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STANDARD ROOM FIRE TEST RESEARCH AT THE NATIONAL BUREAU OF STANDARDS

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STANDARD ROOM FIRE TEST RESEARCH AT THE
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B.T. Lee and J.S. Steel

Abstract

Research results with the proposed ASTM standard room fire test for interior finish materials are presented. The materials selected for the study were two untreated plywoods, a fire-retarded plywood, polystyrene foam, polyisocyanurate foam, and gypsum board. Three 900 s duration test scenarios were considered. Scenario A is a constant 180 kW ignition source exposure. Scenario B achieves the same maximum exposure after three intervals of 30 s each in which the heat release rate is increased in equal steps of 45 kW. Scenario C evaluates a material over a 300 s exposure at a nominal 45 kW, with another 300 s exposure at 180 kW, followed by 300 s at zero exposure. This zero exposure allows the material to be screened for continuation of burning afterwards. The study demonstrated that all three scenarios could adequately differentiate material fire behavior, in terms of the maximum degree of fire buildup attained and the time to reach the maximum, for the materials selected. However, scenario C would allow a more comprehensive evaluation of materials.

Thermal radiation incident on the floor and room and doorway air temperatures were found to be suitable parameters for determining room fire buildup including room flashover. Surface flame spread and rate of heat release are discussed for the room fires. Unit area bench-scale rate of heat release data from the cone calorimeter may be predictive of the full-scale data when melting and dripping (which changes the active burning area) or very slow to ignite fire retarded materials (whose retardants may be baked out) are

not involved. Further full-scale testing is desirable to establish more confidence and delineate the limits of validity.

Keywords: fire growth, flame spread, heat release, interior finish, room fire, fire test method.

1. INTRODUCTION

Room fire testing of interior finish materials is often the only way to evaluate the fire hazards of some materials. Presently, most room fire tests are conducted in enclosures having a single opening. Fire growth studies in rooms having multi-openings are needed to help generalize room fire behavior as a function of room configurations. Traditionally the ASTM E 84 tunnel test [1][1] has been used by the U.S. building codes to rate the flammability of interior finish materials. A Class A material, with a flame spread index (FSI) equal to or less than 25 from the E-84 test, is considered to be safe for use in most applications. A FSI classification of 30 would then also be expected to be almost as safe. However, a room lined with a Class A foam plastic (tested at Underwriters Laboratories) reached flashover in less than 120 s when exposed to the flame from a 9.1 kg (20 lb) wood crib [2]. A subsequent fire test run at the National Bureau of Standards, with a room lined with FSI 30 polyurethane foam, exhibited flashover in 17 s when exposed to a gas burner with a constant net heat output rate of 80 kW [3]. The latter heat output represented only a small fraction of that needed to flash over the

[1]Numbers in brackets refer to references at the end of this report.

It is not clear what the logic of this 2-page paragraph is. Ideas come and go and there is no help to the reader in following them. Break it into shorter ¶s and set up + follow a chain of logic that leads to this project.

space. Previous studies [4] indicated that at least 300 kW was required for a similar sized, well insulated test room to reach flashover in under 600 s. The avoidance of flashover is particularly important as the event represents a transition from a fire in which the flame spread can normally be confined to the room of fire origin to a fire which could readily involve the active burning of adjoining spaces and, eventually, of the entire structure. Once flashover has occurred, the fire can spread outside of the room of fire origin by two mechanisms other than by heat conduction through the walls and ceiling. One is the ignition of combustibles by direct contact with flames and hot combustion products leaving the room. The other is ignition by thermal radiation levels of 20 kW/m^2 or more through the room opening. Time to flashover has been defined in a proposed method for room fire testing [5] as either the time when the radiant flux onto the floor reaches 20 kW/m^2 or the temperature of the air near the ceiling (hence, also in the doorway) reaches 600°C. The proposed method recommended that the spontaneous ignition of a crumpled up single sheet of newspaper on the floor would provide a visual indication of flashover as would be the flame extension beyond the doorway which usually ~~really~~ occur at about the time of flashover. Of these above events indicative of flashover, the value of 20 kW/m^2 on the floor is the most critical. At this flux level, spontaneous ignition of light combustibles occur in the room of fire origin and the fire will very rapidly grow to involve virtually all combustibles in the room. For the above two foam materials, a "safe" E-84 rating was, in fact,not "safe" at all. Indeed, evidence shows that room fire testing offers the only current means for accurately measuring some of the fire hazards of synthetic foam materials [2,6,7]. In studies with painted and unpainted insulation materials [~~5,6~~ 6,7], no correlations were found between their room fire test behavior and their performance on laboratory tests which measure ignitability, flammability, heat release rate, and smoke generation.

The potential fire hazards of such foam plastics led to building code requirements that foam plastic materials must have an E-84 rating of 75 or less and be covered with a thermal barrier layer equivalent to 12.7 mm thick gypsum board; however, if they are to be exposed, their fire safety must be demonstrated by a full-scale room fire test [8,9,10]. In the Uniform Building Code of the International Conference of Building Officials (ICBO), a particular room fire test, with a wood crib as the ignition source, was specified for this purpose [8]. A task group was then set up to develop a modified version of this ICBO test which would be acceptable as an ASTM standard test method. This modified test used a propane burner instead of a wood crib as the ignition source and called for the measurement of heat release rate from the fire. A proposed method has been published in the grey pages of the 1982 ASTM Annual Book of Standards [5] for information purposes. At the present time, Task Group 1 of ASTM subcommittee E 5.13 is actively working on the improvement of this proposed standard. This test method has been used in the United States at the University of California at Berkeley, the Weyerhaeuser Company in Longview, Washington, and the National Bureau of Standards. The results from the University of California and the National Bureau of Standards have been published [11,12,13]. In addition to requirements regarding the room and ignition exposure, the method specifies a hood outside the doorway to collect all of the exhaust gases in order to provide information on the rates of heat, smoke and toxic gas production.

What does the answer ASTM? The purpose of the test determines your interpretation of results

Before the test method can be accepted as an ASTM standard, a suitable heat release rate scenario for the ignition source has to be agreed upon and interlaboratory evaluations of repeatability and reproducibility should be conducted. It is necessary to be able to apply this standard room fire test method to all materials not just foam plastics.

Eventually, room fire tests could be replaced with a mathematical model which could predict fire development for other room sizes and configurations and ignition conditions, based on information from bench-scale tests and material property measurements. Prerequisite to this approach are (a) the need for an improved understanding of surface flame spread and its relation to the thermal environment in the room and (b) a well-documented data base from a variety of room fires.

With all these considerations in mind, the objectives of the present project and of this report are:

There is no build-up in the fire for this test →

1. to investigate the effects of three different heat release rate exposures for the ignition source on the room fire behavior of a variety of interior finish materials having a broad range of fire properties,

in the one 2. to evaluate the various methods used for determining room flashover,

in the one 3. to provide surface flame spread data from room fires as a function of the degree of fire development in the room, and

Reread the introduction and aim it toward why we did this and why the results are important.

in there 4. to examine the practicality of the operational procedure recommended in the proposed standard.

2. EXPERIMENTAL

The inside dimensions of the test enclosure are 2.54 x 3.71 x 2.49 m. The two side walls and rear wall ar constructed of concrete masonry block. The front wall (containing the door) and the ceiling are constructed of 6.4 mm calcium silicate board. The doorway has dimensions of 0.76 x 2.03 m and was located at the center of the wall. Furring strips of either wood or metal are used on the concrete masonry block walls to adjust the finished interior dimensions of the burn room to 2.44 x 3.66 m. Similar strips are used on the ceiling to adjust the finish height of 2.~~55~~44 m. The floor is reinforced concrete, protected by a layer of gypsum wallboard.

Figure 1 is a schematic of the test room and exhaust hood. This hood has horizontal dimensions of 3.7 x 4.9 m and discharges into a 1.2 m square duct. The ducting is comprised of an initial upward section, then a downward portion, and finally another upward section.

2.2 Test Materials

The intro should tell the reader why you are focusing on these

In the assessment of the fire test method, six materials having significantly different flame spread behavior or heats of combustion were used in this study. These materials are indicated in Table 1. Gypsum board is fire resistant and is used extensively in residential occupancies and thus was chosen as a reference material. Polystyrene and polyisocyanurate foams are, in practice, used only when protected with a fire resistant barrier such as 12.7 mm thick gypsum board. In this study, these foams were used fully exposed to exemplify interior finish materials having widely different flame spread characteristics. In addition, polystyrene was chosen for its tendency to melt and drip when exposed to a fire. One plywood was selected as representative of wood paneling having no fire retardant treatment. A thickness of 12.8 mm was selected to assure a sufficiently long involvement without burnthrough for the assessment of the different fire exposure scenarios which last as long as 900 s. The 5.6 mm plywood was similar to that used in the room fire test at the University of California [12] and was used to assess the reproducibility between the two facilities for this material. Fire retarded plywood is becoming commonplace in the home and therefore a representative sample was included.

This means the materials should have a low chance to ignite or to slowly have significant ignition resistance.

2.3 Test Program

This means the burner shouldn't flash the room by itself.

In the selection of ignition exposures, the exposure should be large enough to adequately assess the fire hazard potential of materials, but should not be so large as to overwhelm the materials being evaluated. At the Swedish National Testing Institute [14], full-scale room fire tests have been conducted using a propane burner, positioned in a back corner, operating at 100 kW for the first 600 s and at 300 kW for another 600 s. An earlier study [4] indicated that 300 kW could result in flashover conditions in a non-flammable, well-insulated test room. ~~Thus, this exposure was~~ considered to be too severe. A maximum exposure of 160 kW, proposed in 1982 by Task Group 1 of

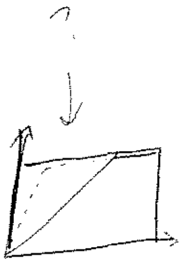
Dead drawing?

cf Vytis paper (Ref 24)

ASTM subcommittee E 5.13, was chosen for this study. However, an error in calibration resulted in a value of 180 kW for the maximum exposure.

Explain why [illegible] rather than in propane flow. ramp

Three ignition exposures, each eventually producing a maximum value of 180 kW net rate of heat release, were used and are shown in Figure 2. This maximum rate corresponded to a nominal propane gas flow rate of 2.06 ℓ/s at 20°C and 100 kPa. Exposure A was a constant 180 kW maintained for 900 s and was chosen to evaluate the effect of a severe sudden thermal insult on materials. Exposure B, proposed by Task Group 1 of ASTM E 5.13, started at 0.25 of its maximum value, increased to 0.50 of its maximum at 30 s, to 0.75 of its maximum at 60 s, to its maximum in 90 s and was maintained at that level to 900 s. This exposure was chosen to evaluate the effect of having an increasingly severe fire exposure on materials. Exposure C started with 0.25 of its maximum value, maintained for 300 s, increased to the maximum for another 300 s, and the ignition source was then turned off for the final 300 s period. Exposure C was selected to evaluate the effect of a longer, low fire exposure on materials, particularly charforming materials such as rigid foams and wood, and to examine their subsequent behavior under a severe fire exposure. This exposure also allowed an evaluation of the self-sustained fire spread characteristics of materials.



The test program is summarized in Figure 3. For tests 1-15, 19 and 24, the test specimen fully covered the back wall, the two side walls, and the ceiling. The remaining tests had either the ceiling or the three (side ~~or~~ and back) walls covered with the test specimen. The 5.6 ~~mm thick~~ plywood 1 was used only once, to check on the reproducibility between tests conducted at the

I realize it would cost too much to do all tests in the grid. You need to present some sense of why these particular ones were selected (including the choice of replicates)

National Bureau of Standards and at the University of California [12] using ignition exposure B. Exposures A and C were used for the plywood 2 to bracket the material's behavior under the least and most severe of the three exposures.

2.4 Test Procedure and Measurements

With the specimen material in place, the interior dimensions of the test room were in conformance with the recommended standard room size of 2.44 m ± 25 mm by 3.66 m ± 25 mm by 2.44 m ± 13 mm high. The interior finish material to be tested was mounted over 13 mm gypsum board. For the foam plastics, the specimen was glued to the gypsum board using 3M-2226 adhesive made by the 3M Corporation.[2] For the 5.6 mm plywood, the room construction replicated that used in the University of California test. When the specimen lined only the wall surface or the ceiling surface; the remaining ceiling or wall surface was the gypsum board substrate.

The relative humidity in the fire room was maintained with a humidifier between 42 and 55 percent for at least 24 hours prior to the test. The temperature of the laboratory was controlled such that the test room was maintained within the proposed test value of 21 ± 3°C.

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[2] Note: Certain commercial materials and equipment are identified in this report for completeness. Such identification does not imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the materials or equipment are necessarily the best available for the purpose. 2

A 305 mm by 305 mm by 305 mm high propane gas diffusion flame burner in one back corner served as the ignition source. In this series of tests, C.P. grade propane was used in lieu of the less pure commercial grade to avoid possible fractionation problems. In each test, the fire was allowed to continue past peak fire intensity before extinguishment. The flux levels on the back wall over the burner, at the 1.22 m and 1.83 m heights above the floor and 0.15 m away from the corner, are given in Table 2 for the burner operating at the 180 kW setting in the room lined with exposed gypsum board. The flux levels in Table 2 can be used as a check on the reproducibility of the ignition source intensity when such tests are repeated at other facilities. The data in the table also showed that there was no significant change in flux levels when the coolant water ? to the fluxmeter was varied from 18°C to 70°C. re-word to be accurate

or fluxmeter

Locations of the instrumentation used for the room fire tests are shown in Figure 1 and listed in Table 3. The output of each transducer was recorded every 2 to 3 seconds. The rate of heat release was calculated from measurements which were made in the ducting leading to the smoke abatement equipment for the building. These measurements were taken in a section of the duct where the gases are flowing downward; the gases are believed to be more than what? uniformly mixed at such a location. The heat release rate was determined using the oxygen consumption method [17] which depends on measurements of mass flow and the oxygen concentration. The mass flow was measured with an array of nine pitot-static tubes, each with its own pressure transducer, and an array of nine thermocouples. The oxygen concentration was measured at the center of the duct using a paramagnetic gas analyzer. The pressure

How accurate is [...], and RHR?

transducers has unsteady output signals reflecting turbulence in the airstream, and these signals were smoothed using active filters with nominal ten second time constants. (Each filter used a 10 microfarad capacitor, two one megohm resistors and a chopper-stabilized operational amplifier to time-average the signal from one transducer.)

