms and out the windows at the west end of the structure.

There were two exceptions to this general course of events in the test of Structure 6, during which a westerly wind of 4 to 13 miles per hour (table 3) was entering the open west windows, the first flashover occurred at 14:30 (table 4) in the large room with flames exiting the east windows. Flamespread into the small west rooms, against the wind direction, occurred about 7 minutes later at 23:15 with flaming out of west windows at 29:22, almost 15 minutes after the initial flashover. Obviously, both of these flashover occurrences were affected by the direction and velocity of the wind.

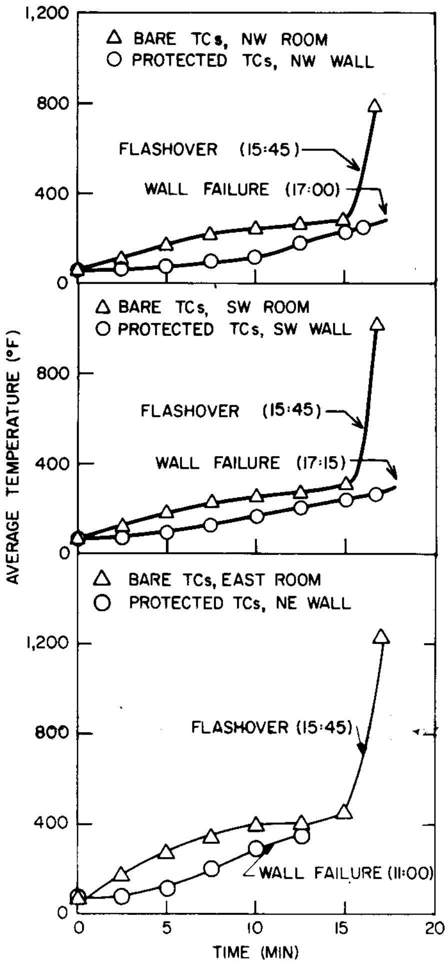

Figure 5.—Temperature development in Structure 1.

(M 148 005)

Events in Structure 5 also indicated some influence of the wind condition. A north wind with a slight westerly component, at 2 to 15 miles per hour (table 3), caused some east to west movement of air through the structure. First flashover with flames out of the east windows occurred at 21:15 (table 4). Ten seconds later flames spread into the small rooms, but were not emitted from the west windows until 35:25. The spread of flames into the small rooms very shortly after the flashover in the large room was typical and occurred with all other tests except Structure 6. Consequently, there is a question if the wind really affected the initial flashover in the test of Structure 5.

Development of average room temperature up to time of flashover was slow; rapid development occurred after flashover (figs. 5-8).

Flashover

Times of flashover varied from 14:30 to 28:30 (table 4). Both of these extremes were in structures with noncombustible wallboard on the walls. Average times of flashover obtained in the structures with combustible linings were 18:45 compared with 24:52 for structures with noncombustible linings. The low flashover value obtained in Structure 6 due to effect of wind is not included.

In a study of fire buildup to flashover in full-size room conditions, Waterman (*18*) described room flashover as the rapid involvement of the combustible contents of a room due to their ignition energies being exceeded almost simultaneously. Schaffer and Eickner (*15*) noted in large-scale corridor fire tests that an important contribution to flashover was the accumulation, near the ceiling, of unburned gases generated from the primary fuel source. The ignition of these gases can occur prior to extensive surface ignition. The additional contribution of heat and radiation by the flames can cause almost immediate ignition of surrounding combustible surfaces. This study confirms these conclusions and shows the significance of the temperature attainment in the upper level of the room on flashover.

The mixture of gases with air had to reach a "critical" temperature for ignition to occur at that composition. Critical temperatures associated with flashover were obtained at seven locations at the 7-foot level in the large room of each of seven structures (table 5). The temperature selected as critical at each location was the reading that occurred just before a significant temperature rise associated with flashover. The criteria for selection was that the temperature rise before the next reading (about 1 min) be equal to, or greater than, 100° F. Thermocouples indicated a cooler layer of air occurred at the ceiling than at the 7-

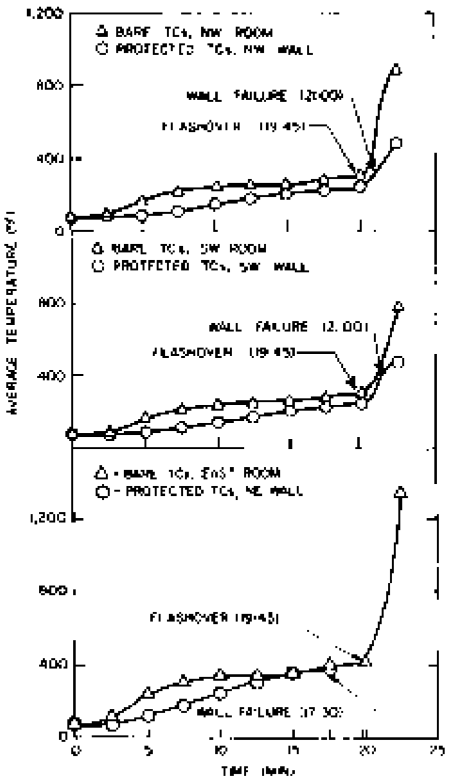

Figure 6.—Temperature development in Structure 3.
(M 148 007)

foot level during fire buildup before flashover. It was also cooler at the 5-foot level. In the four structures with combustible plywood wall linings, the mean critical temperature at the 7-foot level associated with flashover was 640° F (standard deviation, 25°). In structures with noncombustible wall linings, this critical temperature was 709° F (standard deviation, 62°). higher by only 69° F. The two groups of temperature data (table 5) are not very different, indicating that combustible wall linings have only a minor effect on the criteria for flashover—critical temperature and flammable gas composition.

We can assume that the combustible linings during fire buildup underwent some pyrolysis and contributed to the accumulation of flammable volatiles from the wood-crib contents. The higher concentration of volatiles. therefore. required a lower critical temperature for ignition. The plywood wall linings in Structures 1, 3, 4, and 7 added 2 pounds of fuel to the 4.5 lb/ft^2 crib load. Considering the large amount of additional fuel surface area added by the plywood wall linings, the difference in critical temperatures of 69° F (709° - 640°) associated with flashover is not substantial. The difference, too, in average times of flashover between the combustible (18:45) and noncombustible (24:52) lined structures was small.

It should be noted that the critical temperature, as defined above and determined in this study, may not be the same for other thermocouple locations or room geometrics.

Similarity is strong in the areas under the time-temperature curves (figs. 5-8) of the average tempetalures in all the large rooms from ignition to time of flashover (table 6). This area, expressed in degree Fahrenheit minutes (°F min), may be considered a measure of the fire exposure severity in the room. For the structures with combustible plywood linings, the flashover occurred when the temperature buildup as a function of time reached an average of 4,490° F-min with a coefficient of variation of 4 percent. The figure for the two structures with noncombustible wall linings was higher but the accuracy of the data was influenced by the wind effect on Structure 6. There is

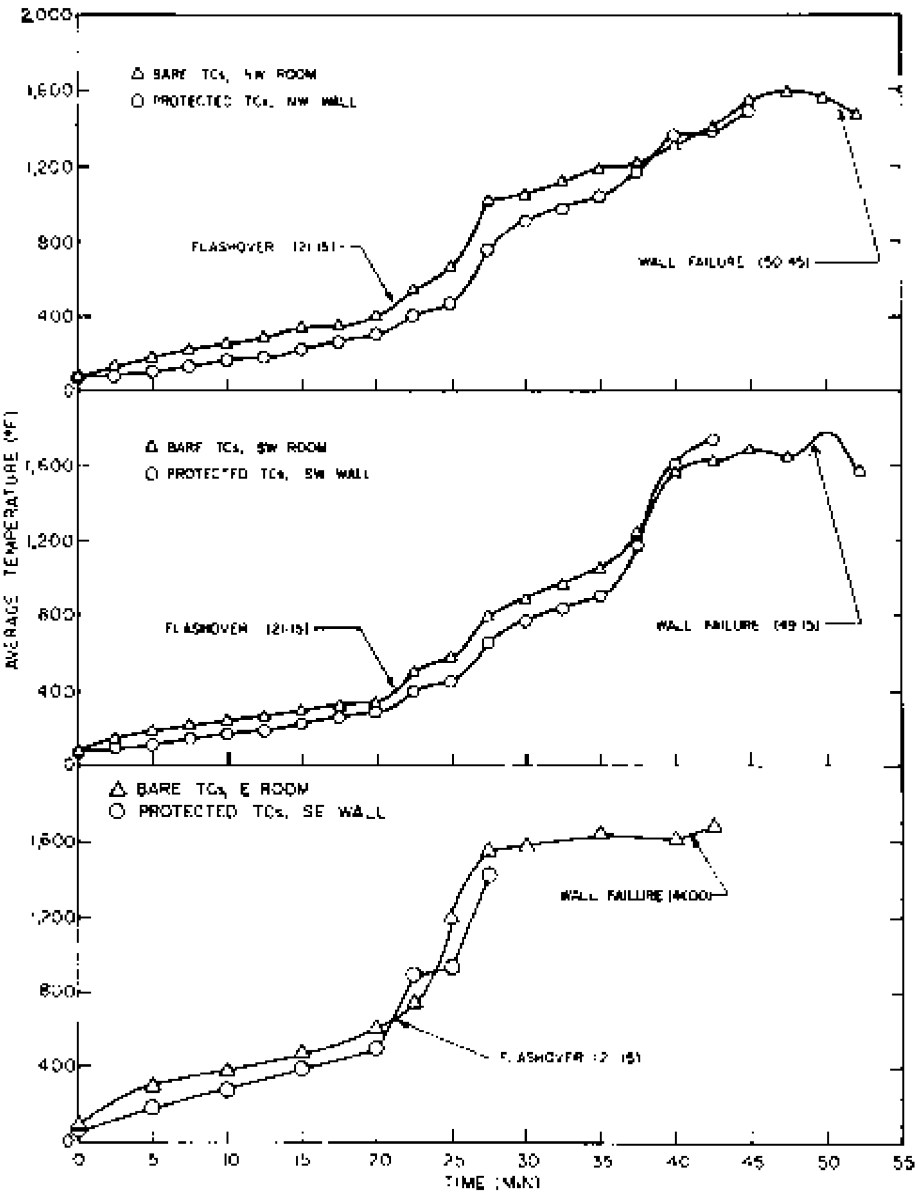

Figure 7.—Temperaturee development in Structure 5.
(M 148 012)

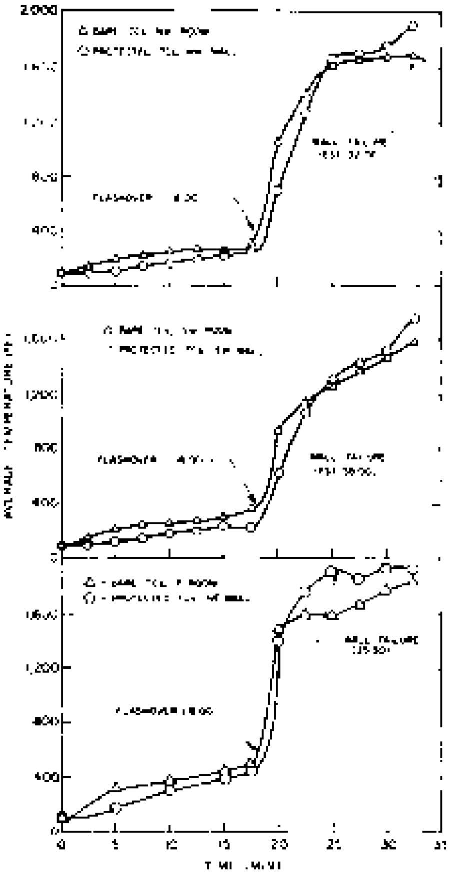

Figure 8. — Temperature development in Structure 7.
(M 148 024)

not a large difference in the average areas for the two sets of structures with combustible (4,490° F-min) or noncombustible wall linings (5,304° F-min), indicating again that the combustible content load, and not the nature of the linings, primarily affected time of flashover. The difference obtained, however, corroborates the information regarding the lower critical temperatures obtained in Structures with combustible wall linings.

Weight Loss of Ignition Cribs

Rate of weight loss increased slowly for about the first 5 minutes after ignition until the entire crib surface was burning (fig. 9). From about 5 to 20 minutes or until flashover, the rate was about uniform. Rate of burning of the ignition cribs differed little between the plywood-lined structures (3 and 4) and the gypsum-wallboard-lined structures (5 and 6). Crib weight loss, or burning rate, decreased after flashover.

When the two wood cribs were ignited in the structures with open windows, their rate of burning was controlled entirely by the fuel surface exposed to the ignition source flames and spreading flames. Ventilation was fully adequate and therefore did not suppress the burning rate. This fuel-surface-controlled stage, or fire-growth stage, then continued until flashover; then all combustibles were involved in the room and the fire entered a fully developed stage. The fire during the fully developed stage was ventilation-controlled by the limiting influence of the window opening area. Burning rates were not obtained during this period.

Fully Developed Fire

Room-temperature development.— Temperature development during the fire-growth stage was slow up to time of flashover, and then rapidly developed as more of the wood cribs became involved and the fire entered a fully developed stage. Average room temperatures were determined at 2-1/2-minute intervals from all bare thermocouples (floor to ceiling) for each room of each structure (figs. 5-8). Temperatures were also plotted from The iron-capped thermocouples next to the wall that failed first in the large room of each structure.

Temperature data are not given for Structure 2 because of instrumentation problems. So that the structures not be completely destroyed, tests were terminated by extinguishing the fire with water when the last wall section failed in each test. As a result, the extent of the fully developed stage and the onset of the decay stage was not definitely determined. In Structure 5, however, the peak burning stage was approached or reached in the southwest and northwest rooms where the average overall

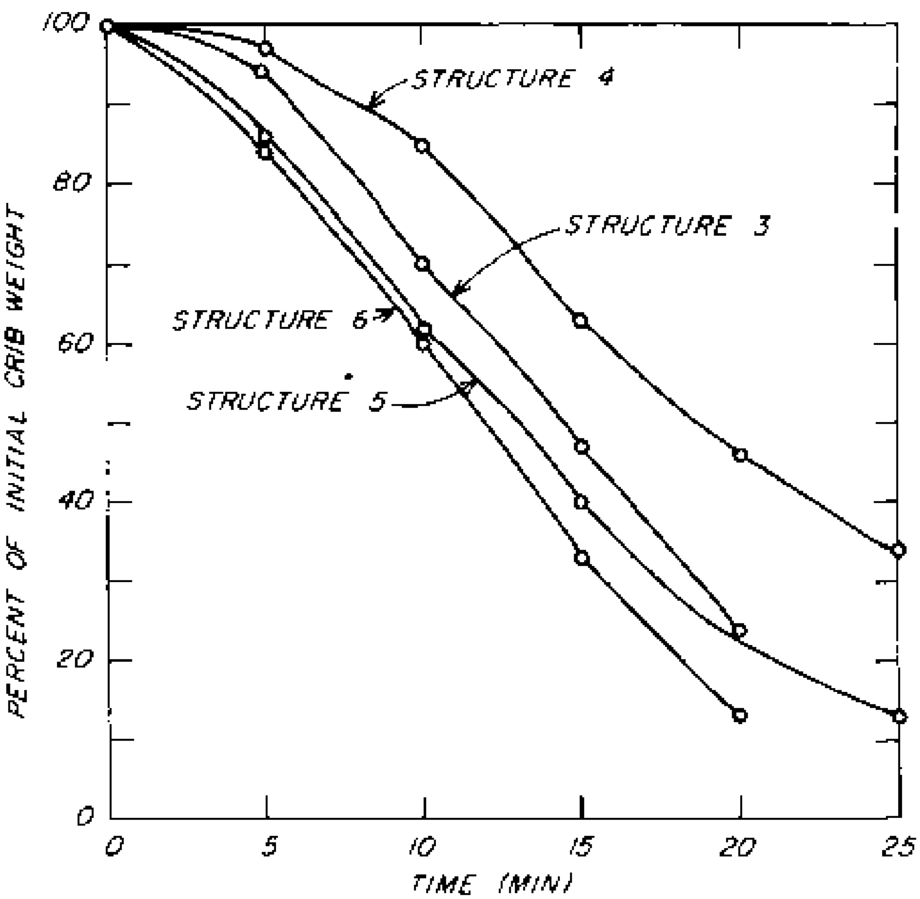

Figure 9.—Percentage of initial crib weight versus time for Structures 3, 4, 5, and 6. Data are the average of the two ignition cribs.
(M 148 028)

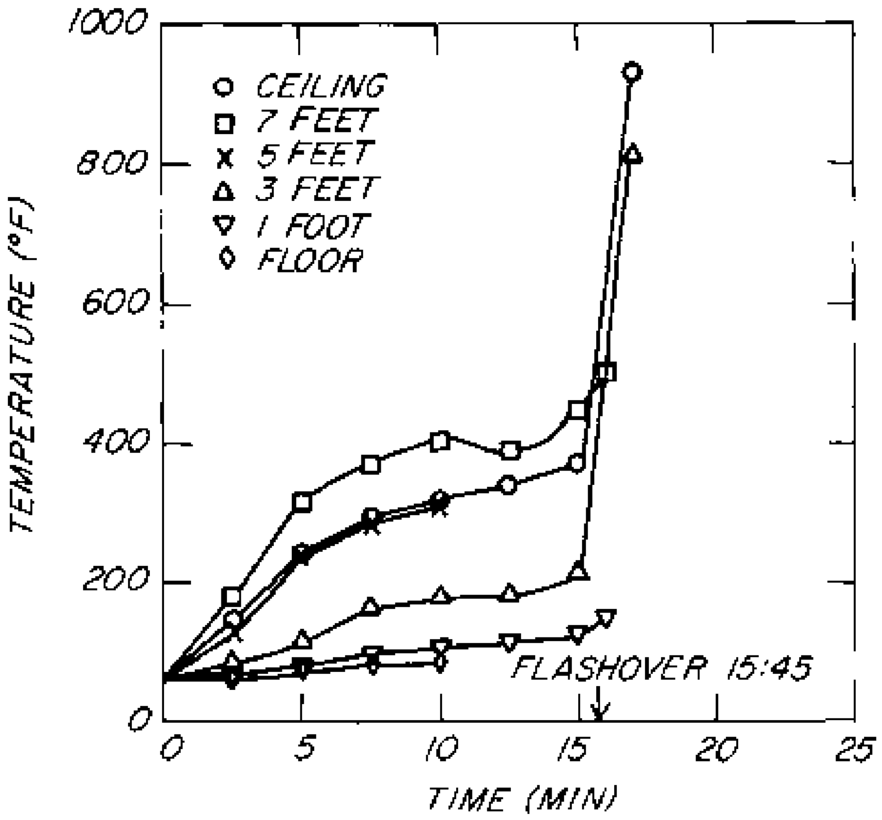

Figure 10.—Temperature at various heights in center of southwest room in Structure 1.

(M 148 008)

room temperature was 1,600° to 1,800° F (fig. 7). Individual temperatures in the east room and the southwest room in this structure reached 2,000° to 2,100° F between 42 and 52 minutes. The fire in Structure 6 also apparently reached the peak of development with average room temperatures of 1,800° F in the southeast room, 1.880° F in the southwest room, and 1,810° F in the northwest room. Several individual readings of over 2,000° F were reached in this structure. The maximum recorded reliable individual temperature in this structure was 2,329° F at 37:31 in the west center of the east room at the ceiling.

Time-temperature profiles at different heights from floor to ceiling in the southwest room (figs. 10-13) show the effect of flashover temperature development .

Window temperatures.—Profiles of temperatures in the southeast and southwest windows of plywood-lined Structure 3 indicated a neutral zone up to time of flashover, at about 16 to 20 inches up from bottom of the windows. Incoming air was below this zone and outgasing above.

Incident Heat Flux

In Structures 3, 4, and 5, the maximum heat flux obtained from the east windows until just before flashover was 0.07 watts per square centimeter. This is insufficient to ignite unpainted wood products which would require an intensity of 2.5 to 3.4 watts per square centimeter for up to 15 minutes to reach autoignition intensity (13).

Smoke:Light Transmission

The light transmission measurements made during the tests are typified by the data from Structure 1. The light transmission data from these experiments were transformed into optical density values using:

$$D = \log \frac{100}{\text{pct } T} \qquad (2)$$

where D is the "optical density" of the atmosphere whose percent transmission is given by pct T. Figure 14 gives the transformed optical Density data for Structure 1.

The optical density data far Structures 1 and 3 seem particularly interesting. These data show that, over certain periods of the tests, straight lines can be drawn through some of the optical density data points. Examples of these lines are shown as lines (1) and (2) in figure 14. If the equation of the lines is written as:

$$D = M\theta + ß \qquad (3)$$

where

D is the optical density (dimensionless),

M is the slope of the line (min $^{-1}$),

θ is the time (min), and

ß is the intercept (dimensionless) at θ = *0,*

the data points associated with lines (1) and (2) (fig. 14) can be used to calculate a least-squares fit for the lines and hence values for *M* and *ß*. Table 7 shows the values of *M, ß,* and "coefficient of determination." r^2, associated with the lines (1) and (2), along with similar calculations for Structure 3, whose lines are designated (3) and (4). Deviations from ideality in Table 7 are not surprising. The curves might be explained in terms of two or more optically dissimilar "atmospheres" whose motion in the structure is influenced by internal convection currents as well as by the breezes blowing through the structure openings. The implication of the short time periods for the correlations is that only relatively dilute suspensions of particles (or droplets) in the evolving fire gases arc considered.