The heat release rate measurement was calibrated at 250 kW using a square diffusion burner, 0.305 m on each side, installed under the hood. The propane flow to the burner was determined both by the mass loss rate of the propane and by the volumetric measurement of propane flow with a rotameter. The calibration factor which had to be applied to the heat release rate calibration was determined by this procedure to be 0.70. For calibration between 250 kW and 4 MW, natural gas was used. An orifice meter made to AGA and ASME specifications and the dry gas displacement meters used for metering the natural gas to the building, were used to measure the gas flow to the burner in this case. The calibration factor of 0.70 was found to hold for the higher heat release rates. This calibration factor was substantially below unity because true straightened streamline flow had not been achieved in the measurement section. The calibration curve for the heat release rate is given in figure ~~3~~ 4.

There is a response delay for the oxygen concentration measurement which is a composite of the transport time for the effluent to reach the gas sampling location, the transport time within the gas sampling system itself, and the response time of ~~actually required by~~ the oxygen analyzer. (In this instance, the time required by the gases to reach the sampling point is much larger than the other two components.) The measurement of the flow velocity also has a response time due to the filtered output of the pressure transducers which monitor the pitot-static tubes. Babrauskas [18] gives a discussion of various methods of correcting for the time delays in this hood before choosing a delay of 30 seconds as a reasonable approximation. Based on a similar analysis? ~~that discussion~~ the data on heat release rate presented in this report have been adjusted by subtracting 30 seconds to correct for the system response time.

for the purposes of this study

The hood was also used to quantify smoke from the room fires in terms of a critical cross section which is based on optical density and mass flow measurements in the hood duct [19]. The optical density across the exhaust duct was measured with a laser photometer and is given by

$$\text{O.D.} = \log_{10} \frac{100}{T} = \log_{10} e^{K\rho L} = 0.434\ K\rho L$$

where T is the percent transmission measured with the photometer, K is the specific extinction coefficient in m^2/kg, ρ is the smoke density in kg/m^3 and L is the path length in m across the exhaust duct. The critical cross section is given by

$$E = \int_0^{t_T} K\rho\dot{V}dt = \frac{2.3}{L} \int_0^{t_T} (\text{O.D.})\ \dot{V}dt$$

where $\dot{V}$ is the volume flow in m^3/s in the duct referred to the stream temperature and t_T is the duration of the test in seconds.

Prior to room flashover, fire growth was followed using the maximum air temperatures reached near the ceiling and near the top of the doorway and by the thermal flux incident on the floor.

redundant

temperatures reached near the ceiling and near the top of the doorway and by the thermal flux incident on the floor.

never defined here

In the determination of room flashover, the times were recorded at which each of five criteria were met:

Other than the #2 on p12, this is the first time flashover measurement has been presented. What is the problem?

1. flameover, defined here as the emergence of visual flames from the doorway (t_F),

2. the visual ignition of crumpled newspaper on the floor (t_{FO}),

3. the attainment of a heat flux of 20 kW/m^2 on the floor (t_{Floor}),

4. the attainment of an average air temperature of 600°C or higher near the ceiling (t_I), and

5. the attainment of an average air temperature of 600°C or higher near the top of the doorway (t_D).

In tests 1B to 19, vertical and horizontal grid lines were drawn on the walls and ceiling, at 0.305 m intervals away from the corner where the burner was situated, to help follow the surface flame spread. In tests 17 to 19, thirty-three surface thermocouples were located on the walls at locations shown in Fig. 10.

Still photography and continuous video coverage of the burner flame and adjacent walls and ceiling were taken to allow mapping of the surface flame spread as a function of time. Only the flame spread along portions of the back wall and ceiling could be viewed through the doorway. The flame spread profiles for the remaining portions of the room had to be estimated based on past experience with room fire testing of interior finish. The estimated profiles along the left and back walls were assumed to be extensions of what were observed along those surfaces and were assumed to connect with the observed spread along the ceiling. Estimated profiles along the right wall were drawn to be consistent with the projected ceiling profiles and assumed to have similar shapes to ~~as~~ those for the left wall.

redundant w/ p17

The operational procedure followed that described in the proposed room fire test method [5], except that purer, C.P. grade propane, instead of commercial grade, was used and that thermocouples penetrating through the ceiling, instead of being mounted on supports inside the room, were used for recording the air temperatures near the ceiling.

3. RESULTS AND DISCUSSION

3.1 Effect of Ignition Source History on Fire Development

Uncertainties must be estimated for the various measurements before a meaningful comparison of the data can be made. Temperature measurements with type K thermocouples used in ~~this study are consistent~~ to within ± 2 K or 0.75 percent, whichever is greater [20]. Flux measurements with Gardon type

but are they accurate? (corrected for radiation, etc.)

fluxmeters, in these room fire tests, are accurate to ± 3 percent [21]. From ~~our experience~~, the heat release rate measurements could be accurate to ± 0.05 MW for rates up to 1 MW and ± 5 percent for higher rates. Smoke measurement, expressed in terms of an extinction cross section could be measurable to within ± 20 percent, although this estimate is somewhat crude. because of mixing? With the newspaper flashover indicators, there is evidence [22] that variation in the thermal and physical properties of newspaper could result in the crumpled newspaper igniting over a range of fluxes between 17 and 25 kW/m^2.

Test reproducibility could pose a problem. Unfortunately, this is difficult to deduce because only one test with the fire-retardant-treated plywood and another test with the polyisocyanurate were repeated. There were problems with the conditioning and uniformity of the treated plywood, and these will be discussed later. As for the polyisocyanurate, the data from test 9 were practically identical with the limited data from its repeat test 24. In tests 17 and 18 with the plywood lining the walls, only the ceiling materials were different. Test 17 had an inert calcium silicate board ceiling, while test 18 used a gypsum board ceiling which had a fairly low combustibility. Much longer times were needed to achieve 600 to 650°C in the doorway in test 18 than those in test 17. This might have been a consequence of the larger thermal losses to the ceiling in test 18 due to the higher thermal conductivity of gypsum board. This apparently did not affect the interior temperatures, because the interior thermocouples were located (0.10 m below the ceiling) below the cooler layer adjacent the ceiling. The funneling of this cooler air out the doorway might have brought the cooler air down past the doorway thermocouples in test 18. Aside from the doorway data, ~~both~~ the two tests which?

gave results which were within 15 percent of each other. This was consistent with findings from a series of quarter-scale room fire tests of interior finish materials [23] that reproducibilities of about ± 20 percent in occurrence times were possible for each of these same flashover indicators.

3.1 Effect of Ignition Source History on Fire Developmen

In this series of tests, one would expect that as the ignition exposure increases in severity from exposure C to A, the values of pre-flashover parameters (peak values of heat release rates[3], air temperatures, and thermal radiation) would increase, with decreasing times of their occurrence, providing the resulting fires are ~~severe~~ different? enough such that the measurement uncertainties would not mask such effects. An examination of Tables 4 to 8 NOT SO shows that the uncertainties in measurement masked any effects of ignition exposure in tests 1B to 3B with the gypsum board. In tests 7 and 19 with plywood 2 and tests 9 to 14 involving the polystyrene and polyisocyanurate, the times to reach flashover, based on all five criteria discussed in section 2.4, were considerably shortened as the ignition exposures changed from C to A. For the polyisocyanurate foam in test 14, exposure C initially had little effect on the material. When the burner level was increased to that of exposure A at 300 s into the test, the fire development in test 14 then proceeded to behave much like that for test 9 with the scenario A ignition exposure. Smoke production at exposure A for both ~~beams~~ foams was considerably grater than those at exposures B and C. In tests 16 to 18 and 20 to 23, where the test material was used only on the walls, similar changes in the room fire development occurred with increasing severity of the ignition exposure.

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[3] Note that these values are determined by measurements in the exhaust system, and thus include both the heat being released within the test room and any burning in a fire plume outside the door.

The different ignition exposures gave erratic results for the fire retarded plywood. This was attributed to two factors: (1) nonuniformity of material properties in the batch of treated plywood. (A second batch of fire retardant treated plywood received from the same supplier appeared significantly different in color, suggesting that some differences in wood or in treatment may have occurred even through the plywood was stamped with the same treatment identification. This new batch was not used in the present study.) And (2) difficulty in conditioning the material over a reasonable period of time. An electrical resistance moisture gage was periodically inserted into the material to ascertain whether steady state conditions had been achieved. The gage could not be used to quantify the moisture content as the measurement was affected by the fire retardant additive. However, after two weeks, the gage readings indicated steady values and tests 4 to 6 were performed. With exposure A, no ignition of the newspaper flashover indicators occurred and a flux of only 13.8 kW/m^2 was measured on the floor. Subsequent tests 5 and 6, with exposures C and B, respectively, resulted in ignition of one or both newspaper indicators in each test with higher fluxes incident on the floor. Test 15 was a repeat of test 4, using the remaining panels, which had been conditioned at about 22°C and 50 ± 5 percent relative humidity for several months. Test 15 resulted in ignition of the newspaper flashover indicators and reached 20 kW/m^2 on the floor at 847 s. It can be concluded that materials having probably differences in composition or nonuniformity in fire retarded treatments should be conditioned over a range of times and fire-tested periodically to check on their consistency in fire performance.

How - More full-scale tests?

The data in Tables 4 and 5 show that the three ignition exposure conditions could result in different fire behavior when the test material covered only the walls and when the material covered both the walls and ceiling. ~~However~~, the relative fire hazard ranking ?? of these materials depended on the exposure condition used and on whether the material lined both walls and ceiling. For example, when the room was fully lined with the test material, exposure A ranked the materials in the following order of increasing hazard, based on times to reach room flashover (20 kW/m^2 on the floor, except for test 10, where the newspaper indicator was used in lieu of no flux datum): gypsum board, fire retarded plywood, plywood 2, polystyrene foam, and polyisocyanurate foam. However, when exposure C was used with a fully-lined room or when exposure A was used in a room where the material lined only the walls, the polyisocyanurate material resulted in longer times to flashover than those for the plywood 2 and polystyrene. Exposure A was chosen for the case where the test material lined only the ceiling because tests 2 and 3B showed that the burner flames for the initial parts of exposures B and C did not reach the ceiling. With the test material on the ceiling under exposure A, the polyisocyanurate also resulted in longer times to reach flashover than did those for the plywood 2 and polystyrene.

You don't have a ranking scheme.

So ? What have we done regarding the choice of an ignition simulation and why?

3.2 Comparison of Results with University of California Test

The conditions in test 8 with the 5.6 mm grade AD plywood were planned to be the same as in test C-213 conducted at the University of California [12]. A comparison of results from the two tests is given in Table 9. The rate of heat release curves are shown in Figure 5. These indicate a substantial difference between the two tests. Test 8 resulted in a more rapid fire buildup than C-213, in part because the ignition exposure in test 8 was found to be 12 percent higher than that used in test C-213. In addition, the plywood specimens used in the two tests were each purchased locally and might not have been identical. Third, the specimen conditioning prior to test might not have been the same. Despite those factors, it is interesting that all of the five flashover indicators occurred at times within the experimental repeatability expected between similar runs. Therefore ...

3.3 Comparison of Various Methods for Determining Flashover

The occurrence times for the five criteria discussed in section 2.4 are shown in Tables 4 and 5 under headings of t_F, t_{FO}, t_{Floor}, t_I, and t_D.

In almost all of the tests, all five flashover parameters for each test gave times which were close to each other for severe room fires (e.g., fires having a flux of 20 kW/m^2 or more on the floor, or newspaper flashover as in test 10 when the flux was not available). Table 10 compares statistically the data from the five methods for determining room flashover for each test. The high coefficients of variation for runs 9 and 15 were not surprising as some of the data for run 9 were estimated values (interpolated between data values 10 s apart when the fire was growing rapidly) and localized heating at the ceiling in test 15 resulted in t_I values that were much too fast. Table 11 used the same data excluding the values for t_I and t_D for 600°C. This lowered the coefficient of variation for most of the runs meaning that t_I and t_D based on the higher temperatures of 700°C and 650°C, respectively, resulted in better agreement with the rest of the flashover parameters. Table 11 indicated that, aside from tests 9 and 15, the flashover indicators had coefficients of variation of less than 14 percent. For less severe fires, one or more flashover criteria were not satisfied. Since the range of the five times was narrow, one can use the most comfortable or practical criteria. The following discussion helps with which to use.

Flameover did not always occur for the situation where there was sufficient thermal radiation to ignite combustible items in the lower part of the room. Test 6 illustrates this case. In that test, both newspaper flashover indicators ignited and both interior and doorway air temperatures exceeded 600°C. Yet no flameover occurred.

In the case of the newspaper indicators and fluxmeters, burning material falling from the ceiling could affect their reliability. For example, test 15 had its newspaper indicator at the back of the room ignited by falling embers. For rapidly-developing fires, it is sometimes difficult to determine whether this is the case. Material falling over the flux meters could either obscure or transfer additional heat to the fluxmeters.

Air temperatures measured near the ceiling could be affected by local heating and flame contact, resulting in readings that are higher than average with consequent premature times for flashover. For example, in tests 15 and 18, the times for t_I based on the attainment of 600°C were too soon compared with the times for t_F, t_{FO}, t_{Floor}, and T_D. Tables 4 and 5 show that having t_I correspond to an interior air temperature of 700°C resulted in closer agreements with the other flashover indicator times for test 18. However, the value for t_I was still too short for test 15 and the t_I for test 4 indicated flashover at 240 s, which was inconsistent with a floor flux of 13.8 kW/m^2 and no ignition of the newspaper flashover indicator.

The peak doorway air temperature may be a more reliable indicator of the fire buildup than is the interior air temperature. The hot air inside the room usually becomes well mixed by the time it is exhausted through the doorway. However, inconsistencies still occurred with the use of doorway air temperatures. For example, Table 4 indicates that a t_D based on 600°C gave a flashover time of 300 s for test 4, which was inconsistent with a no flashover indication from the floor flux and newspaper ignition indicators. A t_D based on 650°C resulted in a no flashover indication for tests 4. However, a t_D based on 650°C resulted in a no flashover indication for test 26 in Table 5 in contrast to the other ~~indicators showing~~ flashover.

In summary, there are problems which can arise in determining flashover by each method. Thus, it is necessary to have more than one reliable method for indicating flashover. Analysis of Tables 4 and 5 indicates that flameover, a 20 kW/m^2 flux incident on the floor, flaming ignition of crumpled newspaper, an interior upper layer air temperature of 700°C and a doorway upper layer temperature air temperature of 650°C comprise a reasonable list from which to choose. For following fire buildup short of flashover, all but flameover and the newspaper indicator are useful. If the test is to be standard, then a specific recommendation is needed (with substance)

3.4 Fire Growth Data

Figures 6 to 10 show the flame spread patterns at selected times for the five test materials which were evaluated under test conditions of exposure A and where the test specimen covered both the walls and the ceiling (tests 1B, 9, 10, 15, and 19). These five tests were chosen as the easiest cases for mathematical simulation of the room fire growth due to their constant ignition exposures and uniformity of materials on both the walls and the ceiling. The room surface areas covered by flames at selected times for these tests (except for test 1B) are given in Tables 12 to 15. Test 1B was lined with gypsum board. There was little or no flame spread with just the flame impingement zone darkened by the burner flame. In test 19 with the plywood 2, the exposed surface was instrumented with surface thermocouples as shown in Figure 10. The times of arrival of the flame front at specific locations on the back wall agreed with those estimated from isotherms based on an ignition temperature of 350°C for wood.