Fire-Gas Atmosphere Analyses

Typical rebuild of the fire-gas atmosphere analyses (the actual data for Structure 5) are given in table 8; a complete set of data is reported in Eickner et al. (*6*). The effects of interfering components and the accuracy of this detection method have been reported (*10*). In general, the accuracy for CO and HCN is shown to be about ± 20 percent of the indicated reading.

Structure 1—In Structure 1, none of the atmosphere analysis samples drawn from the larger room indicated the presence of either CO or HCN, even though both the plywood facings and the sandwich panels were heavily involved and there was much smoke. Apparently, conditions of temperature and oxygen supply were such that any CO present was burned to CO_2 and conditions were also unfavorable for formation of HCN.

Structure 2—The data for Structure 2 also show that no HCN was detected. At 16:40 after ignition, CO was detected in the east room; CO was first observed in the southwest bedroom at 18:45. On the basis of narrative observations it is concluded that the CO measured in the southwest bedroom at 18:45 had been carried there by an east-to-west draft. The appearance of CO in Structure 2 at 16:40 might be due to the fact that the paper covering of the gypsum wallboard burned rapidly with the evoluction of sparks and embers. If the burning of this paper covering was rapid enough to deplete the surrounding oxygen supply, the production of CO could resust. The largest CO concentration was measured in the small room at a time corresponding roughly to "flashover" It is possible that the high CO levels and the "flashover" are somehow related.

Structure 3 —In addition to trace amounts of CO in the large room of Structure 3 at 4 to 7 minutes. CO began to be observed at about 13 minutes in a smaller room. Concentrations of CO were greater in the smaller room than in the larger. This might be dur to the breeze blowing into the east window at 16:30, carrying fresh air into the large room and sweeping combustion products into the smaller rooms. Still another effect might occur because combustion reactions in the small room were possibly carried out in an oxygen-deficient atmosphere due to the blow-through of combustion products. Maximum CO concentrations were measured after flashover, suggesting that flashover may be oxygen-limited. HCN was not observed in the combustion atmosphere until around 21 minutes after ignition. The HCN was probably produced from thermal degradation of the isocyanurate foam, this degradation taking place after structural failure of two walls and after flashover. The highest levels of HCN were measured in the small room, possibly due to the breez blowing through the structure.

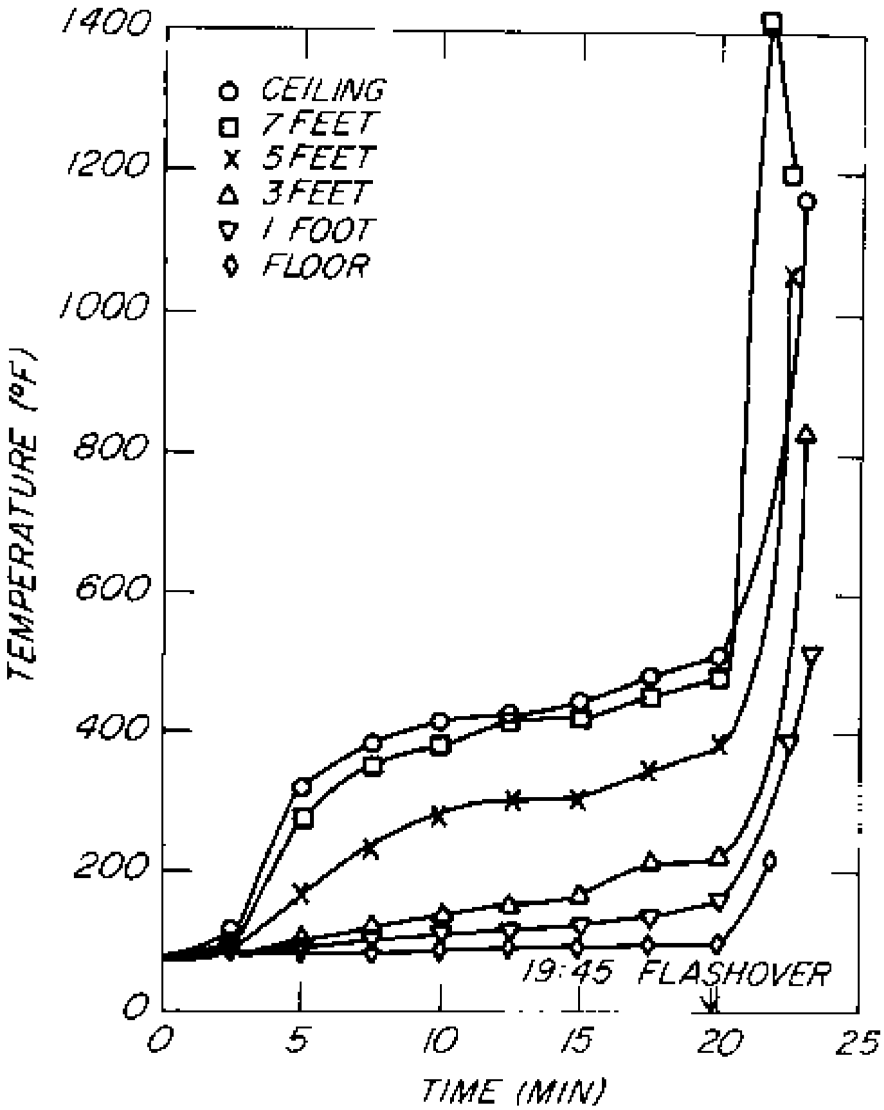

Figure 11.—Temperature at various heights in center of southwest room in Structure 3.

(M 148 009)

Structure 4—Structure 4 was the first in the series in which the fire atmosphere was sampled for carbon dioxide (CO_2) along with CO and HCN. HCN was not detected at any time during the test.

In the large room, CO was not observed until about 25 minutes after ignition, while in the smaller room CO was found at about 23:30. The sequence of CO detection seems consistent with observed airflows during the test. Thus, the ignition cribs appear to burn under conditions where there is sufficient oxygen for complete combustion. The CO in the small room was probably generated by partial pyrolysis of the structure walls and/or ceiling; a rapid increase in CO concentration at 23 minutes may have been related to the spraying of water in and on the structure.

Measurements of CO, concentration depict the accumulation of combustion products as the structure becomes more fully fire involved.

Structure 5—In Structure 5, the fire atmosphere was sampled for all three components (table 8). HCN was found on only two occasions, both of these in the mall room, and both very near the flashover time. Because flashover is characterized by the presence of a wide variety of organic vapors and pyrolysis products, it is likely that the observed "hydrogen cyanide" was really an interfering substance that caused a color

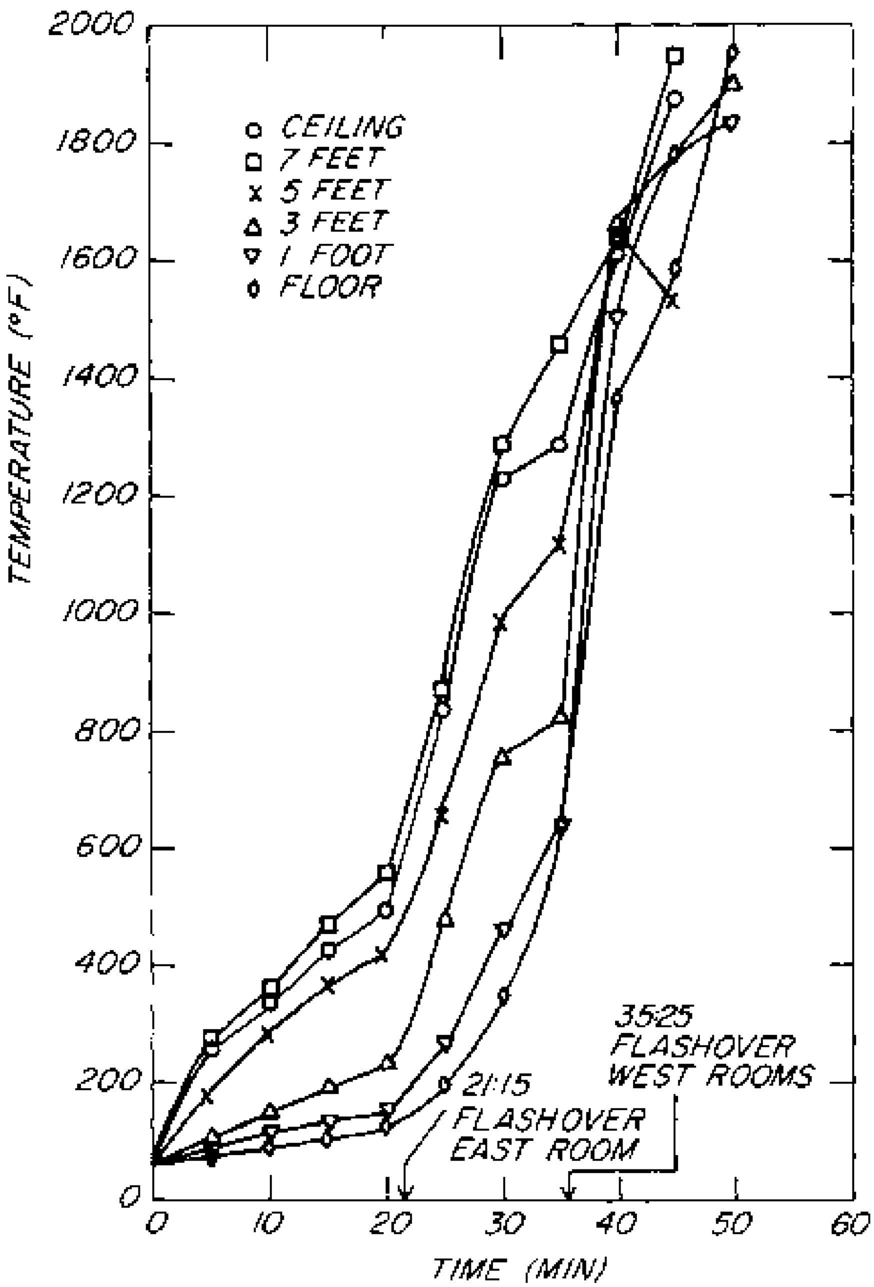

Figure 12.—Temperature at various heights in center of southwest room in Structure 5.

(M 148 011)

change in the colorimetric detection tubes.

CO appeared first in the small room at about 21 minutes and subsequently in the large room at about 25:30. Apparently, due to the heavy involvement of all of the cribs in the fire, there was not enough oxygen present at flashover (21:00) to completely burn the buildup of organic pyrolysis products present: Hence the production of CO. The appearance of CO in the large room (25:30) coincides with a second flashover-type phenomenon and may also be due to a similar oxygen depletion. The sudden increase of CO at 42:30 might have been due to oxygen depletion resulting from the fire intensity or to the water sprayed on the glowing portions of the structure. CO_2 levels attest to the intensity of the test fire; they were higher than could be measured with the analytical test method.

Structure 6—In Structure 6, the fire atmosphere was sampled for CO and HCN. HCN was detected and measured on only one occasion and, because this occurred during a period when water was sprayed inside the test structure, it is likely that this HCN value too was an interfering substance CO was detected in the fire atmosphere beginning at about 20 minutes. The CO measurements tended to be higher in the small room than in the large; CO also appeared at an appreciable time after flashover. Spraying the end walls with water, begun at about 15 minutes after ignition, complicated the analysis of composition data.

Structure 7—In Structure 7, the fire atmosphere was sampled for all three components. It appears that the atmospheric composition data from the test can be divided roughly but distinctly into two segments—divided by the point 22 minutes after ignition.

Before 22 minutes there was no observable HCN at either sampling point. Low levels of CO and the gradual accumulation of CO_2 indicate a plentiful supply of oxygen present, even for the rapid burning at flashover (18:00). After the 22-minute time interval there was a rapid rise in CO and CO_2 concentrations at both sampling locations. In addition, HCN (which may have been an interfering substance) was observed in the large room for about a 5-minute period. High levels of CO_2 reflect the high rate of burning after 22 minutes when much of the structure was fire involved; such high CO levels during this interval indicate that some of the combustion was incomplete. Thus the time interval after 22 minutes is characterized by a relatively high rate of burning and a high fire involvement even though there is not always enough oxygen present for complete combustion.

Performance of Walls

Structural failure of the walls was recorded when the dead weights applied through a pulley and cable system came down to rest completely on the ground (table 9). These recorded times, based on observation of the dead weights, generally agree with the times at which the potentiometer-deflection measurements

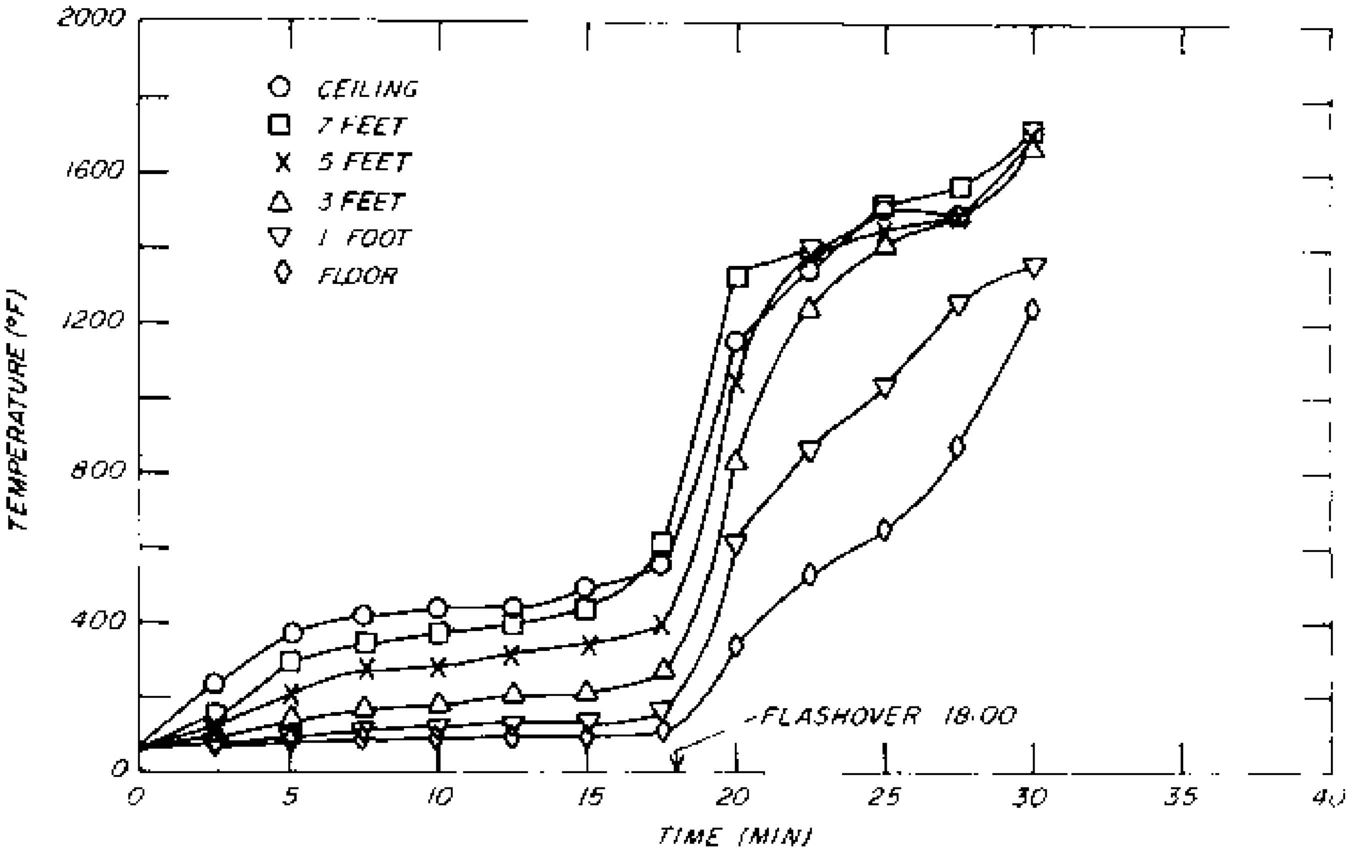

Figure 13.—Temperature at various heights in center of southwest room in Structure 7.
(M 148 019)

indicated substantial and erratic lateral deflections associated with buckling failure of the wall. The walls are ranked for each type of construction and for the ASTM Standard E 119 test results (*5*) (table 9).

The additional time required for the large-scale fires to become fully developed increased the fire endurance (structural integrity only) of the walls, as compared with the ASTM E 119 tests (table 9) (*5*). by 2 to 22 minutes. While the total times were longer, the total fire endurance times substantially agreed with the relative ranking of the seven walls that were ASTM E 119 tested.

Based on total endurance times, the relative performance of the protected sandwich wall (with gypsum wallboard) in the large-scale tests did not agree with the laboratory test results. The ASTM E 119 results suggested that the protected sandwich is equivalent in fire endurance to the unprotected wood frame wall (with plywood as interior facing) and has less fire endurance than the protected wood-frame wall. The large-scale tests suggests that the protected standwich wall is superior to the unprotected wood-frame and equivalent to the protected wood-frame (with gypsum wallboard). But in comparing the results for the different types of construction, possible differences in the temperature severity of the interior fires must be considered.

Variations in the environmental conditions for the large-scale tests were greater than desirable. Wind direction and velocity may have affected the development of the interior fire in some structures and thus the performance of the walls. As noted before, there was about a 15-minute delay between the times that flames first were emitted from the east windows and the time flames were emitted from the west windows of Structures 5 and 6. This delay is reflected in the gradual rise in the average temperature of the small west rooms (fig. 7) compared with the rapid ruse in temperature observed in the other structures. The data also indicate more of a temperature-height gradient in the small rooms after the flashover in the east room for Structures 5 and 6 than for other structures. The time of structural failure minus the time of flashover, or the areas under the time-temperature curves, are probably more reasonable parameters to use for comparison.

Fire endurance relative to the time of flashover is an alternative measure of fire endurance times (table 10). Using this reduced time elminates the fire growth period from consideration and corresponds with the fully developed fire at the beginning of the ASTM E 119 test. The time of flashover for all three rooms was assumed to be the time flames were emitted from the east windows. An alternative for the small rooms (southwest and northwest walls) would have been to use the time that flames were emitted from the west windows. For Structures 5 and 6, the flames emerged from the west windows about 15 minutes after flames first emerged from the east windows. For the other structures, the delay was less than 1 minute. Using the appearance of flames from the west windows for time of flashover, the fire endurance times

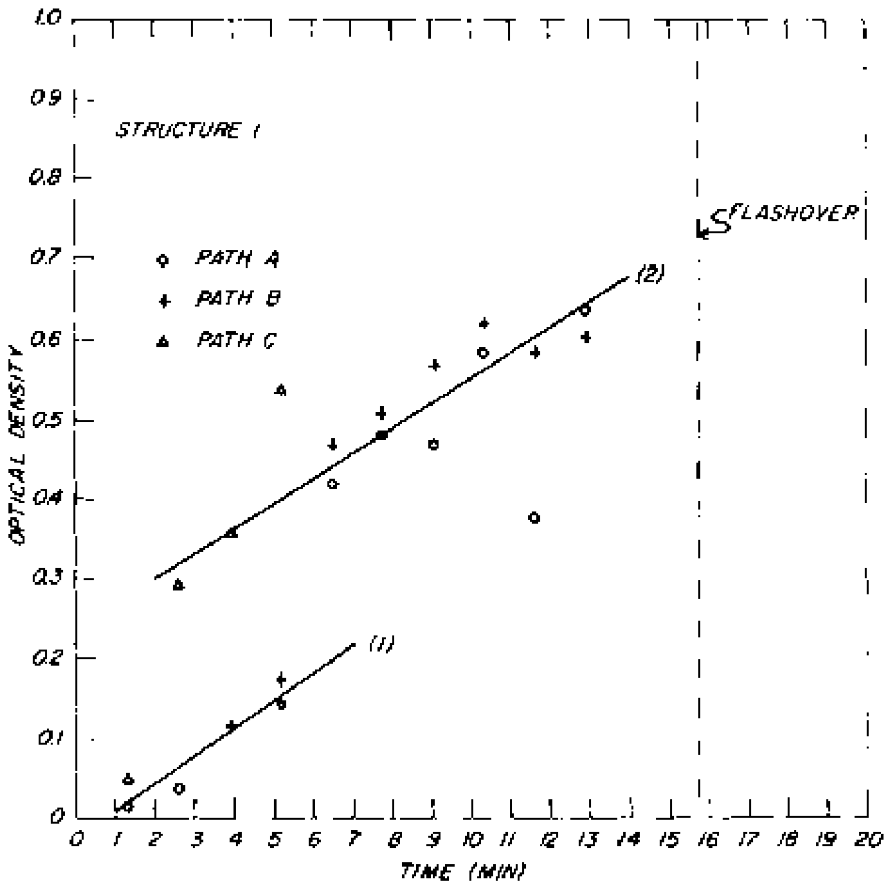

Figure 14.—Optical density versus time for Structure 1.
(M 148 015)

relative to the time of flashover are 13:45 for the southwest wall and 15:15 for the northwest wall of Structure 5, and 13:15 and 12:45 for the southwest and northwest walls, respectively, of Structure 6.