This same procedure was repeated for tests 17 and 18 with the plywood 2 lining just the walls of the room. The flame spread results are given in Figures 11 and 12.

As an aid for future understanding of surface flame spread and its dependence on the environment, oxygen concentrations in the room were monitored for tests 17 to 19. The data are given in Figures 13 to 15. Ceiling fluxes were also measured in tests 17 to 19, and these are shown with fluxes taken at other locations in the room in Figures 16 to 18.

Wall flux data at two locations on the back wall are given for all of the above tests in Tables 16 to 21. Times were also indicated in these tables for the arrival of the flame front over each fluxmeter, for room flashover, and for complete coverage of the room linings.

3.5 Heat Release Measurements

The rate of heat release histories for tests 7 to 27 are shown in Figures 19 to 27. For the gypsum board tests, these curves were the same as those for the propane burner within the measurement scatter of ± 50 kW. Thus they were not included. For the fire retarded plywood, the peak rates in tests 4 to 6 were an order of magnitude lower than that for test 15. The heat release histories for tests 4 to 6 look similar, but with lower peak values, to the first 600 s of that for test 15. Only the worst case for the rate of heat release history is given, i.e., test 15, and is shown in Figure 19 along with the history for test 8 with plywood 1. Figure 20 compares the results for plywood 2 under exposures A and C. Figure 21 shows the heat release rate histories for plywood 2 lining just the walls under similar exposures. The same figure shows the differences in the rate history when the gypsum board ceiling was replaced with calcium silicate board. Figure 22 compares the case where the plywood 2 lined just the ceiling with those where the plywood lined the walls alone and lined both walls and ceiling. Figures 23 to 25 give the heat release rate behavior for the room partially and fully lined with the polystyrene under different ignition exposures. Similar rate histories for the polyisocyanurate are given in Figures 26 and 27.

Peak rates of heat release and the rates occurring at the time, when 20 kW/m^2 was measured at the floor (t_{Floor}), are presented in Tables 6 and 7. For the plywood materials covering the walls and ceiling, the rates at time t_{Floor} ranged from 1.7 to 1.9 MW. This was consistent with a value of 2.1 MW found for plywood tested at the University of California [12]. When polystyrene was used on the walls and ceiling, the rates at time t_{Floor} ranged from 3.1 to 4.2 MW. Tests with polyisocyanurate resulted in heat release rates of 2.2 to 3.2 MW at time t_{Floor}. The data on heat release as a function of time had been adjusted by subtracting an estimated measurement system response time of 30 s, as discussed in section 2.4. In the tests of the polystyrene and polyisocyanurate foams, the heat release rates were rapidly increasing at the time of t_{Floor}. A small uncertainty in the system response time could thus result in apparently significantly smaller or larger? rates at time t_{Floor}.

These measured values can be compared with those predicted with a rough analytical procedure [24] which assumes that only the fuel heat release rate and the available air supply, expressed in terms of the room ventilation factor $WH^{3/2}$ (where W and H were the width and height of the opening), are needed to estimate the room flashover potential. Use of that analytical procedure resulted in the prediction of a typical rate of about 1.3 MW required for flashover in the tests conducted in this study. This is in reasonable agreement with the range of 1.0 to 1.6 MW for the walls-only tests. Flashover for the faster-developing fires, as represented by the walls-and-ceiling tests, occurred at higher than predicted heat release rates, making the estimate conservative for these purposes. As for minimum rates needed for room flashover, evidence showed that for long duration fires and fires in highly-insulated rooms, rates

cf p 13 300 kW why?

as low as 300 kW could suffice [4]. A more exacting procedure, which takes into account the physical properties of the interior finish, room size, and doorway openings, is also available for estimating room temperature, and hence the potential for flashover, as a function of heat production rate [25]. However, it can not accommodate rapidly varying fires.

Integrating the rates of heat release shown in Figures 19 to 27 over time gives the total heat produced in each fire test. In Table 22, this total heat was compared with that calculated from the total weight loss of the test material multiplied by the net heat of combustion to determine the combustion efficiency for the material. (The net heat is equal to the gross heat minus the heat of vaporization of the water produced.) In all of these tests, it

THIS IS IMPORTANT

was assumed that the net heat of combustion of the residue was the same as that for the virgin material. The net heat of combustion for the plywoods 1 and 2 and the fire-retarded plywood were about 15.1 [15 For the plywoods, the combustion efficiency was about 0.90 when the material lined both the walls and ceiling. When the plywood lined just the walls or the ceiling alone, the combustion efficiencies were about 0.73 and 1.0, respectively. These two latter values were too high because the combustion of the gypsum board paper surface was included in their calculation. The combustion efficiency was about 0.4 for the fire retarded plywood. Representative net heat of combustion values of 38 MJ/kg and 26 MJ/kg for the polystyrene and polyisocyanurate [16], respectively, were used.

Same frame?

The combustion efficiency for the polystyrene, covering both walls and ceiling, was 0.53. This compared with a value of 0.59 from laboratory material property tests [26]. Similarly, the combustion efficiency for the polyisocyanurate averaged about 0.57 compared with 0.53 from laboratory tests [26]. With the material lining just the walls, the combustion efficiency for the polystyrene was less than 0.13 and was uncertain for the polyisocyanurate due to uncertainties in measuring the small mass loss and heat release.

3.6 Comparison with Cone Calorimeter Data

The same materials tested in full-scale were tested in bench-scale in the cone calorimeter [27]. This test method also used oxygen consumption as its measurement principle for determining rate of heat release and was published by ASTM as a grey-pages proposal [28]. The materials were tested at 25, 50, and 75 kW/m^2 irradiances, using a spark ignitor as the ignition source. With the exception of the room tests with the polystyrene and possibly with the polyisocyanurate, Tables 16 to 21 showed that the flux incident on the back wall surface fluxmeters away from the burner flame, at about the time of flame passage, varied roughly over the same range as from the exposure levels of 25 to 75 kW/m^2 used in the cone calorimeter. With the exception of these same tests with the polystyrene, the fluxes to the back wall in the upper part of the room generally exceeded 40 kW/m^2 several seconds following flashover. In the tests of the polystyrene, the wall fluxmeters measured relatively low flux levels at the time of flame passage and at times shortly following flashover. This could have been due to some obscuration and cooling of the fluxmeters by the melting and dripping foam plastic. In all of the tests, these fluxes to the wall reached between 50 and 140 kW/m^2 shortly after full flame involvement of the room lining. Thus, the calorimeter exposure levels were representative over much of the room thermal environment when fire spread and involvement were present.

Dividing the instantaneous heat release rate from a room fire by the corresponding area of room surface flame involvement results in ratios which can be compared with those obtained from the cone calorimeter. Tables 12 to 15 show some of these comparisons. For plywood 2, the ratios of the rate of heat release to the surface area covered by flames agreed with the average 60 s values from the calorimeter. In room test 15 with the fire retarded plywood, the pre-flashover ratios were much lower than the calorimeter data, with the post-flashover ratios looking like the calorimeter data for the untreated plywood 2. This post-flashover behavior could have been due to the volatilization of the fire-retardant chemicals resulting from the prolonged low room fire exposure of the fire retarded plywood. In test 10 with the polystyrene, the volumetric flow of combustion products from the fire exceeded the exhaust capability of the hood system, and a small part of the exhaust spilled into the laboratory. Consequently, the peak room unit area heat release rates were too low. There was also the possibility that the area behind the flame front was not fully involved with flames. If part of the surface had melted and dripped away, or if vitiated air had prevented the upper surfaces from sustaining flames, a smaller surface area would be releasing the heat. This would mean much higher values of heat release rate per unit area of flame-covered surface more like those from the calorimeter. For the polyisocyanurate in room test 9, the flame spread was very rapid, such that the peak values, rather than the 60 s average values, were more appropriate for comparison with the room ratios. The data in Table 15 indicate that the peak values from the calorimeter did indeed bracket the unit area heat release rate values from the room fire.

3.7 General Remarks and Recommended Changes in the Proposed ASTM Test Procedure

1. The study demonstrated that all three exposure conditions could result in different fire behavior for the materials evaluated when the test material covers only the walls or both the walls and ceiling of the room. Consequently, each condition could be used to help indicate the fire safety level for room interior finish materials. However, ignition exposure C has advantages over exposures A and B in that materials can be evaluated and rated over a reasonable length of time (300 s) at a low exposure of about 40 kW/m^2, 300 s at an high exposure of about 160 kW/m^2, and then over another 300 s period for continuation of burning without enhancement from the burner source. Exposure A cannot evaluate interior finish materials at low exposures nor sustained flame spread with no external irradiance. Exposure B included four successive exposure levels, but the period of change from lowest to highest exposures lasted only 90 s. This may not be adequate time to evaluate some materials at the lower exposures. Furthermore, no evaluation of sustained flame in the absence of external irradiance was included.

The 4 suggested [illegible] of the [illegible] proposed [illegible] room fire test. If we were available A, B & C could be recommended against it.

2. In determining the fire severity, including room flashover, measurements of the incident flux on the center of the floor and of the air temperatures near the ceiling and near the top of the doorway are recommended. Flameover times and newspaper

[illegible] evaluate

indicators cannot characterize the fire severity short of room flashover.

3. Materials having probable differences in composition or non-uniformity in fire retarded treatment should be conditioned over a range of times and fire-tested periodically to check on their consistency in fire performance.

See earlier note

4. The present proposed standard room fire test method called for thermocouples, mounted on supports, to be located 100 mm down from the center of the ceiling and from the center of each of the four ceiling quadrants and from the ceiling directly over the center of the ignition burner. The method cautioned against attachments to the test specimens. However, for the tests conducted in this study, 6.4 mm holes were drilled through the ceiling at these positions for the thermocouples and then resealed with gypsum spackling compound. No adverse effects on the fire development due to these penetrations in the ceiling were observed.

5. The proposed test method suggested either photographic coverage or video taping to record the fire spread in the room. Both methods were used in this study. When still photographic coverage, such as with 35 mm color slides, was used, the flame spread and even the ignition of the newspaper flashover indicators could not be determined in some instances due to obscuration from the smoke and glare of the fire. Continuous coverage made such determin-

ations much easier. If still photographic coverage is used, shorter intervals of 1 or 2 s ~~is~~ are recommended during the rapid fire growth period. Either still photographic coverage with a wide angle (e.g., 18 mm) lens through the floor or side wall would be helpful when used in conjunction with the photographic coverage through the doorway. [For research tests, these could be supplemented by surface thermocouples on the walls and ceiling to indicate the pyrolyzing area as a function of time. This procedure is more tedious, but provides a better indication of the limits of the actual surface involvement than a visual accounting of the flame front.]

4.0 CONCLUDING REMARKS

1. In this study, the combustion efficiencies of the material in the room fires were obtained with some of the values being close to the published combustion efficiencies obtained from laboratory tests.

2. Unit-area-benchscale rate of heat release data from the cone calorimeter may be predictive of the full-scale data when melting and dripping (which changes the actual burning area) or very slow to ignite fire retardant materials (whose retardants may be baked out) were not involved. Additional studies are needed to ascertain possible correlations and further limitations.

3. The degree~~s~~ of repeatability within a laboratory and reproducibility among laboratories need to be established for full-scale tests of interior finish materials before correlations with bench scale tests could be developed with confidence.

4. Fire growth studies in rooms having multi-openings are needed to help generalize room fire behavior for other room configurations.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

1. Standard Test Method for Surface Burning Characteristics of Building Materials. ASTM E 84. Philadelphia, PA: American Society for Testing and Materials; 1981.

2. Castino, T.G.; Beyreis, J.R.; Metes, W.S.; Flammability Studies of Cellular Plastics and Other Building Materials Used for Interior Finishes, Subject 723. Underwriters Laboratories, Inc. Northbrook, IL. 1975 June.

3. Parker, W.J., Private communication.

4. Lee, B.T., Quarter-Scale Modeling of Room Fire Tests of Interior Finish. Nat. Bur. Stand. (U.S.) NBSIR 81-2453; 1982 March.

5. Proposed Standard Method for Room Fire Test of Wall and Ceiling Materials and Assemblies. 1982 Annual Book of Standards, Part 18. Philadelphia, PA: American Society of Testing and Materials; 1982.

6. Lee. B.T.; Breese, J.N.; Submarine Compartment Fire Study -- Fire Performance Evaluation of Hull Insulation. Nat. Bur. Stand. (U.S.) NBSIR 78-1584; 1979 May.

7. Lee, B.T., Fire Hazard Evaluation of Shipboard Hull Insulation and Documentation of a Quarter-Scale Room Fire Test Protocol. Nat. Bur. Stand. (U.S.) NBSIR 83-2642; 1983 August.

8. Uniform Building Code. International Conference of Building Officials. Whittier, CA. 1982 Edition.

9. The BOCA Basic Building Code. Building Officials and Code Administrators International, Inc. Homewood, IL. 1981.

10. Standard Building Code. Southern Building Code Congress International, Inc. Birmingham, AL. 1985.

11. Williamson, R.B.; Fisher, F.L.; Fire Growth Experiments - Toward a Standard Room Fire Test. Western States Section of the Combustion Institute; 1979 October.

12. Fisher, F.L.; Williamson, R.B.; Intralaboratory Evaluation of a Room Fire Test Method. University of California (Berkeley) UCB FRG 82-1; 1982 August.

13. Lee, B.T., Standard Room Fire Test Development at the National Bureau of Standards. Fire Safety Science and Engineering ASTM STP 882; 1984 June.

14. Wickström, U.; Sundström, B.; and Holmstedt. G.; The Development of a Full-Scale Room Fire Test. Fire Safety Journal, Vol. 5, pp. 191-197; 1983.

15. Parker, W.J.; Lee, B.T.; A Small-Scale Enclosure for Characterizing the Fire Buildup Potential of a Room. Nat. Bur. Stand. (U.S.) NBSIR 75-710; 1975 June.

16. Materials Bank Compendium of Fire Property Data. Products Research Committee. 1980 February.

17. Parker, W.J., Calculations of the Heat Release Rate by Oxygen Consumption for Various Applications. Nat. Bur. Stand. (U.S.) NBSIR 81-2427-1; 1982 March.

18. Babrauskas, V., Upholstered Furniture Heat Release Rates Measured with a Furniture Calorimeter. Nat. Bur. Stand. (U.S.) NBSIR 82-2604; 1982 December.

19. Lee, B.T., Effect of Ventilation on the Rates of Heat, Smoke, and Carbon Monoxide Production in a Typical Jail Cell Fire. Nat. Bur. Stand. (U.S.) NBSIR 82-2469; 1982 March.

20. Temperature Measurements Thermocouples. American National Standards Institute ANSI MC 96.1; 1982.

21. Heat Flux Transducers for The Direct Measurement of Heat Transfer Rates, Bulletin 118, Medtherm Corporation, Huntsville, AL; 1981.

22. Fang, J.B., Fire Buildup in a Room and the Role of Interior Finish Materials. Nat. Bur. Stand. (U.S.) Technical Note 879; 1975 June.

23. Huang, D., Evaluation of Quarter-Scale Compartment Fire Modeling for Constant and Stepped Hat Inputs. Fire and Materials. Publication pending.

24. Babrauskas, V., Estimating Room Flashover Potential. Fire Technology. volume, p. 1980 May.

25. McCaffrey, B.J.; Quintiere, J.G.; Harkleroad, M.F.; Estimating Room Temperatures and the Likelihood of Flashover Using Fire Data Correlations. Fire Technology. 1981 May.

26. Tewarson, A., Physico-Chemical and Combustion/Pyrolysis Properties of Polymeric Materials. Factory Mutual Research FMRC J.1 OEON6.RC; 1980 November.

27. Babrauskas, V., Development of the Cone Calorimeter -- A Bench-Scale Heat Release Rate Apparatus Based on Oxygen Consumption. Nat. Bur. Stand. (U.S.) NBSIR 82-2611; 1982 November.

28. Proposed Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter, ASTM Vol. 04.07; 1986 November.

Table 1. Interior Finish Materials Used in Standard Room Fire Test

Material	Measured Thickness (mm)	Density (kg/m^3)	ASTM E-84 (FSI)**	Net Heat of Combustion (MJ/kg)
Fire retarded plywood*	13.1	545	≤25	15.1+
Gypsum board	13.2	757	≤25	0++
Plywood 1	5.6	586	~178	15.1+
Plywood 2	12.8	534	~178	15.1+
Polyisocyanurate foam	50.8	33	≤25	26+++
Polystyrene foam	50.8	30	≤25	30+++

*Amino phosphate boric acid treated.

**FSI (Flame Spread Index) values are typical values given in reference [2] for these materials.

+Reference [15]

++Net value is approximate. Paper surface contribute to heat of combustion while calcination of gypsum absorbs heat.

+++Reference [16]

Table 2. Average Flux Levels on Back Wall of Room at 1.22 m and 1.83 m Heights Over Burner.

Water Temp. for Cooling Fluxmeter (°C)		1.22 m Height Flux Level (kW/m^2)	1.83 m Height Flux Level (kW/m^2)
18	are these different? No	59 ± ~~[illegible]~~ 2	52 ± ~~[illegible]~~ 2
70		62 ± ~~[illegible]~~ 2	56 ± ~~[illegible]~~ 2

Notes:

2 ~~1~~. Wall and ceiling finish were fire-exposed gypsum board.

3 ~~2~~. In each run, burner operated at a constant ~~nominal 160~~ 180 kW for 300 s. Measurements taken between 180 and 300 s.

4 ~~3~~. Average values based on four runs with 18°C water and four runs with 70°C water.

1. Fluxmeters were the Gardon type positioned at 0.15 m from the corner having the burner at heights of 1.22 and 1.83 m

Table 3. Location of Instrumentation

	Instrument	Key Number*	Location
1	Smoke meter	1	exhaust collection system
1	Gas sample port	1	exhaust collection system
9	Pitot-static tubes	1	exhaust collection system
25	0.51 mm thermocouples	1	entrance to exhaust collection duct, in 5 x 5 grid
11	0.51 mm thermocouples	2	located in pairs (one of each diameter) 0.3 m from front and left walls at the following distances, below the ceiling: 0.20, 0.41, 0.61, 0.81, 1.02, 1.22, 1.42, 1.63, 1.83, 2.03, and 2.24 m.
11	0.05 mm thermocouples	2	
6	0.05 mm thermocouples	3	located in pairs (one of each diameter) in the center of the doorway at the following distances below the lintel: 0.10, 0.20, 0.51, 0.81, 1.12, and 1.73 m. Single 0.51 mm thermocouples also at 0.36, 0.66, 0.97, and 1.42 m. One extra 0.51 mm thermocouple at 0.10 m for a total of three thermocouples at this location.
11	0.51 mm thermocouples	3	
11	0.51 mm thermocouples	4	All these thermocouples were located 0.10 m below the ceiling. One thermocouple was at the center of the room. Eight were located in pairs down from the centers of each quadrant of the ceiling. Another pair was located above the center of the burner, 0.15 m from the left wall and 0.15 m from the back wall.
34	0.51 mm thermocouples	-	Thirty three surface thermocouples located on back, right, and left walls in tests 17 to 19. One

Table 4. Test Results (material on both walls and ceiling)

Test No.	Wall and Ceiling Material	Exposure	Occurrence Times for Flashover Indicators in Seconds: Flameover t_F	Newspaper Ignition* t_{FO}	Floor Flux† 20 kW/m^2 t_{Floor}	Average Interior Air Temp.†††, T_I 600°C t_I	Average Interior Air Temp.†††, T_I 700°C t_I	Average Doorway Air Temp.†††, T_D 600°C t_D	Average Doorway Air Temp.†††, T_D 650°C t_D
1B	Gypsum Board	A	None	None	(4.5 kW/m^2,740 s)	None	None	None	None
2	Gypsum Board	B	None	None	(3.5 kW/m^2,870 s)	None	None	None	None
3B	Gypsum Board	C	None	None	(3.2 kW/m^2,600 s)	None	None	None	None
15	Fire retarded plywood	A	861	**B,861 F	847	~~163~~ 165	~~186~~ 185	~~851~~ 850	855
4	Fire retarded plywood	A	None	***B,NoneF	(13.8 kW/m^2,900 s)	~~186~~ 185	240	300	None
6	Fire retarded plywood	B	None	483 B,568F	(18.5 kW/m^2,510 s)	~~434~~ 435	~~462~~ 460	~~469~~ 470	None
5	Fire retarded plywood	C	None	528 B,***F	(16.1 kW/m^2,580 s)	390	455	~~528~~ 530	None
19	Plywood 2	A	83	98 B, 110 F	88	~~57~~ 55	~~87~~ 85	~~83~~ 85	~~98~~ 100
7	Plywood 2	C	193	206 B,209 F	195	~~167~~ 165	~~189~~ 190	200	~~211~~ 210
8	Plywood 1	B	134	143 B,165 F	140	~~98~~ 100	120	~~137~~ 135	~~141~~ 140
10	Polystyrene	A	48	39 B, 40 F	††	~~48~~ 50	~~51~~ 50	50	~~52~~ 50
11	Polystyrene	B	83	80 B, 82 F	71	~~74~~ 75	~~76~~ 75	~~83~~ 85	85
12	Polystyrene	C	110	107 B,109 F	101	~~106~~ 105	~~108~~ 110	~~112~~ 110	~~113~~ 115
9	Polyisocyanurate	A	14	15 B, 16 F	19[a]	20 ~~22~~[a]	25 ~~26~~[a]	30 ~~28~~[a]	30[a]
24	Polyisocyanurate	A	14	15 B, 17 F	-- b: not observed? not measured?	--[b]	--[b]	--[b]	--[b]
13	Polyisocyanurate	B	50	51 B, 52 F	42	~~46~~ 45	~~48~~ 50	50	~~51~~ 50
14	Polyisocyanurate	C	312	314 B,315 F	315	~~311~~ 310	~~313~~ 315	315	315

Watch the significant figures. O.K.

* Back and front newspaper flashover indicators denoted by B and F respectively.
** Back indicator ignited prematurely by falling embers.
*** Newspaper discolored due to heating, but did not ignite.
† Maximum flux and its time of occurrence given in parentheses.
†† Resolution inadequate.
††† Average interior temperature T_I based on eight 0.51 mm thermocouples located 0.10 m down from ceiling. T_D based on the average of two 0.51 mm thermocouples located 0.10 m down from top of doorway. all temperatures taken to nearest 5°C

a - Estimated values based on linear interpolation between rapidly increasing values.

Table 5. Test Results (material on walls or on ceiling)

Test No.	Wall and Ceiling Material	Exposure	Occurrence Time for Flashover Indicators in Seconds						
			Flameover	Newspaper Ignition*	Floor Flux† 20 kW/m^2	Average Interior Air Temp.††, T_I 600°C	Average Interior Air Temp.††, T_I 700°C	Average Doorway Air Temp.††, T_D 600°C	Average Doorway Air Temp.††, T_D 650°C
			t_F	t_{FO}	t_{Floor}	t_I	t_I	t_D	t_D
	Wall Material (Gyp. Bd. Ceiling)								
17	Plywood 2†††	A	121	122 B, 136 F	123	85	110	~~103~~ 105	~~108~~ 110
18	Plywood 2	A	137	136 B, 151 F	122	~~74~~ 75	110	~~161~~ 160	170
16	Plywood 2	C	340	345 B, 359 F	336	~~314~~ 315	~~323~~ 325	---	---
20	Polystyrene	A	65	55 B, 66 F	47	45	50	~~57~~ 55	~~61~~ 60
23	Polystyrene	B	108	89 B, 100 F	81	~~78~~ 80	~~83~~ 85	~~86~~ 85	90
21	Polystyrene	C	133	125 B, 133 F	116	~~112~~ 110	~~117~~ 115	~~128~~ 130	~~132~~ 130
22	Polyisocyanurate	A	None	193 B, None F	(8.1 kW/m^2, 890 s)	None	None	None	None
	Ceiling Material (Gyp. Bd. Walls)								
27	Plywood 2	A	384	401 B, 427 F	396	370	390	~~382~~ 380	~~387~~ 385
26	Polystyrene	A	297	**B, 297 F	282	~~283~~ 285	~~289~~ 290	300	None
25	Polyisocyanurate	A	605	615 B, 619 F	606	~~611~~ 610	~~614~~ 615	~~612~~ 610	615

* Back and front newspaper flashover indicators denoted by B and F respectively.
** Back indicator ignited prematurely by falling embers.
† Maximum flux and its time of occurrence given in parentheses.
†† Average interior temperature T_I based on eight 0.51 mm thermocouples located 0.10 m down from ceiling. T_D based on the average of two 0.51 mm thermocouples located 0.10 m down from top of doorway.
††† Calcium silicate (Marinite) board ceiling in test 17.

All temperatures taken to nearest 5 °C.

Table 6. Summary of Test Results (material on both walls and ceiling)

Test No.	Material	Exposure	Rate of Heat Release† at t_{Floor} (MW)	Peak Rate of Heat Release† and Time (MW)	(s)	Peak T_I and Time (°C)	(s)	Peak T_D and Time (°C)	(s)	Ambient Conditions Temp. (°C)	(F)	Relative Humidity (%)
1B	Gypsum Board	A	None	0.3	70	400	60	325	780	19	67	45
2	Gypsum Board	B	None	0.2	840	395	120	305	880	21	70	42
3B	Gypsum Board	C	None	0.2	560	405	350	320	360	19	66	52
15	Fire retarded plywood	A	2.1	6.2	860	865	890	810	900	23	73	51
4	Fire retarded plywood	A	None	0.5	260	715	260	600	300	23	73	42
6	Fire retarded plywood	B	None	0.6	480	745	487	640	530	21	70	47
5	Fire retarded plywood	C	None	0.5	480	720	468	610	530	22	71	48
19	Plywood 2	A	2.6	7.6	150	915	210	895	200	21	70	54
7	Plywood 2	C	1.7	6.7	260	930	340	895	360	21	70	51
8	Plywood 1	B	1.9	8.5	260	850	312	860	180	21	70	55
10	Polystyrene	A	††	9.4	100	1050	75	930	60	21	70	48
11	Polystyrene	B	4.2	4.1	70	1015	86	800	90	22	71	50
12	Polystyrene	C	3.1	3.5	110	970	120	940	120	22	71	48
9	Polyisocyanurate	A	2.2	5.1	50	1200	80	1245	100	21	70	54
24	Polyisocyanurate	A	–	–	–	–	–	–	–	22	71	53
13	Polyisocyanurate	B	2.9	4.2	50	1065	60	1040	60	22	72	55
14	Polyisocyanurate	C	3.2	4.1	310	1095	320	1020	320	24	75	47

† Includes contribution from gas burner WHY? READER NEEDS TO CHECK FIG 2A AND SUBTRACT DIFFERENT NUMBERS.

Table 7. Test Results (material on walls or ceiling)

Test No.	Material	Exposure	Rate of Heat Release† at t_{Floor} (MW)	Peak Rate of Heat Release† and Time (MW)	(s)	Peak T_I and Time (°C)	(s)	Peak T_D and Time (°C)	(s)	Ambient Conditions Temp. (°C)	(F)	Relative Humidity (%)
	Wall Material (Gyp. Bd. Ceiling)											
17	Plywood 2†	A	1.3	5.6	170	860 ~~859~~	180	885	180	21	70	52
18	Plywood 2	A	1.1	6.1	190	940 ~~939~~	240	910 ~~908~~	240	20	68	53
16	Plywood 2	C	1.0	5.8	380	1045	750	--	--	21	69	50
20	Polystyrene	A	1.4	5.4	90	1030 ~~1029~~	90	970	80	22	71	53
23	Polystyrene	B	1.6	3.4	120	1040	120	1035 ~~1033~~	110	19	67	54
21	Polystyrene	C	1.5	3.7	140	1005 ~~1007~~	150	980 ~~979~~	150	22	71	47
22	Polyisocyanurate	A	None	0.3	30	470 ~~471~~	30	385 ~~383~~	840	23	73	55
	Ceiling Material (Gyp. Bd. Walls)											
27	Plywood 2	A	2.3	2.5	430	715 ~~717~~	430	815 ~~814~~	410	24	75	54
26	Polystyrene	A	1.7	2.0	290	760	300	605 ~~606~~	300	24	75	52
25	Polyisocyanurate	A	2.0	2.6	610	895 ~~894~~	620	775	620	22	72	52

†Includes contribution from gas burner

~~le this standard notation~~ E

Table 8. Peak Smoke Concentration and Total Smoke Production

Test No.	Material	Exposure	(O.D./m)*	Extinction Cross Section ε** 300 s (m^2)	600 s (m^2)	900 s (m^2)
Material on Walls and Ceiling						
1B	Gypsum Board	A	0.07	90	230	370
2	Gypsum Board	B	0.05	70	180	270
3B	Gypsum Board	C	0.07	30	190	210
15	Fire retarded plywood	A	0.73	700	870	1250
4	Fire retarded plywood	A	0.35	380	630	860
6	Fire retarded plywood	B	1.19	170	1200	1470
5	Fire retarded plywood	C	0.62	50	810	1230
19	Plywood 2	A	1.08	2010	–	–
7	Plywood 2	C	0.91	690	2100	–
8	Plywood 1	B	1.43	2210	2870	–
10	Polystyrene	A	> 2.5	>8600	–	–
11	Polystyrene	B	> 2.5	>1900	–	–
12	Polystyrene	C	> 2.5	>1900	–	–
24	Polyisocyanurate	A	–	–	–	–
9	Polyisocyanurate	A	> 2.5	>4000	–	
13	Polyisocyanurate	B	> 2.5	>2000	–	–
14	Polyisocyanurate	C	> 2.5	310	>2900	–
Material on Walls						
17	Plywood 2	A	2.07	1640	–	–
18	Plywood 2	A	1.83	–	–	–
16	Plywood 2	C	2.00	60	3990	–
20	Polystyrene	A	> 2.5	–	–	–
23	Polystyrene	B	> 2.5	–	–	–
21	Polystyrene	C	> 2.5	> 6160	–	–
22	Polyisocyanurate	A	0.99	920	1200	1510
Material on Ceiling						
27	Plywood 2	A	0.63	220	1020	1240
26	Polystyrene	A	> 2.5	740	–	–
25	Polyisocyanurate	A	> 2.5	290	550	–

* Peak ratio of optical density to path length L. Smoke optical density measured over path length of 1.22 m

** $E = \frac{2.3}{L} \int_0^{t_T} (O.D.)\, \dot{V} dt$ where O.D. is the optical density of the smoke measured in the hood system duct, L(m) is the path length of the smoke meter, $\dot{V}$ (m^3/s) is the volume flow in the duct referred to the stream temperature, and t_T(s) is the duration of the test [~~13~~ 19].