There is close agreement in relative ranking between the laboratory and large-scale tests when the large-scale ranking is based on the time of structural failure minus the time of flashover (table 10). Thus the long total fire endurance times for the protected sandwich are probably due to the longer time till flashover and the resulting lower severity of the interior fire. Reasonably good linear correlation can be obtained between the structural failure minus flashover times of the large-scale tests and the ASTM E 119 results (fig. 15). In the large-scale tests, the structural failure minus flashover times indicate that the best fire endurances were obtained with the wood-frame walls with 3/8-inch gypsum wallboard interior lining. Structural failure of these walls occurred from 19:45 to 29:30 after flashover. The fire endurance of the woodframe walls with 1/4-inch lauan plywood interior lining was similar to the protected sandwich walls. Structural failure of these wood-frame walls occurred from 7:30 to 20:00 after flashover in the large rooms. The structural failure of the sandwich walls with 1/2-inch type-x gypsum wallboard occurred from 6:15 to 16:30 after flashaver inn the large room.

A measure of fire endurance exposure is the area under the time-temperature curve from ignition to the time of structural failure. The areas for the large-scale tests are compared with the areas of the corresponding E 119 tests (table 11). The time-temperature curves for the large-scale tests are the average temperatures recorded from three iron-capped thermocouples located 6 inches from the exposed surface of each of the four walls at heights of 1, 4, and 7-1/2 feet. The time-temperature curves for the E 119 tests (*5*) and for the first wall to fail in the large-scale tests are plotted (figs. 16-19).

Using the areas under the time-temperature curves from ignition to structural failure (fig. 20), or flashover to structural failure, reasonably good linear correlation can be obtained between the large-scale tests and the ASTM E 119 results.

The ratios of the area under the large-scale time-temperature curve to the area under the ASTM E 119 time-temperalure curve from ignition to the time of structural failure range from 0.32 to 1.84 (table 11). The averages for Structures 1, 3, 4, 5, 6, and 7 are 0.98, 1.52, 1.10, 0.93, 0.81, and 0.86, respectively. The average of the ratios for the structures with combustible wall linings is 1.13; for noncombustible wall linings, 0.87. The average of all the ratios is 1.04. The closeness of the averages to 1.0 suggests that the fire exposure as represented by the area under the time-temperature curve may be a significant factor in the fire endurance of a wall. But it should be noted that there was a wide variation in the ratios. Also, similar combustible-content loading in the structures limited the variation in the severity of the interior fires.

Fire resistance failures are burn-through or excessively high temperatures on the unexposed surface. In standard tests (*2*), excessively high temperatures are indicated when an individual thermocouple indicates a temperature exceeding ambient by more than 325° F, or the average temperature for the thermocouples on the unexposed surface exceeds ambient by more than 250° F. Excessively high temperatures on the unexposed surface were not observed for any of the walls before failure by burn-through or termination of the tests. Burn-through was observed in the wood-frame walls (table 12) but there was no burn-through in any of the sandwich walls before the last structural failure and termination of the test.

In most cases, there was extensive burn-through of the wood-frame walls before structural failure (table 12). For Structure 6, three of the walls burned through in less than the time obtained in the ASTM E 119 test. The holes in the walls for the smoke measurements may have lowered the resistance of the walls to burn-through. While the initial growth

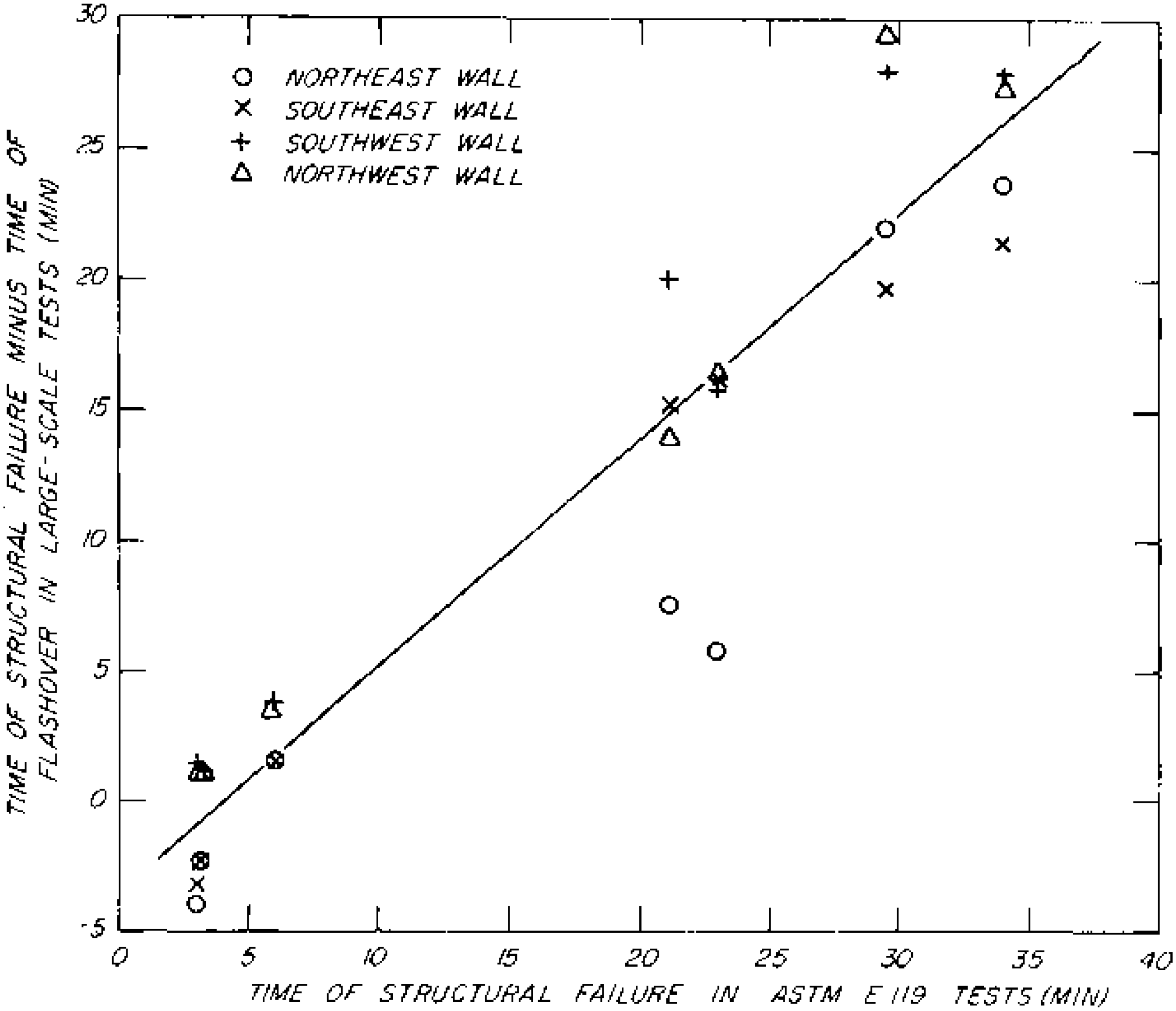

Figure 15.—Time of structural failure minus time of flashover in large-scale tests versus time of structural failure in ASTM E 119 tests (see table 10).
(M 148 027)

period does not seem to greatly affect the times for burn-through of the walls, the effect is obvious in the times for the fire resistance of the interior lining or facing material (table 13). The fire resistance (finish rating) of the interior lining material is a measure of the protection the wall lining provides to the combustible structural members of the assembly.

The poor performance of the unprotected sandwich walls (walls with no gypsum wallboard) in the ASTM E 119 tests was confirmed in the large-scale tests. The structural failure of the unprotected sandwich walls occurred from 4:45 before flashover in 3:45 after flashover in the large room. In the structure with unprotected urethane foam, the structural failure of the northeast and southeast walls occurred when the interior 1/4-inch plywood faces partially delaminated and bowed inward while the rest of the panel bowed outward. In the structure with unprotected isocyanurate foam cores, explosive noises were heard 5:30 before the structural failure of the northeast and southeast walls. Past experience has indicated that the noises were probably the isocyanurate core cracking up (*8*). Delamination was also associated with the failure of the isocyanurate sandwich panels. The structural failures of the southeast and northeast walls before flashover occurred when the higher temperatures near the walls range from 400° to 800° F.

To ensure life safety, it is reasonable to require that the load-bearing component supports its load beyond the time of flashover. Thus, the results of the large-scale tests

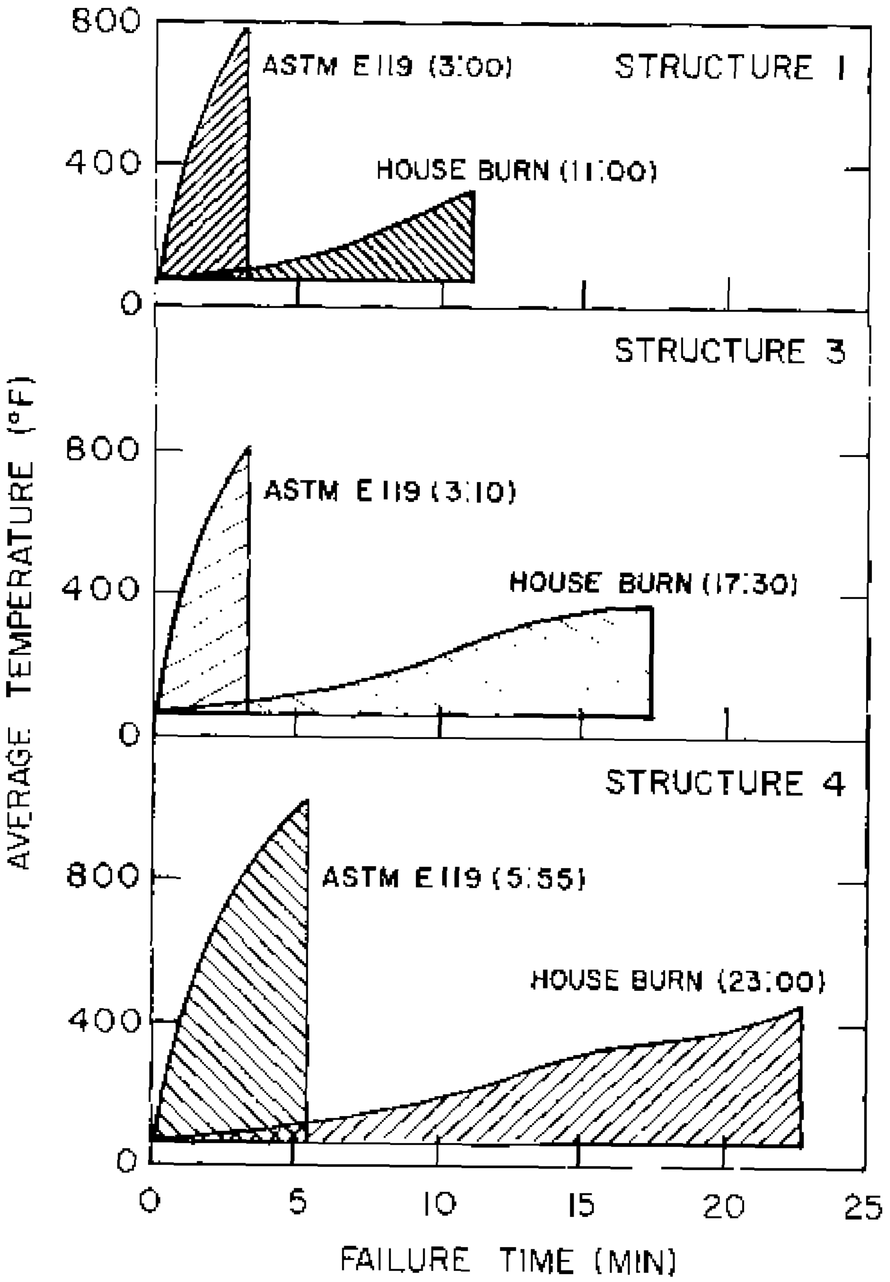

Figure 16.—Time-temperature relationship to time of structural failure for wall construction in ASTM E 119 laboratory test compared to first wall failure (northeast) in each case, in full-scale test of (top) Structure 1, (center) Structure 3, and (bottom) Structure 4.