~~Flashover~~ Times to Flashover

Table 9. Comparison of ~~Data~~ Between NBS and University of California for Room Fire Tests of Plywood

TIME OF OCCURRENCE

Test	Flameover t_F(s)	Ignition of Newspaper t_{FO}(s)	20 kW/m^2 Flux at Floor t_{Floor}(s)	600°C Avg. Interior Air Temp t_I(s)	Rate of Heat Release at Flashover Based on t_{Floor} $\dot{Q}$ (MW)
C-213(U.C.)	170	210	205	115	2.1
8 (NBS)	134	165	140	101	1.9

Table 10 Statistical comparisons of various flashover indicators

TIME? UNITS?

Test	Number of flashover indicators considered *	Median	Average	One σ, std. deviation	Coefficient of variation**
19	8	87.50	88.00	15.57	17.69
7	8	197.50	196.25	14.19	7.23
8	8	138.50	134.75	19.36	14.37
10	7	48.00	46.86	5.24	11.19
11	8	81.00	79.25	5.01	6.32
12	8	108.50	108.25	3.77	3.48
9	8	20.50	21.25	6.20	29.20
24	3	15.00	15.00	1.00	6.67
13	8	50.00	48.75	3.33	6.83
14	8	314.50	313.75	1.58	0.50
17	8	115.50	113.50	15.54	13.69
18	8	136.50	132.62	30.78	23.21
16	6	338.00	336.17	15.99	4.76
20	8	56.00	55.75	7.98	14.31
23	8	87.50	89.37	10.08	11.28
21	8	126.50	124.50	8.43	6.77
27	8	388.50	392.12	16.90	4.31
26	6	293.00	291.33	7.76	2.66
25	8	613.00	612.12	4.73	0.77
15	7	851.00	660.57	332.15	50.28

SIG FIGS

* Unless specified, the following eight points used: t_F, $t_{FO}(B)$, $t_{FO}(F)$, t_{Floor}, $t_I(600)$, $t_I(700)$, $t_D(600)$, $t_D(650)$

In test 10 — t_{Floor} not included.

In test 24 — t_{Floor}, $t_I(600)$, $t_I(700)$, $t_D(600)$, and $t_D(650)$ not included

In test 16 — $t_D(600)$ and $t_D(650)$ not included

In test 26 — $t_{FO}(B)$ and $t_D(650)$ not included

In test 15 — $t_{FO}(B)$ not included

** Defined as the standard deviation divided by the average value and expressed as a percentage

Table 11 Statistical comparison of various flashover indicators

Tests	Number of flashover indicators considered *	Median	Average	One σ std. deviation	Coefficient of variation **
19	6	87.50	91.50	10.60	11.58
7	6	197.50	198.67	7.76	3.91
8	6	138.50	139.83	14.69	10.50
10	5	48.00	45.60	5.68	12.46
11	6	81.00	79.17	4.79	6.05
12	6	108.50	107.83	3.76	3.49
9	6	17.50	19.67	5.96	30.28
24	3	15.00	15.00	1.00	6.67
13	6	50.00	48.83	3.60	7.37
14	6	314.50	314.00	1.26	0.40
17	6	121.50	119.17	11.44	9.60
18	6	136.50	136.17	18.56	13.63
16	5	340.00	340.60	13.13	3.85
20	6	56.00	56.67	7.71	13.61
23	6	87.50	91.17	10.61	11.64
21	6	126.50	125.33	7.50	5.98
27	6	393.00	396.67	16.49	4.16
26	5	297.00	293.00	7.38	2.52
25	6	613.00	611.83	5.42	0.89
15	5	851.00	721.20	299.25	41.49

* Number of flashover indicators considered identical to those used in Table 10 except t_I (600°C) and t_D (600°C) were excluded

** Defined as the standard deviation divided by the average value and expressed as a percentage

Table ~~10~~ 12. Comparison of Heat Release Rates from Calorimeter Test and Room Test 15 for Fire Retarded Plywood

Room Test

Time (s)	Area Covered by Flames A_f (m^2)	Room Heat Release Rate Per Unit Area ** $\dot{Q}/A_f$ (kW/m^2)
70	~~3.9~~ 4	35
165	~~6.4~~ 6	55
205	~~11.9~~ 12	50
360	~~3.9~~ 4	55
738	~~7.2~~ 7	~~32~~ 30
858*	~~19.3~~ 19	275
864*	~~30.2~~ ~~[illegible]~~ 30	185
870*	~~32.7~~ 33	155
880*	~~32.7~~ 33	150

Cone Calorimeter

Exposure (kW/m^2)	Heat Release Rate Per Unit Area: Peak (kW/m^2)	Heat Release Rate Per Unit Area: 60 s Avg. (kW/m^2)
25	~~82~~ 80	~~68~~ 70
50	~~108~~ 110	~~102~~ 100
75	~~184~~ 185	~~113~~ 115

* Post flashover. Time of flashover (20 kW/m^2 on floor) at 847 s.
** Excluding heat release rate of burner.

Table ~~11~~ 13. Comparison of Heat Release Rates from Calorimeter Test and Room Test 19 for Plywood 2

Room Test

Time (s)	Area Covered by Flames A_f (m^2)	Room Heat Release Rate Per Unit Area ** $\dot{Q}/A_f$ (kW/m^2)
70	~~5.1~~ 5	165
85	~~12.6~~ 13	180
95*	~~15.8~~ 16	175
130*	~~23.6~~ 24	265
140*	~~26.3~~ 26	280
160*	~~32.7~~ 33	220

Cone Calorimeter

Exposure (kW/m^2)	Heat Release Rate Per Unit Area	
	Peak (kW/m^2)	60 s Avg. (kW/m^2)
25	205	175
50	295	225
75	360	280

* Post flashover. Time of flashover (20 kW/m^2 on floor) at 88 s.
** Excluding heat release rate of burner.

Table ~~12~~ 14. Comparison of Heat Release Rates from Calorimeter Test and Room Test 10 for Polystyrene

Room Test

Time (s)	Area Covered by Flames A_f (m^2)	Room Heat Release Rate Per Unit Area ** $\dot{Q}/A_f$ (kW/m^2)
35	~~4.8~~ 5	260
43*	~~9.7~~ 10	345
45*	~~14.9~~ 15	255
48*	~~23.3~~ 23	195
70*	~~32.7~~ 33	270
100*	~~32.7~~ 33	305
120*	~~32.7~~ 33	295

Cone Calorimeter

Exposure (kW/m^2)	Heat Release Rate Per Unit Area: Peak (kW/m^2)	Heat Release Rate Per Unit Area: 60 s Avg. (kW/m^2)
25	405	365
50	710	590
75	835	575

* Post flashover. Time of flashover (no floor flux data, earliest time is newspaper ignition) at 39 s.

** Excluding heat release rate of burner.

Table ~~13~~ 15. Comparison of Heat Release Rates from Calorimeter Test and Room Test 9 for Polyisocyanurate

Room Test

Time (s)	Area Covered by Flames A_f (m^2)	Room Heat Release Rate Per Unit Area ** $\dot{Q}/A_f$ (kW/m^2)
10	~~7.6~~ 8	70
12	~~12.5~~ 13	65
14	~~18.7~~ 19	65
15	~~26.4~~ 26	50
16	~~32.7~~ 33	45
30*	~~32.7~~ 33	120
50*	~~32.7~~ 33	155

Cone Calorimeter

Exposure (kW/m^2)	Heat Release Rate Per Unit Area	
	Peak (kW/m^2)	60 s Avg. (kW/m^2)
25	50	15
50	135	110
75	155	110

* Post flashover. Time of flashover (20 kW/m^2 on floor) at 19 s.
** Excluding heat release rate of burner.

Table ~~14~~16. Wall Flux as a Function of Time for Test 15
(fire retarded plywood, exposure A)

Time (s)		Wall Fluxmeter 0.46 m from Ceiling (kW/m^2)		Wall Fluxmeter 0.91 m from Ceiling (kW/m^2)
153	21	21.2 ~~SIG FIGS~~	10	10.1
163	32	32.3	15	14.8
173	40	39.5	12	12.1
183	40	40.2	20	20.4
193	58	58.1	21	20.6
202	*	*	—	(-) ?
203	69	68.6	23	22.7
213	62	62.1	44	44.0
253	65	65.1	44	44.0
263	61	60.5	42	42.2
270	—	(-)	*	*
273	65	64.7	46	46.3
843	48	48.1	27	27.4
847	**	**	**	**
853	58	57.7	50	49.6
870	***	***	***	***
883	100	100.4	130	130.3

* Flame front over fluxmeter.
** Flashover at 847 s.
*** Complete flame coverage of room lining.
(–) No data available

Table ~~15~~ 17. Wall Flux as a Function of Time for Test 19
(plywood 2, exposure A)

Time (s)	Wall Fluxmeter 0.46 m from Ceiling (kW/m^2)		Wall Fluxmeter 0.91 m from Ceiling (kW/m^2)	
23	7	6.6	3	2.6
43	14	14.0	7	7.0
63	27	26.7	13	12.6
70	*	*	—	-
73	43	42.7	17	17.0
83	70	69.9	26	25.9
88	**	**	**	**
93	92	91.7	42	42.1
96	—	~~*~~ ?	*	*
103	103	103.4	70	69.8
113	107	107.2	89	88.6
133	121	121.4	113	113.4
143	117	116.8	130	129.5
143	***	***	***	***
163	90	89.7	93	92.8

* Flame front over fluxmeter.
** Flashover at 88 s.
*** Complete flame coverage of room lining.
(—) No data available

Table ~~16~~ 18. Wall Flux as a Function of Time for Test 17
(plywood 2, exposure A)

Time (s)	Wall Fluxmeter 0.46 m from Ceiling (kW/m^2)	Wall Fluxmeter 0.91 m from Ceiling (kW/m^2)
53	24 24.4	10 9.5
93	53 53.3	16 15.7
103	74 73.7	22 21.9
113	93 92.5	35 35.1
120	— (—) ?	* *
123	107** 107.4**	70** 69.6**
133	104 103.6	73 73.4
153	130 130.3	101 100.5
171	*** ***	*** ***
173	138 137.9	137 136.5
183	101 100.6	117 117.1

* Flame front over fluxmeter; not observable for 0.46 m location.
** Flashover at 123 s.
*** Complete flame coverage of room lining.
(—) No data available

Table ~~1~~ 19. Wall Flux as a Function of Time for Test 18
(plywood 2, exposure A)

Time (s)	Wall Fluxmeter 0.46 m from Ceiling (kW/m^2)		Wall Fluxmeter 0.91 m from Ceiling (kW/m^2)	
60	19	19.3	8	8.3
93	49	49.0	14	13.9
99	*	*	—	—
103	51	51.3	17	16.5
113	70	70.1	23	22.7
122	**	**	**	**
123	84	83.8	35	35.4
131	—	—	*	*
133	101	100.6	67	66.7
143	100	100.1	72	71.6
163	121	121.4	96	95.9
183	127	126.5	130	130.3
188	***	***	***	***
193	99	99.3	113	112.9

* Flame front over fluxmeter.
** Flashover at 122 s.
*** Complete flame coverage of room lining.
(—) No data available

Table ~~18~~ 20. Wall Flux as a Function of Time for Test 10
(polystyrene, exposure A)

Time (s)	Wall Fluxmeter 0.46 m from Ceiling (kW/m^2)		Wall Fluxmeter 0.91 m from Ceiling (kW/m^2)	
0	0	0	0	0
23	5	5.3	3	2.6
35	*	*	—	[illegible]
39	**	**	**	**
43	14	14.1	7*	6.9*
50	***	***	***	***
63	69	69.0	51	51.4
93	33	33.3	36	35.6
113	84	83.7	64	64.1

* Flame front over fluxmeter.
** Flashover at 39 s.
*** Complete flame coverage of room lining.
(—) No data available
Note: Data recording interval was 20 s or longer due to recording system malfunctioning every other scan period.

Table ~~19~~ 21. Wall Flux as a Function of Time for Test 9
(polyisocyanurate, exposure A)

Time (s)	Wall Fluxmeter 0.46 m from Ceiling (kW/m^2)	Wall Fluxmeter 0.91 m from Ceiling (kW/m^2)
0	0 ~~0~~	0 ~~0~~
8	* ~~*~~	— ~~0~~
11	— ~~0~~	* ~~*~~
16	*** ~~***~~	*** ~~***~~
19	** ~~**~~	** ~~**~~
23	92 ~~92.3~~	66 ~~65.6~~
43	89 ~~88.6~~	92 ~~91.6~~
63	135 ~~135.4~~	128 ~~127.9~~
83	144 ~~143.6~~	196 ~~196.4~~
103	117 ~~117.3~~	131 ~~131.0~~

* Flame front over fluxmeter.
** Flashover at 19 s.
*** Complete flame coverage of room lining.
(—) No data available
Note: Data recording interval was 20 s due to recording system malfunctioning every other 10 s scan period.