(M 148 016)

indicate that had-bearing sandwich panels must have thermal protection (e.g., gypsum wallboard) to ensure a reasonable level of fire endurance. It should be noted that the unprotected sandwich panels did give adequate burn-through protection. Thus, unprotected sandwich panels may provide sufficient fire resistance to burn-through in sandwich systems in which the sandwich panel is not a load-bearing component.

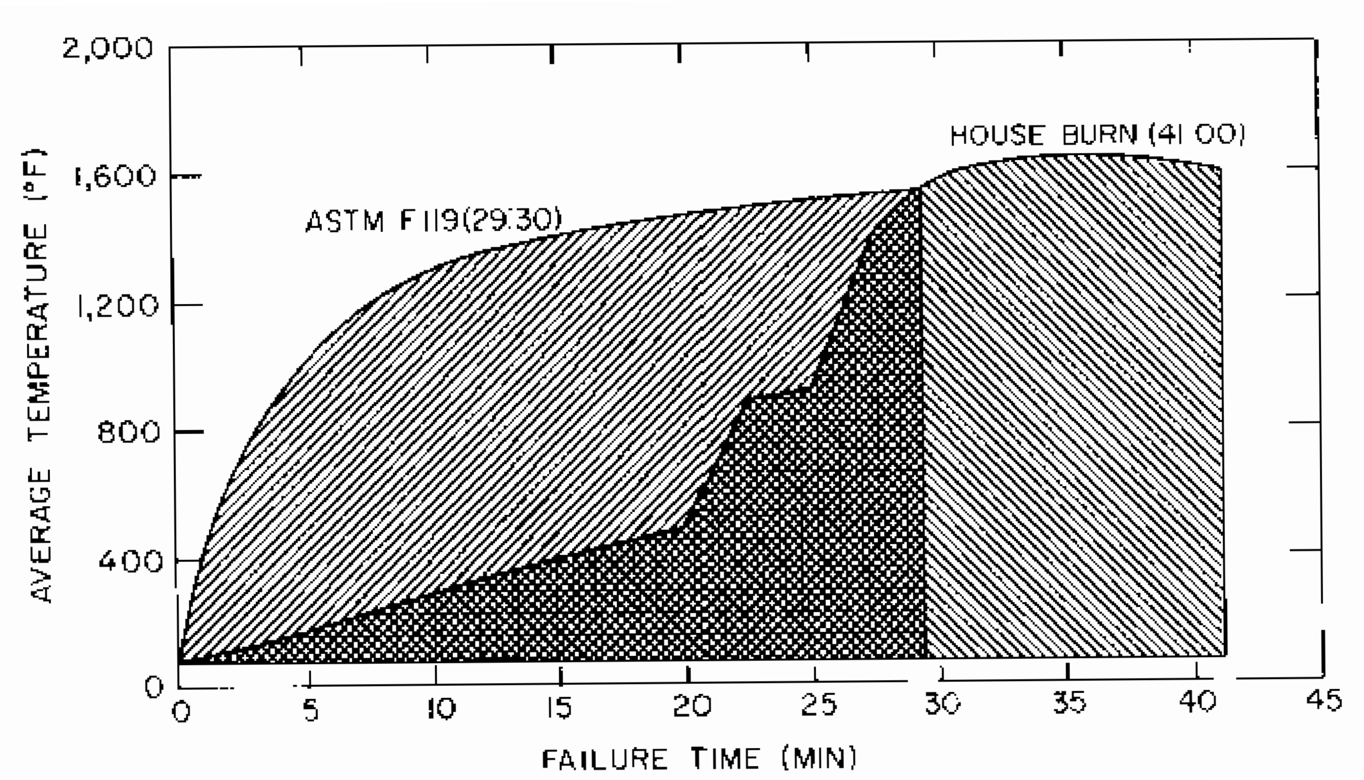

Figure 17.—Time-temperature relationship to time of structural failture for wall construction in ASTM E 119 laboratory test compared to first wall failure (southeast) in full-scale test of Structure 5.
(M 148 022)

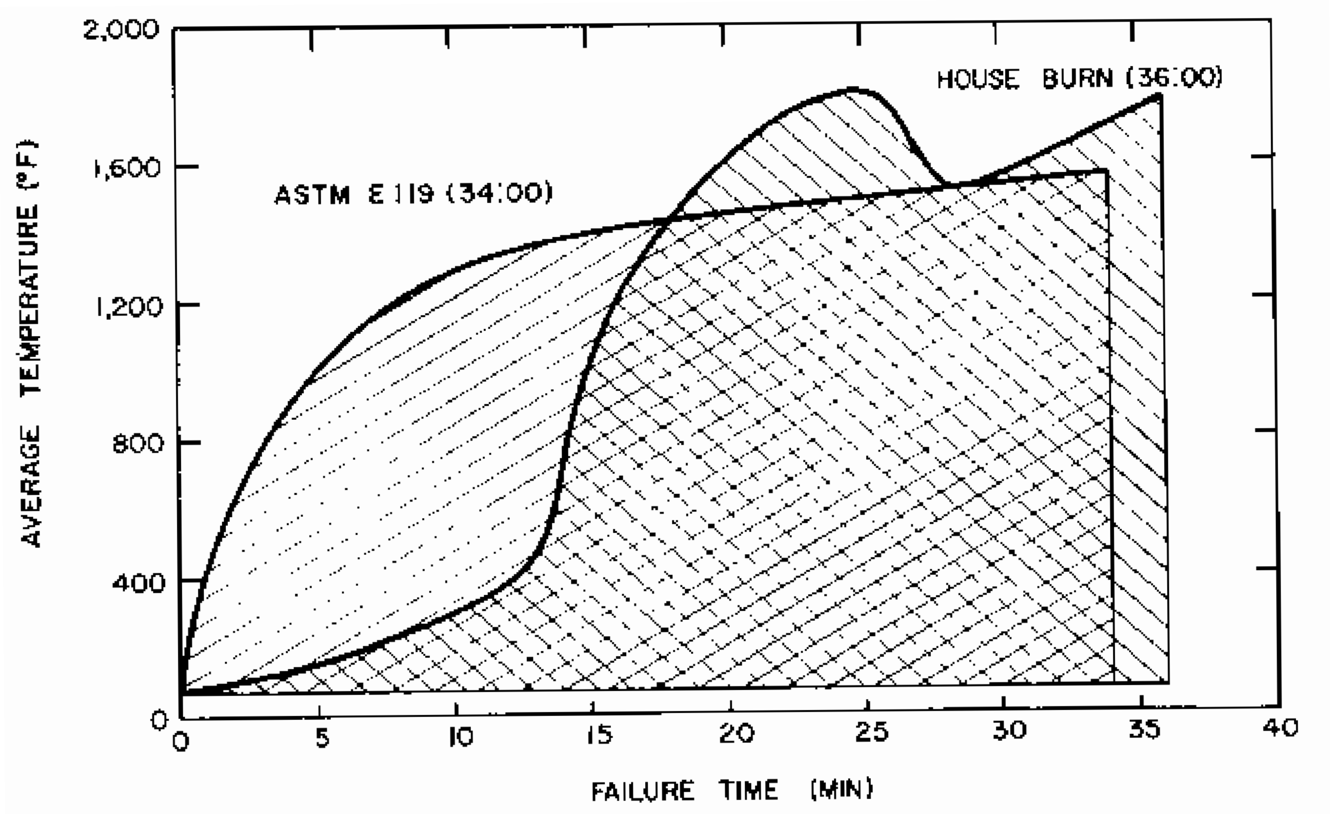

Figure 18.—Time-temperature relationship to time of structural failure for wall construction in ASTM E 119 laboratory test compared to first wall failure (southeast) in full-scale test of Structure 6.
(M 148 017)

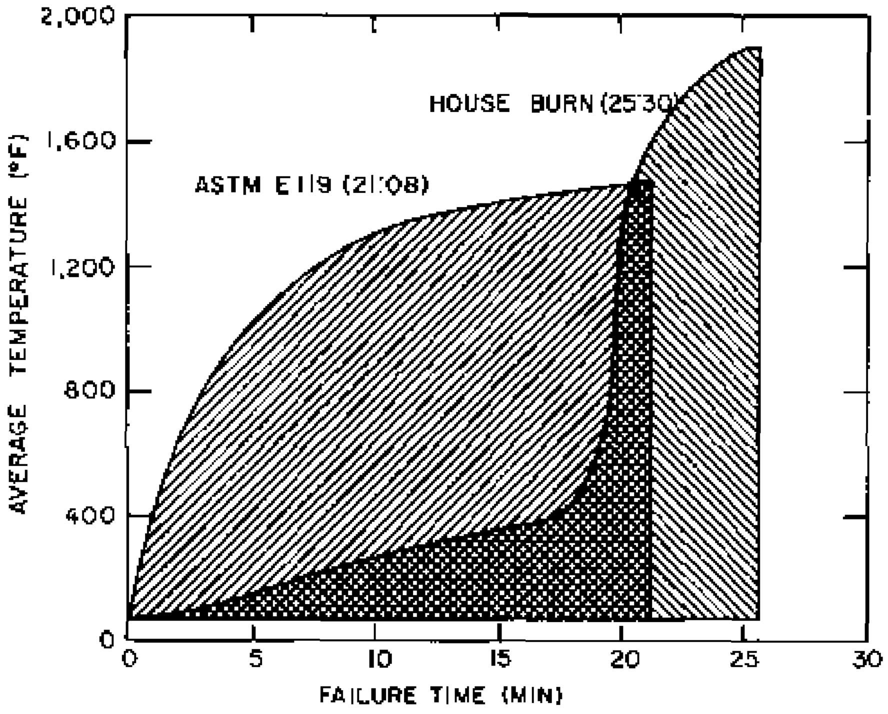

Figure 19.—Time-temperature relationship to time of structural failure for wall construction in ASTM E 119 laboratory test compared to first wall failure (northeast) in full-scale test of Structure 7.