Table ~~20~~ 22. Combustion Efficiency of Test Materials in Room Fire Tests

Test No.	Material	Original Weight (kg)	Weight Loss (kg)	Measured Net Heat Release[5] Q_s (MJ)	Combustion Efficiency[6] (x ?)
Material on Walls and Ceiling					
15	Fire retarded plywood	233.1	69.2	420	0.40
19	Plywood 2	239.7	48.6	640	0.87
7	Plywood 2	222.6	65.1	890	0.91
8	Plywood 1	107.1	107.1	1480	0.92
10	Polystyrene	49.3	49.3	1000	0.53
11	Polystyrene	49.3	11.9	*	*
12	Polystyrene	49.3	5.9	*	*
9	Polyisocyanurate	55.4	25.3	450	0.68
24	Polyisocyanurate	50.9	1.8	*	*
13	Polyisocyanurate	55.4	8.3	100	0.46
14	Polyisocyanurate	55.4	8.4	*	*
Material on Walls					
17	Plywood 2**	169.3	21.5†	230	0.71††
18	Plywood 2	176.2	41.3†	430	0.69††
16	Plywood 2	173.1	131.5†	1540	0.78††
20	Polystyrene	30.4	30.4†	180	0.16††
23	Polystyrene	30.4	30.4†	130	0.11††
21	Polystyrene	30.4	30.4†	150	0.13††
22	Polyisocyanurate	36.8	1.6†	*	*
Material on Ceiling					
27	Plywood 2	64.7	8.9†	150	1.0††
26	Polystyrene	13.5	9.8†	*	*
25	Polyisocyanurate	13.7	3.0†	*	*

Notes:

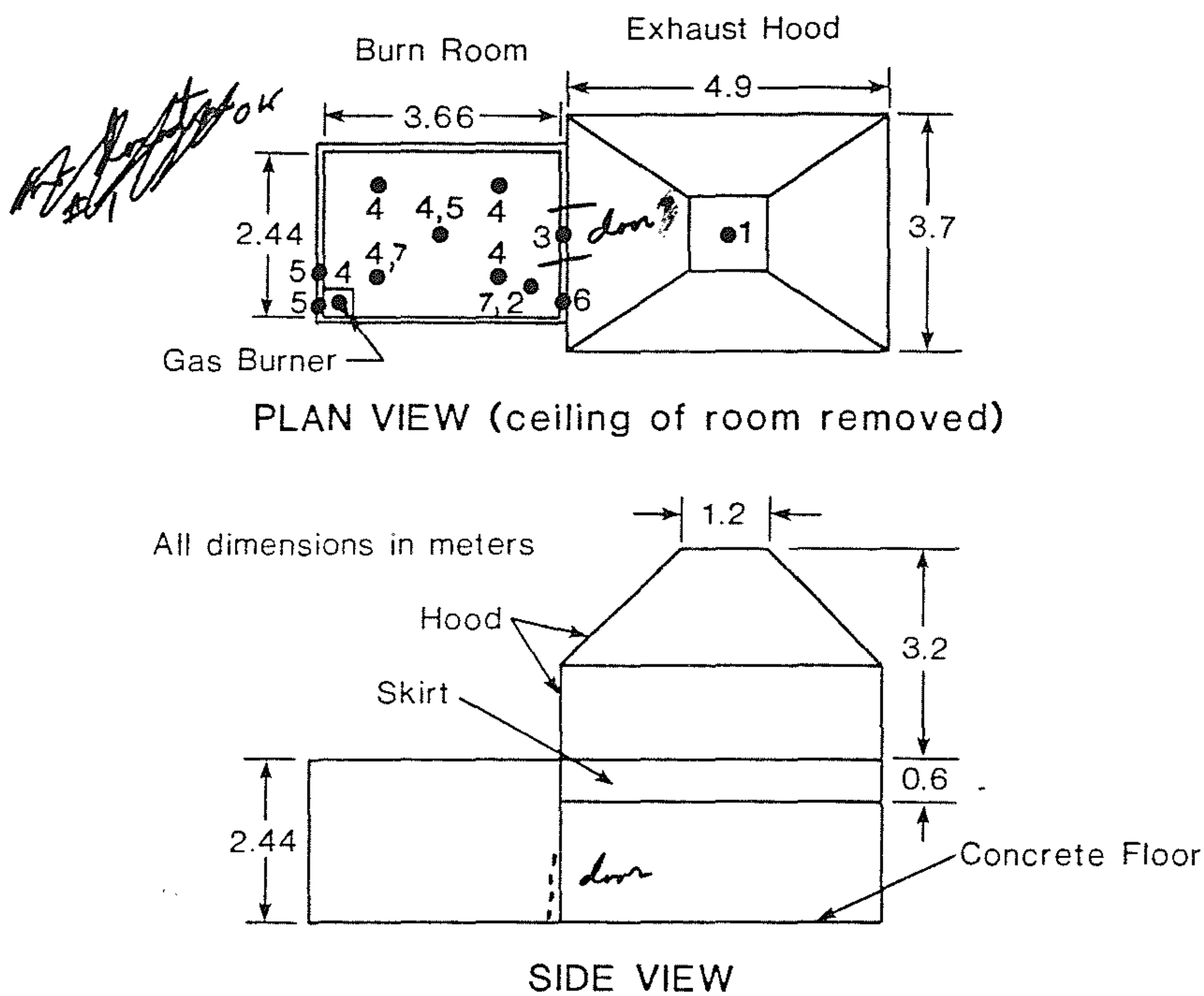
1. Lining material in tests 1B, 2, 3B, 4, 5, and 6 did not burn well. Consequently, measurements of total heat and mass loss would not be accurate and were not included.
2. Net heat of combustion of 15.1 MJ/kg for treated and untreated plywood [15].
3. Net heat of combustion of 38 MJ/kg for polystyrene foam GM 47 in reference [~~17~~ 16] used for polystyrene.
4. Net heat of combustion of 26 MJ/kg for polyisocyanurate foam 29 in reference [~~17~~ 16] used for polyisocyanurate.
5. Q_s = integrated value of room heat release rate history excluding contribution of burner.
6. Combustion efficiency is Q_s divided by the product of weight loss and net heat of combustion.

*Uncertain due to small changes in mass and heat release.

**Test 17 had a calcium silicate board ceiling.

†Weight loss of paper on gypsum board surface not included.

††Upper limit for combustion efficiency because combustion of paper on gypsum board surfaces was not included in weight loss.

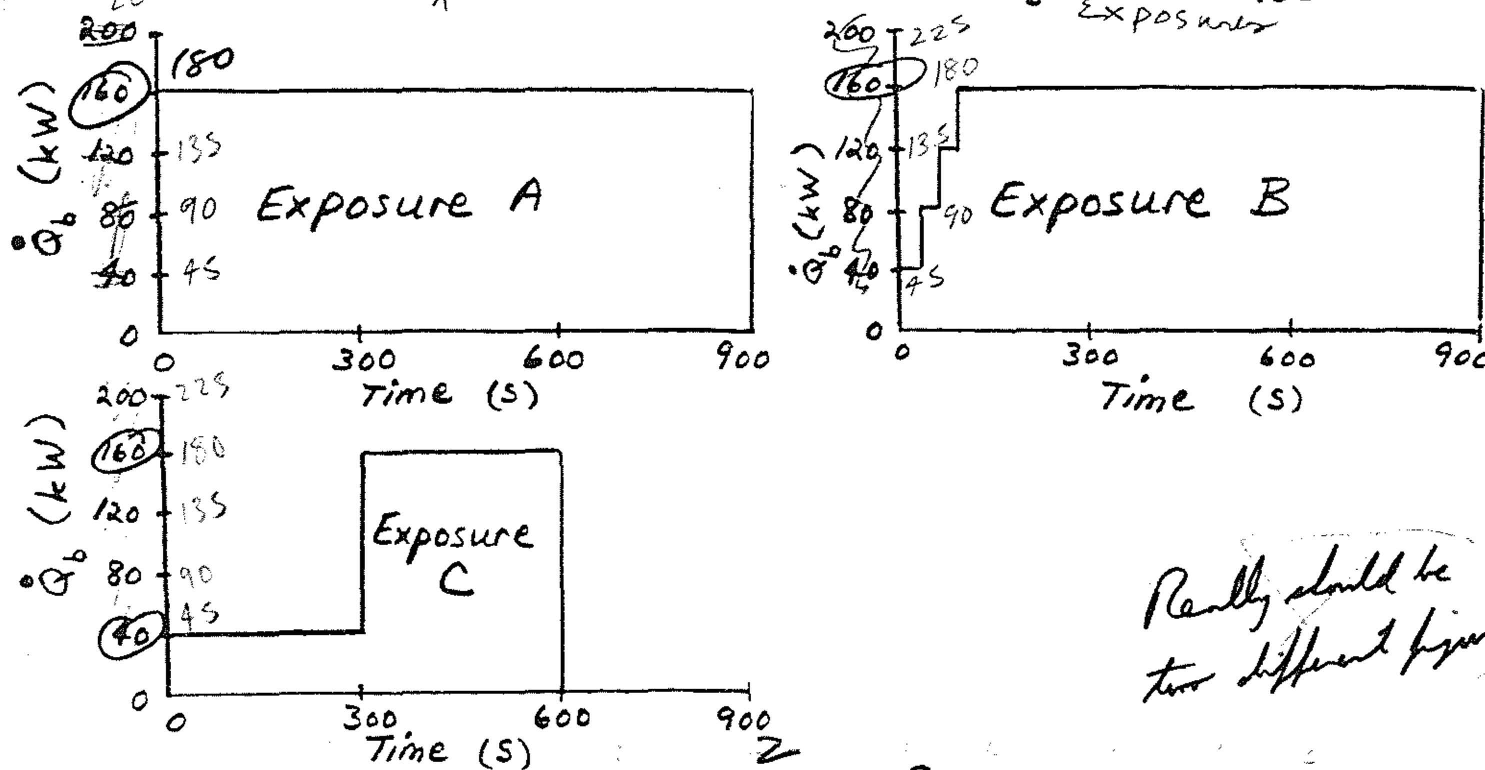


Note: Key numbers 1 to 7 refer to instrumentation in Table ~~1~~ 3.

Figure 1. Schematic of test room and exhaust hood

These are not the scenarios, but the ignition exposures simulating them

Burner ~~Nominal~~ Net Heat Release Rate ($\dot{Q}_b$) ~~Scenarios~~ Exposures



Really should be two different figures

2
~~Test Program~~

	Material Location							
	Walls & Ceiling			Walls			Ceiling	
MATERIAL \ EXPOSURE LEVEL	C	B	A	C	B	A	A	
Gypsum Bd.	3B+	2	1B					
Plywood 1		8						
Plywood 2*	7		19	16		18, 17++	27	
Plywood FR**	5	6	4, 15					
Polyisocyanurate**	14	13	9, 24			22	25	
Polystyrene**	12	11	10	21	23	20	26	

~~Actual net heat release rates were 12 percent higher than nominal values~~

~~* 160 kW net Equivalent to 174 kW gross~~

** 13 mm gypsum wallboard sheathing on wall and ceiling surfaces

+ Numbers 1B to 27 refer to test numbers

++ Calcium silicate (Marinite) board ceiling in test 17

Figure 3 ~~2~~ ~~Ignition~~ ~~Exposure Conditions~~ ~~Scenarios and~~ Test program

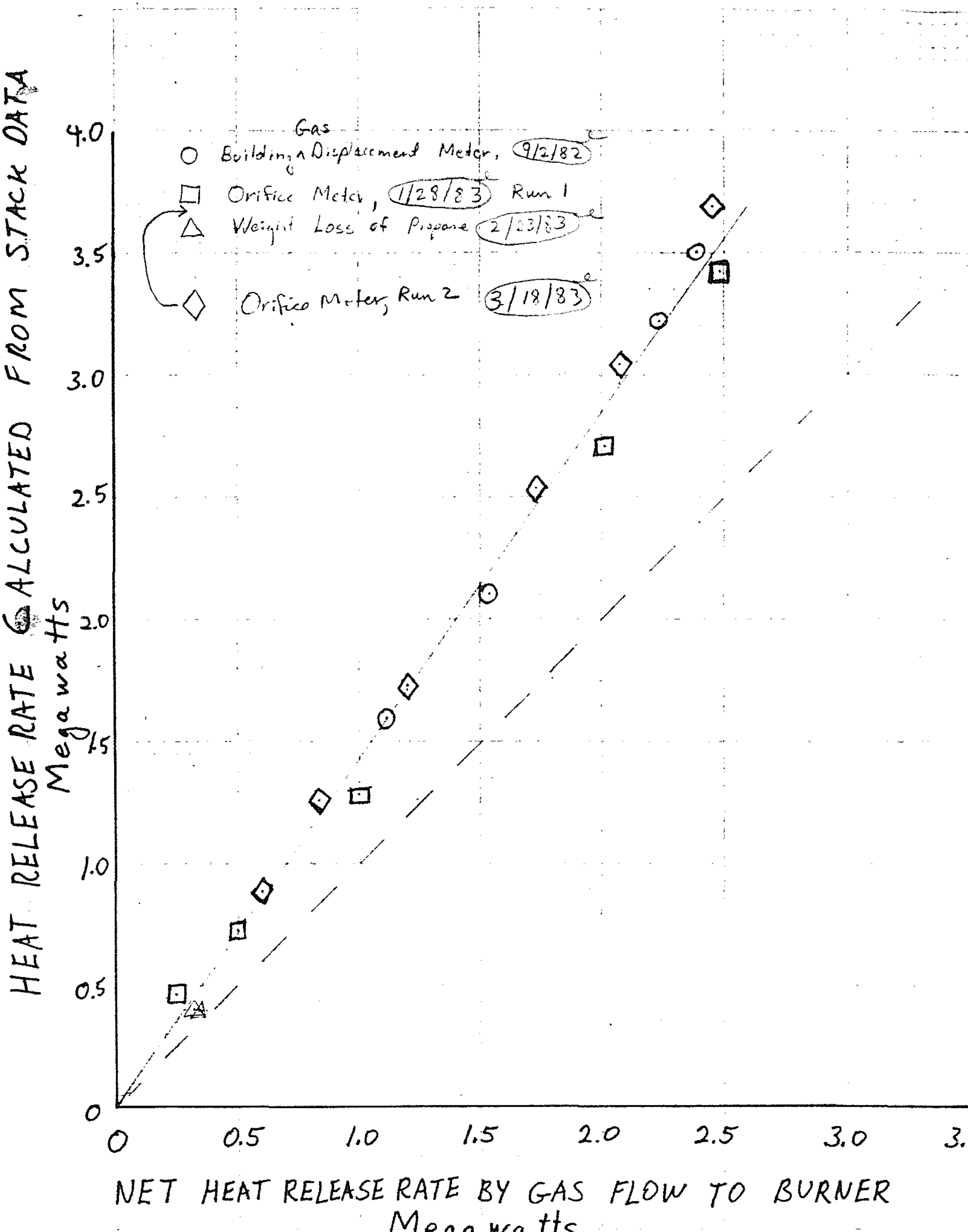
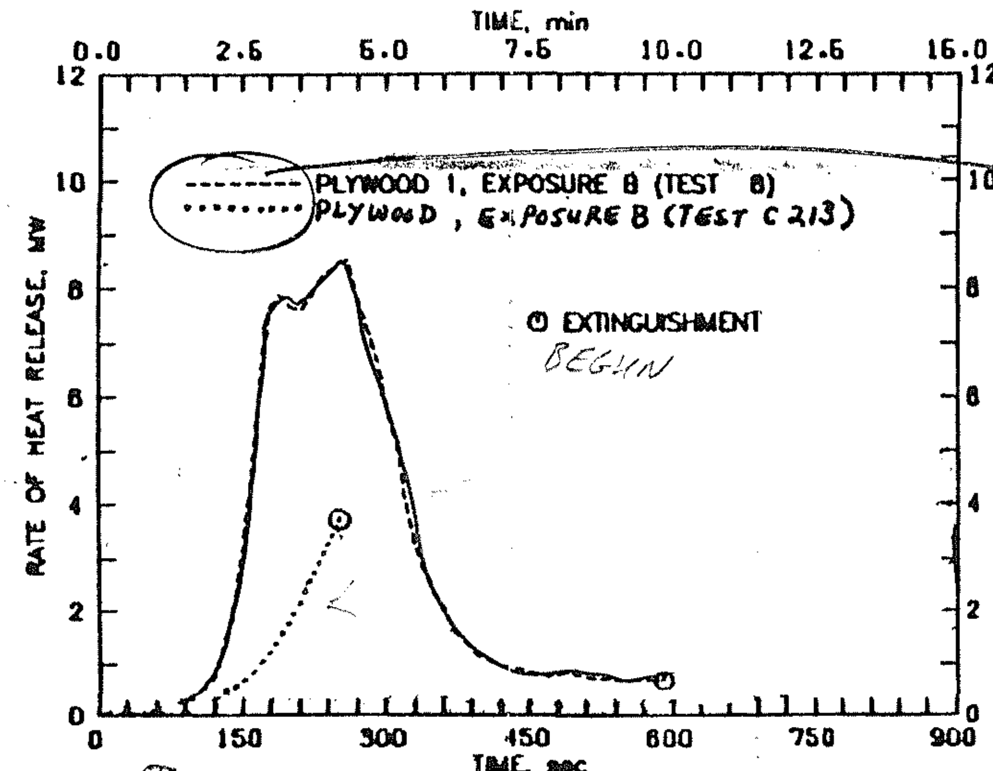