(M 148 023)

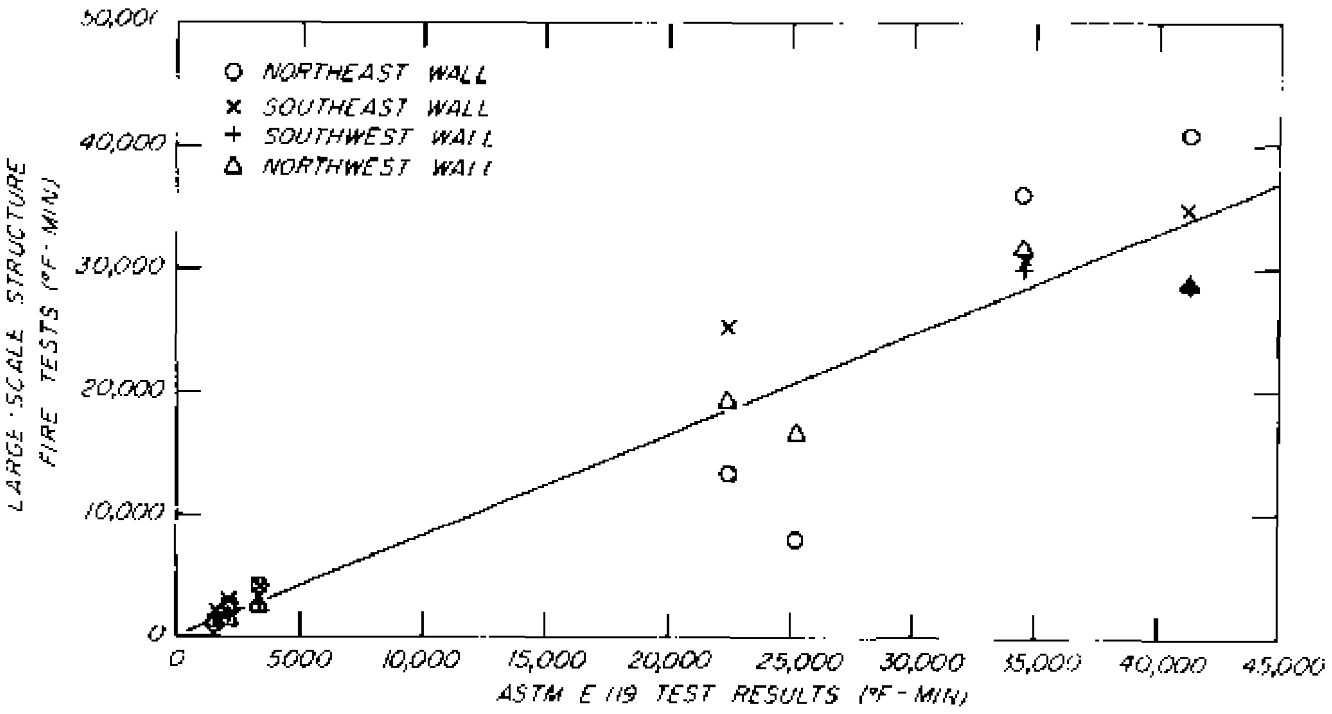

Figure 20.—Areas under the time-temperature curves (average of three protected thermocouples) from ignition to wall failure (see table 11). The two points with ASTM E 119 areas of 25,218° F· minutes are for Structure 2. Because of instrumentation difficulties, temperature data for Structure 2 are limited and erratic, and the accuracy of the areas is not known.

(M 148 029)

SUMMARY

Large-scale fire tests were conducted on seven 16- by 24-foot structures: Four were of sandwich construction with cores of plastic or paper honeycomb, and three of wood-frame construction. The long walls of each structure were loaded to a computed design loading. Fire endurances of the walls were determined under a fire exposure from a typical building contents loading—represented by wood cribs—of 4.5 lb/ft^2 of floor area. Two open windows at each end of the structures were sized to obtain a ventilation-controlled fire during the fully developed stage.

the large-scale tests confirmed the poor fire endurance performance of the unprotected sandwich construction as previously indicated by laboratoory tests. Interior thermal protection in the form of gypsum wallboard improved the performance of the sandwich and wood-frame walls. For fire endurance, conventional wood-frame construction appeared to be better than load-bearing sandwich panels with plywood faces. Under the experimental conditions employed, the large-scale and the laboratory-scale tests were in general agreement as to the relative performance of the different types of wall construction.

Flashover, which occurred in all tests, was observed as the rapid extension and blending of flames throughout the room from the burning wood cribs, up the walls, across the ceiling, and out of the east windows of the ignition room. Within 1 minute (when not affected by wind conditions), the flames spread throughout the two adjacent rooms and out of the west windows. The buildup of unburned flammable gases from the burning crib material and from cribs and wall linings undergoing pyrolysis of thermal degradation contributed to the flashover effect. Time of flashover varied from 14:30 (Structure 6) to 28:30 (Structure 2), and may have been affected by direction and velocity of the wind, particularly in Structure 6. Flashover occurred at a somewhat earlier time, about 6 minutes average, in structures with combustible wall linings. The significance of the difference is questionable.

Temperature development in the structures was slow prior to flashover and rapid after flashover, with peak temperatures of over 2,000° F.

A critical temperature (average at 7-foot level in ignition room) associated with flashover was an average of 640° F in the four structures with combustible plywood wall linings, and an average of 709° F in the three structures with noncombustible wallboard linings.

During the early stages of some of the structure tests, the optical density of the fire atmosphere seemed to vary linearly with time. Chemical analysis of the atmosphere showed very little evidence of hydrogen cyanide accumulation, even though this compound could be one of the degradation products of some of the polymer formulations used in the sandwich panels. Concentrations of carbon monoxide (CO) and carbon dioxide (CO_2) observed in the test atmosphere seemed generally consistent with the geometry of the test structure, the outside weather conditions during the test, and the overall stage of fire growth at the time of measurement.

Table 1.—Wall and roof construction of test structures

Structure No.	Interior lining	Studs	Insulation	Sheathing	Siding	Core	Protection	Roof and ceiling
1	¼-in. exterior grade A-C Douglas-fir plywood					3-in. polyurethane foam board,[1] 1.8 lb/ft^3	None	Sandwich panels with 5/8-in. type-X gypsum wallboard and faced with ¼-in. Douglas-fir plywood
2	. . . . . do					. . . . . .do.	½-in. type-X gypsum wallboard	As abobe but with ½-in. type-X gypsum wallboard in place of plywood facing
3	. . . . . do					3-in. isocyanurate foam board,[2] 1.8 lb/ft^3	None	Reused sandwich assembly of Structure 1 with new 5/8-in. type-X wallboard and ¼-in. Douglas-fir plywood
4	. . . . . do					3-in. kraft paper (80-lb) honeycomb, ½-in. cell size, 11 % phenolic resin, 1.9 lb/ft^3	None	Sandwich panels with 5/8-in. type-X wallboard and ¼-in. Douglas fir plywood
5	3/8-in. gypsum wallboard	Hem-fir 2- by 4-in. 16-in.o.c.	3½-in. glass-fiber roll, kraft-paper faced	3/8-in. exterior Douglas-fir plywood (24-0 sheathing)	½-by 8-in. cedar bevel siding			Hem-fir 2- by 6-in. 16-in. o.c. faced with two layers of 5/8-in. type-X gypsum wallboard
6	. . . . . do . . . . .[3]	. . . . . do	. . . . . do	½-in. regular density fiberboard	. . . . . do			Reused roof from Structure 5 with two new layers of 5/8-in. type-X wallboard
7	¼-in. lauan prefinished plywood grooved[4]	. . . . . do	. . . . . do	3/8-in. exterior Douglas-fir plywood (24-0 sheathing)	. . . . . do			Hem-fir 2- by 6-in. 16-in.o.c. one layer 5/8-in. type-X, one layer 3/8-in. wallboard

[1] ASTM E 84 (*3*): Flame spread 51, smoke density 140.
[2] ASTM E 84: Flame spread 25, smoke density 135-200.
[3] Two layers of wallboard on east wall.
4 Voluntary product standard PS 51-71 (*17*). ASTM E 84: Flame spread 100-200, smoke density less than 100. One layer 3.8-in. gypsum wallboard under plywood on east and west walls.

Table 2.—Structural loads on walls in large-scale tests

Structure No.	Maximum design load	Ratio of applied load to maximum design load	Structure No.	Maximum design load	Ratio of applied load to maximum design load[1]
	Lb/lin ft			*Lb/lin ft*	
1	3,178	0.39	4	4,287	0.29
2	3,178	.39	5-7	[2]964	[2]1.30
3	2,621	.48			

[1] Applied load is 1,250 lb/lin ft.
[2] The maximum design load of the wood-frame walls is based on the plates. Due to the conservative nature of the design procedure and the allowable properties, the excess load on the plates is not critical. The design load for buckling failure is 2,075 lb/lin ft and the corresponding ratio of applied load to design load is 0.60. The ratio for buckling failure is more important since the effect of fire exposure is the reduction of the cross-sectional area which leads to buckling failure.

Table 3.—Ambient conditions during fire tests of sandwich-panel and wood-frame structures

Structure No	Wood-crib fuel loading	Ambient	Predominant wind direction	Wind velocity[1]	Sky cover	Relative humidity
	Lb/ft^2	°F		Mph	Tenths	Pct
1	4.7	68	S	<7.5	10	50
2	4.7	71	E	5-12	10	69
3	4.6	81	SE	(3) 0-6	2	47
4	4.6	80	WSW	(6) 3-10	7	54
5	4.3	60	N	(8) 2-15	10	69
6	4.4	62	WSW	(8) 4-13	9	54
7	4.5	68	ESE	(6) 2-10	10	48

[1] Number in parentheses was most prevalent velocity.

Table 4.—Fire growth events during fire tests of structures—first observations

Event	Elapsed time from ignition to first observation for each structure[1]						
	1 (C)	2 (NC)	3 (C)	4 (C)	5 (NC)	6 (NC)	7 (C)
	Min:sec						
Flames reach ceiling in large east room	2:15	4:00	2:30	4:00	4:45	6:00	3:30
Ignition of adjacent crib next to ignition crib	7:30	3:45	14:40	11:45	6:45	5:20	7:35
Flashover in large room—flames being emitted, east windows	15:45	28:30	19:45	21:30	21:15	14:30	18:00
Ignition in small west rooms	15:35	—	—	—	27:05	23:08	—
Moderate or heavy smoke being emitted, west windows	14:51	—	18:10	18:45	22:18	14:05	15:18
Flame spread into or across ceiling at small west rooms	15:35	28:40	19:47	21:25	21:25	23:15	17:05
Flames being emitted, west windows	15:30	29:00	20:07	21:25	35:25	29:22	18:00

[1] C or NC after structure number indicates combustible (plywood) or noncombustible (gypsum wallboard) interior wall linings.