Fig 4 Calibration curve for heat release rate



Curves both too much alike.

Figure ~~16~~ 5. Rate of heat release histories for test ~~8~~ and C-213

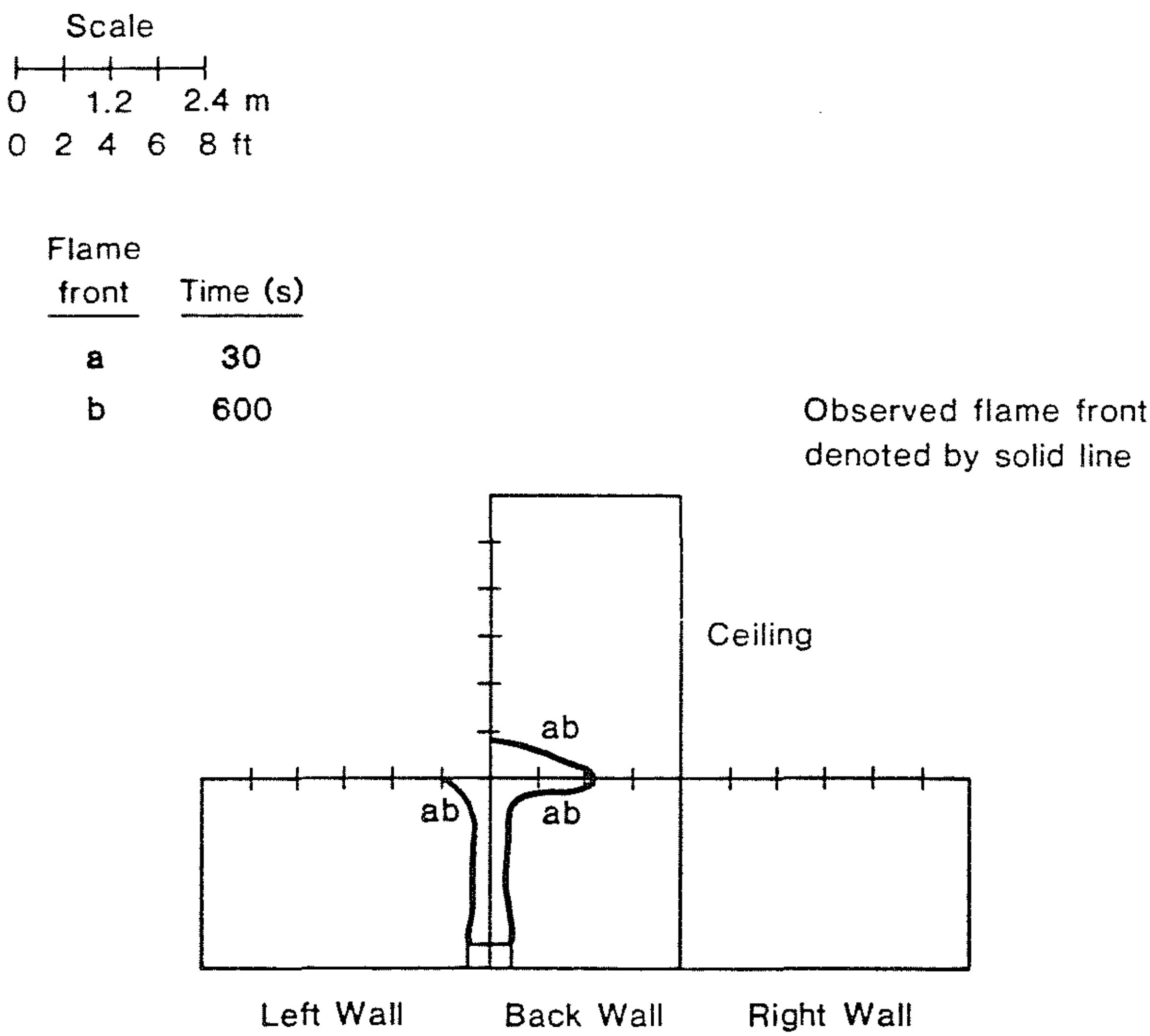


Fig. 46 Flame spread profiles for test 1B (gypsum board, exposure A)

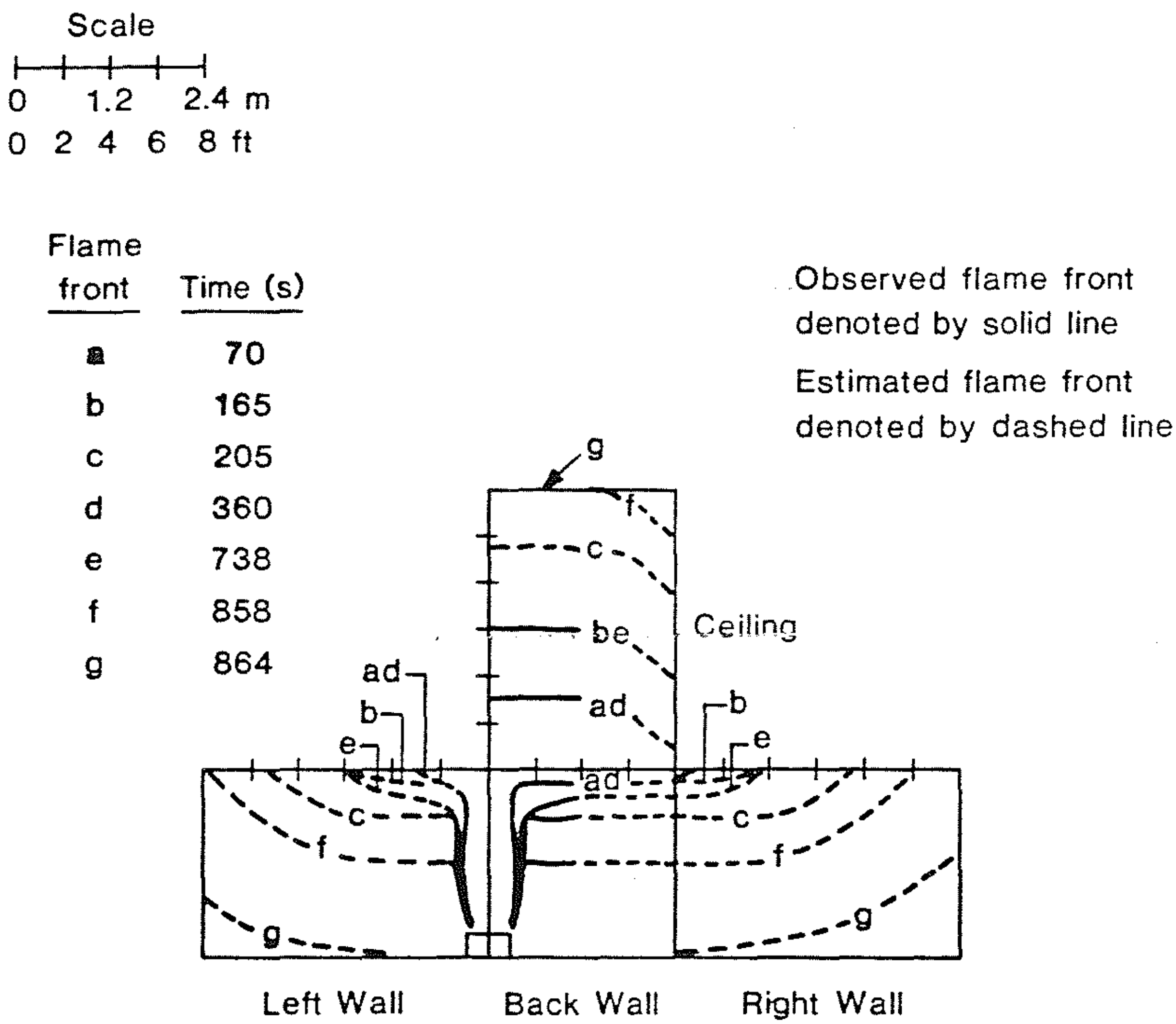
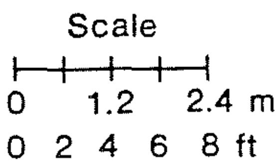


Fig. 7 Flame spread profiles for test 15 (fire-retarded plywood, exposure A)



Flame front	Time (s)
a	20
b	35
c	43
d	45
e	48

Observed flame front denoted by solid line

Estimated flame front denoted by dashed line

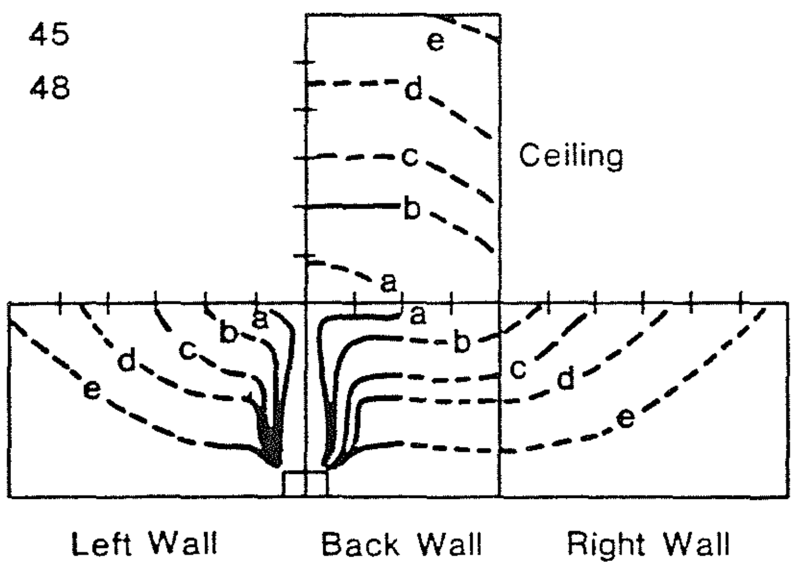


Fig. 68 Flame spread profiles for test 10 (polystyrene, exposure A)