Table 5.—Critical average temperature at 7-foot level in large room just prior to significant temperature increase associated with flashover

Structure No.	Average room temperature and range at 7-foot level[1]	Grand average temperature at 7-foot level	Standard deviation	Coefficient of variation
	°F	°F	°F	
Combustible wall lining		640	25	0.039
1	656 (583-726)			
3	627 (552-685)			
4	666 (558-764)			
7	612 (559-708)			
noncombustible wall lining		709	62	0.87
[2]2	680 (615-715)			
5	781 (550-897)			
6	667 (541-813)			

[1] Obtained at the seven locations in large room.
[2] Temperature data for Structure 2 is questionable due to instrumentation difficulties.

Table 6.—Areas under the time-temperature curves for average east-room temperatures from ignition time to flashover[1]

Structure No.	Flashover time	Area under time temperature curve	Average	Standard deviation	coefficient of variation
	Min:sec	*°F·min*	*°F·min*	*°F·min*	
Combustible wall linings			4,490	195	0.04
1	15:45	4,209			
3	19:45	4,557			
4	21:30	4,658			
7	18:00	4,536			
Noncombustible walllinings			5,304	1,712	.32
5	21:15	6,515			
6	14:30	4,094			

The average room temperature is obtained from all bare thermocouples located throughout the large east room in the test structure. Area is determined above 68°F baseline.

Table 7.—Least-squares-fit determination of M, ß, and r^2 for equation 3

Source	Time interval	M	ß	r^2
	Min	*Min*$^{-1}$		
Line (1) (test 1)	$1.3 \leq \theta \leq 5.2$	0.0346	− 0.0252	− 0.90
Line (2) (test 1)	$2.6 \leq \theta \leq 12.9$	.0317	.236	−.90
Line (3) (test 3)	$0.3 \leq \theta \leq 6.0$	.0149	.0026	−.81
Line (4) (test 3)	$3.2 \leq \theta \leq 8.6$	.117	−.346	−.93
Ideal	–	—	0	±1.00

Table 8.—Results of fire atmoshere analysis for CO, CO_2, and HCN[1] in Structure 5

Time	CO	CO_2	Time	CO	CO_2
Min : sec	*Volume pct*	*Volume pct*	*Min : sec*	*Volume pct*	*Volume pct*
		LARGE ROOM			
5:20	0		30:30	0.5	
7:30		2.7	33:00		> 7.0
10:00	0		35:20	.2	
13:15		2.7	38:30		> 7.0
15:00	0		40:25	6.0	
17:00		4.3	43:15		> 7.0
20:10	0		45:32	.4	
22:30		[2] >7.0	48:25		>7.0
25:25	0.3		50:40	.6	
27:10		> 7.0	54:00		1.6
		SMALL ROOM			
5:25	0		30:30	.5	
7:35		1.8	33:20		> 7.0
10:20	0		35:30	2.4	
13:00		2.7	38.15		>7.0
15:47	0		40:35	<0.1	
18:50		3.8	43:55		> 7.0
21:07	0.2		45:20	2.5	
23:53		> 7.0	48:35		> 7.0
25:30	1.1		50:35	5.0	
28:25		>7.0	53:05		2.4

[1] The only HCN detected during the test was 5.0 and 2.0 ppm at 23:08 and 27:35, respectively, in the small room.

[2] The maximum reading on the CO_2 tubes was 7.0 pct CO_2. An indicated reading of >7.0, therefore, indicated a concentration that was off-scale on the high side.

Table 9.—Fire endurance as time to structural failure and relative randing of structures

Structures	Wall sections: Northeast		Southeast		Southwest		Northwest		Average		ASTM E 119 Tests	
	Min : sec	*Rank*	*Min : sec*	*Rank*	*Min : sec*	*Rank*	*Min : sec*	*Rank*	*Min : sec*	*Rank*	*Min : sec*	*Rank*
1	11:00	7	12:30	7	17:15	7	17:00	7	14:30	7	3:00	7
2	34:45	3	44:45	1	44:15	2	45:00	2	42:15	2	23:00	3
3	17:30	6	17:30	6	21:00	6	21:00	6	19:15	6	3:10	6
4	23:00	5	23:00	5	25:15	5	25:00	5	24:00	5	5:55	5
5	43:15	1	41:00	2	49:45	1	50:45	1	46:00	1	29:30	2
6	38:15	2	36:00	3	42:30	3	42:00	3	39:30	3	34:00	1
7	25:30	4	33:15	4	38 (est.)	4	32 (est.)	4	32:15	4	21.08	4

Table 10.—Fire endurance telative to flashover (time from flashover to structural failuire) in large-scale tests

Structure	Wall sections: Northeast		Southeast		Southwest		Northwest		Average		ASTM E 119 tests	
	Min : sec	*Rank*	*Min : sec*	*Rank*	*Min : sec*	*Rank*	*Min : sec*	*Rank*	*Min : sec*	*Rank*	*Min : sec*	*Rank*
1	– 4:45	7	– 3:15	7	1:30	6	1:15	6,7	– 1:15	7	3:00	7
2	6:15	4	16:15	3	15:45	4	16:30	3	13:45	4	23:00	3
3	– 2:15	6	– 2:15	6	1:15	7	1:15	6.7	– 0:30	6	3:10	6
4	1:30	5	1:30	5	3:45	5	3:30	5	2:30	5	5:55	5
5	22:00	2	19:45	2	28:00	1,2	29:30	1	24:45	2	29:30	2
6	23:45	1	21:30	1	28:00	1,2	27:30	2	25:15	1	34:00	1
7	7:30	3	15:15	4	20:00	3	14:00	4	14:15	3	21:08	4

Table 11.—Fire exposure of loaded walls in large-scale structure tests compared to fire exposure in laboratory ASTM E119 wall tests[1]

Structure No	Test wall	Structural fire tests: Ignition to wall failure	Structural fire tests: Rank[2]	Structural fire tests: Flashover to wall failure	Ratio of large-scale fire exposure to ASTM E 119 test wall: From ignition to wall failure	Ratio of large-scale fire exposure to ASTM E 119 test wall: From flashover to wall failure
		°F·min		*°F·min*		
1	Northeast[1]	970	7	[4]—	0.70	—
	Southeast	1,830		[4]—	1.31	—
	Southwest	1,550		260	1.11	0.18
	Northwest	1,080	7	195	.78	.14
	ASTM Lab	1,398	7	[4]—		
2	Northeast [3,5]	8,000	4	2,900	.32	.11
	Northwest [5,6]	15,000	4	5,600	.66	.22
	ASTM Lab	25,218	3	[4]—		
3	Northeast [3]	2,550	6	[4]—	1.73	—
	Southeast [3]	2,710		[4]—	1.84	—
	Southwest	1,930		295	1.31	.20
	Northwest	1,790	6	55	1.21	.04
	ASTM Lab	1,476	6	[4]—		
4	Northeast [3]	4,180	5	580	1.26	.17
	Southeast [3]			500	1.28	.15
	Southwest	3,440		1,500	1.04	.45
	Northwest	2,720	5	1,100	.82	.33
	ASTM Lab	3,325	5	[4]—		
5	Northeast	36,060	2	30,870	1.04	0.89
	Southeast[3]	30,610		26,080	.88	.75
	Southwest	30,330		28,300	.88	.82
	Northwest	31,670	1	29,590	.91	.85
	ASTM Lab	34,629	2	[4]—		
6	Northeast	40,820	1	37,960	.99	.92
	Southeast[3]	34,830		32,140	.84	.76
	Southwest	28,850		28,140	.70	.68
	Northwest	28,870	2	28,250	.70	.68
	ASTM Lab	41,360	1	[4]—		
7	Northeast[3]	13,310	3	10,290	.59	.46
	Southeast	25,260		21,760	1.12	.96
	Southwest	—		—	—	—
	Northwest	19,370	3	17,950	.86	.30
	ASTM Lab	22,575	4	[4]—		

[1] Fire exposure is the area under the time-temperature curve for the protected thermocouples above 68° F baseline, computed from: (1) Time of ignition to wall failure; or (2) time of flashover to wall failure.
[2] Southeast and southwest walls were not ranked, as temperature data for these walls were not available for all seven structures.
[3] First wall section(s) in structure tests to fail.
[4] Wall failure occurred before flashover in structures. In laboratory tests, flashovers do not occur.
[5] Due to instrumentation difficulties, temperature data for Structure 2 are limited and eratic. Accuracy of areas shown and the derived information is not known.
[6] Area is measured under time-temperature curve for bare thermoculples in northwest room; insufficient data obtained from protected thermocouples.

Table 12.—Time of burn-through in loaded walls

Structure No.	Wall section[1]: Northeast	Wall section[1]: Southeast	Wall section[1]: Southwest	Wall section[1]: Northwest	Average	ASTM E 119 tests
	Min : sec					
5	38:20	38:30	44:15	40:15	40:20	[2]33:30, 35:00
6	34:30	34:30	41:15	35:09	36:21	37:00
7	24:10	33:30	—	24:40	27:27	16:00

[1] Times given are for the first observation of burn-through. In some instances, burn-through may have occurred prior to the time shown.
[2] Two E 119 tests were made with this wall construction.

Table 13.—Fire resistance of interior wall lining material

Structure No.	Lining material	ASTM E 119 tests[1]: Average exceeded 250° F above ambient	ASTM E 119 tests[1]: Single thermocouple exceeded 325° F above ambient	Large-scale tests[2]: Average exceeded 250° F above ambient, Southeast	Large-scale tests[2]: Average exceeded 250° F above ambient, Southwest	Large-scale tests[2]: Single thermocouple exceeded 325° F above ambient, Southeast	Large-scale tests[2]: Single thermocouple exceeded 325° F above ambient, Southwest
		Min : sec					
3	¼-in. Douglas-fir plywood	4:06	4:12	21:26	—	22:20	—
4	¼-in. Douglas-fir plywood	5:28	3:56	24:55	—	24:40	—
5	3/8-in. gypsum wallboard	[3]11:48, 11:00	[3]11:12, 11:18	25:55	37:19	26:44	37:38
6	3/8-in. gypsum wallboard	11:54	11:30	18:42	28:38	17:48	28:44
7	¼-in. lauan plywood	2:12	2:06	16:00	21:26	18:46	21:38

1 Based on five or six thermocouples located in back of the lining.
2 Based on three thermocouples at heights of 1, 4, and 7 ft and located in back of the lining.
3 Two ASTM E 119 tests were made with this type of wall construction.

Conversion of Units

1 Btu/ft^{2}s = 1.13 W/cm^2

1 ft = 0.305 m

1 in. = 25.4 mm

1 lb = 0.454 Kg

1 lb/ft^2 = 4.88 Kg/m^2

1 lb/ft^3 (pcf) = 16.0 Kg/m^3

1 lb/lin ft = 14.6 N/m

1 mile/hour = 0.447 m/s

1 °F = 0.556° C

T (°F) = 1.8 T (°C) + 32

* U.S. GOVERNMENT PRINTING OFFICE: 1980-651-111/53

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