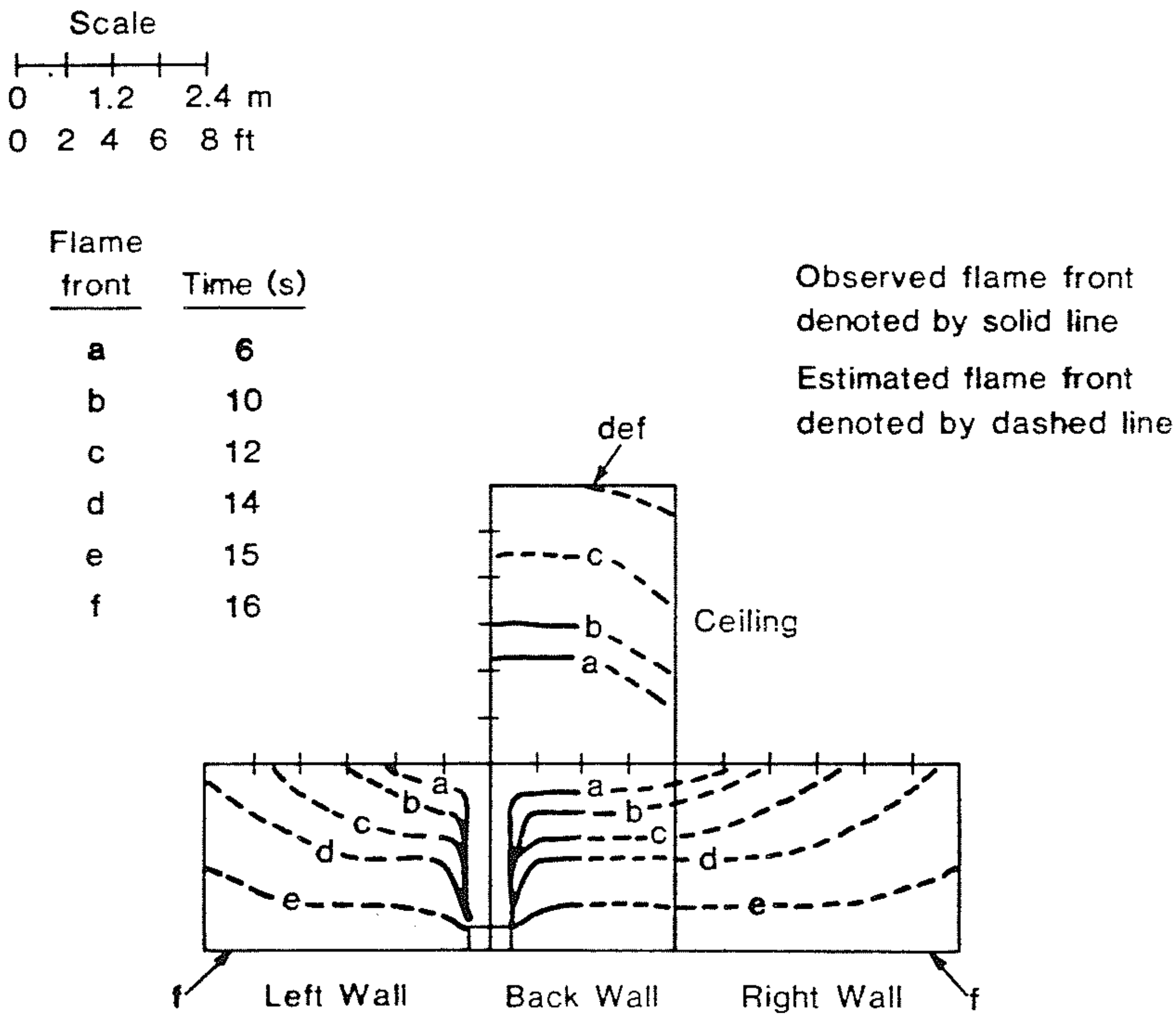
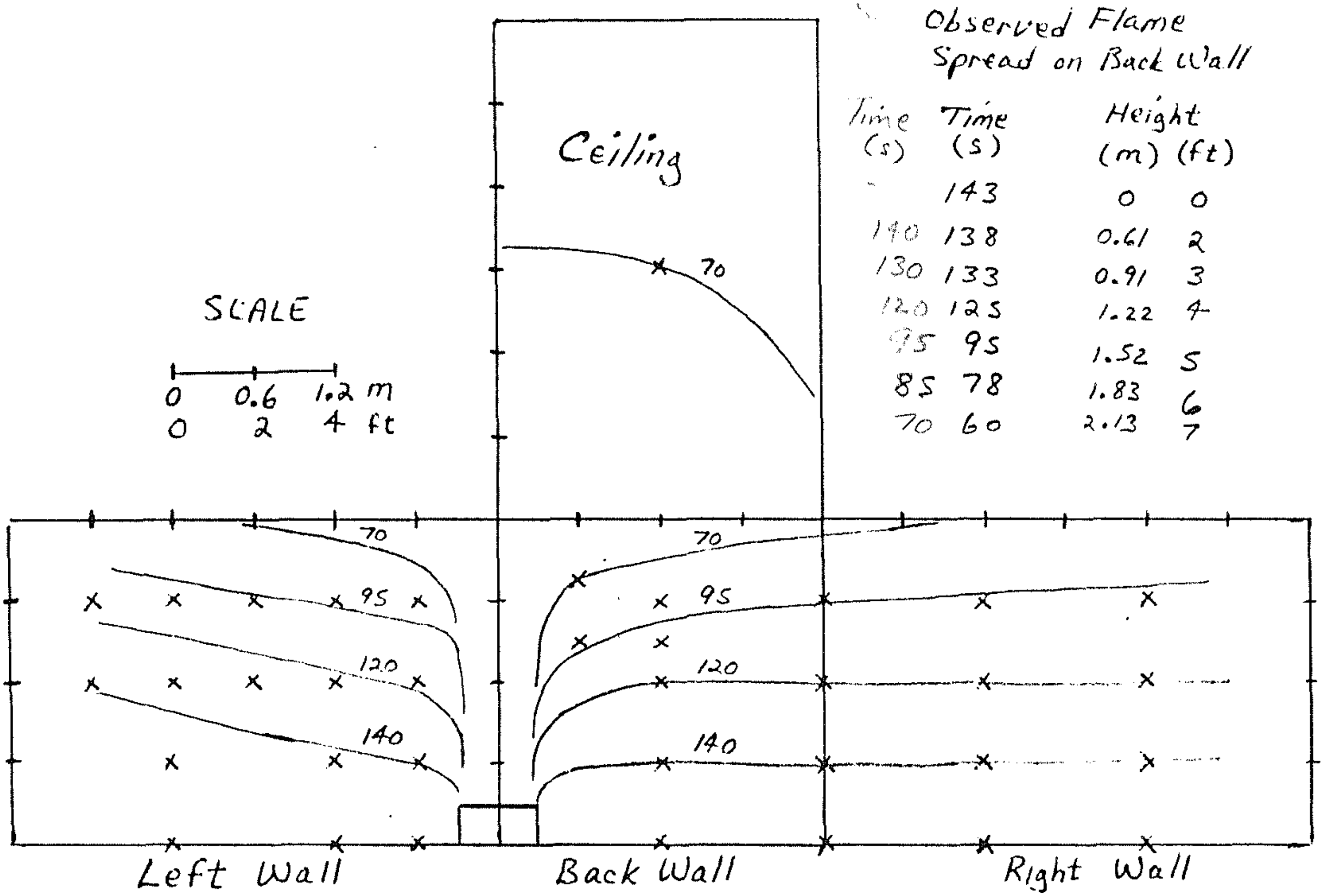


Fig. ~~6~~ 9 Flame spread profiles for test 9 (polyisocyanurate, exposure A)

Estimated Flame Spread from 350°C Isotherm

Observed Flame Spread on Back Wall

Time (s)	Time (s)	Height (m)	Height (ft)
–	143	0	0
140	138	0.61	2
130	133	0.91	3
120	125	1.22	4
95	95	1.52	5
85	78	1.83	6
70	60	2.13	7



x – Placement of surface thermocouples

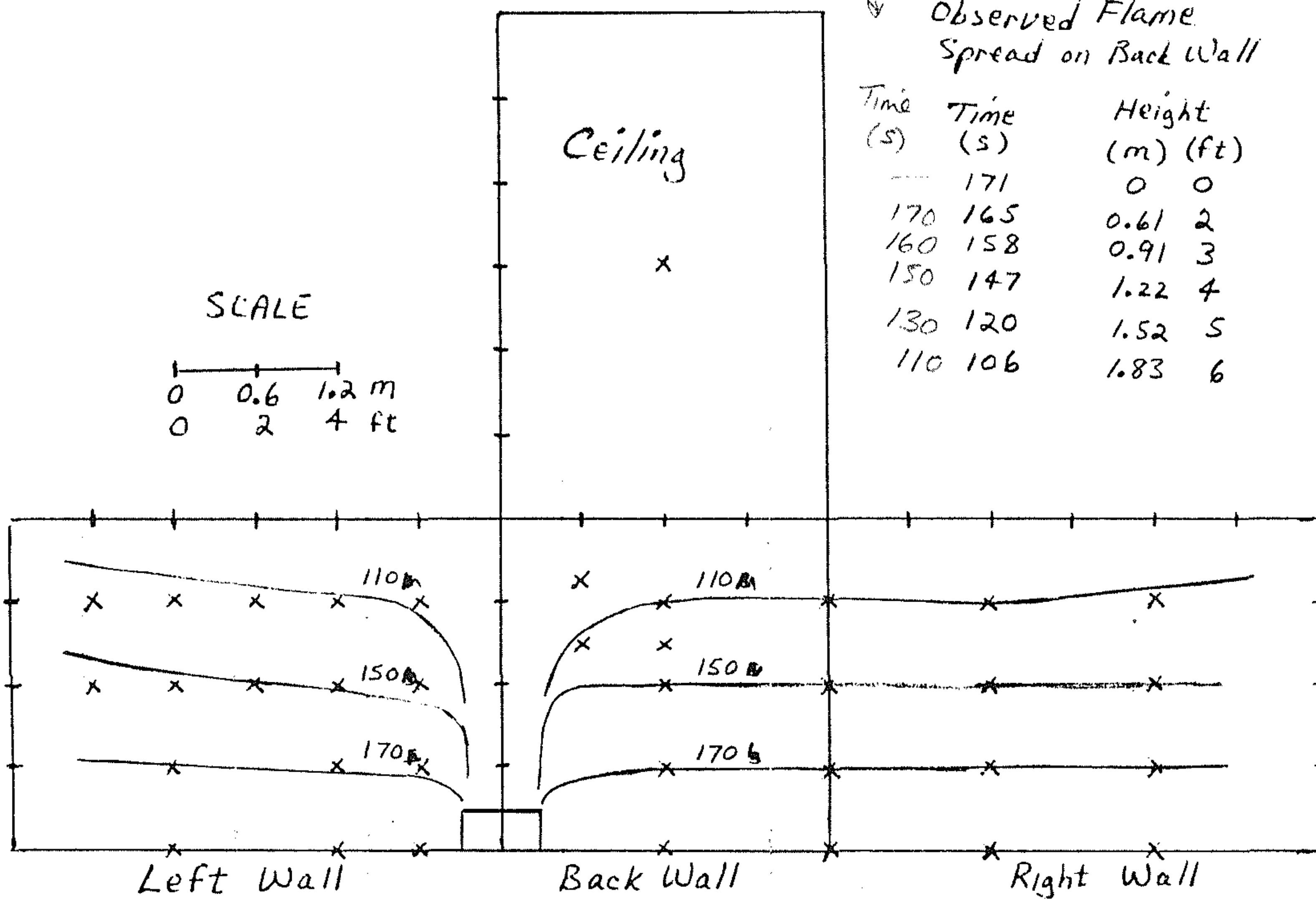
(———) 350 °C isotherms estimated from surface thermocouple data
Time of occurrence in seconds shown over each isotherm

Fig. 40 Flame spread profiles for test 19 (plywood 2, exposure A)

Estimated Flame Spread from 350°C Isotherms

Observed Flame Spread on Back Wall

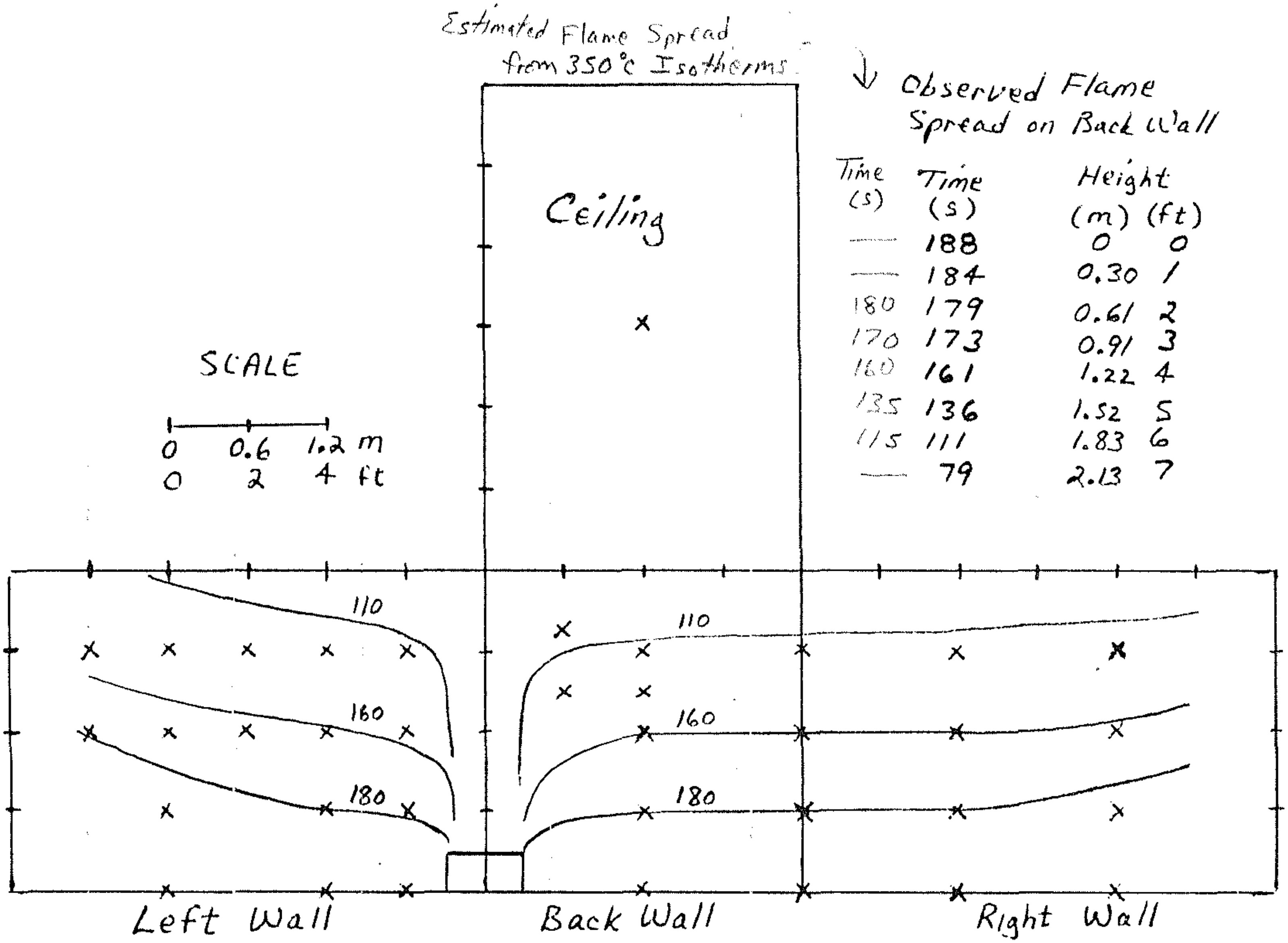
Time (s)	Time (s)	Height (m)	(ft)
—	171	0	0
170	165	0.61	2
160	158	0.91	3
150	147	1.22	4
130	120	1.52	5
110	106	1.83	6



x – Placement of surface thermocouples

(———) 350 °C isotherms estimated from surface thermocouple data. Time of occurrence in seconds shown over each isotherm.

Fig. ~~8~~ 11 Flame spread profiles for test 17 (plywood 2 walls, calcium silicate ceiling, exposure A)



Observed Flame Spread on Back Wall

Time (s)	Time (s)	Height (m)	(ft)
—	188	0	0
—	184	0.30	1
180	179	0.61	2
170	173	0.91	3
160	161	1.22	4
135	136	1.52	5
115	111	1.83	6
—	79	2.13	7

x – Placement of surface thermocouples

(———) 350 °C isotherms estimated from surface thermocouple data
Time of occurrence in seconds shown over each isotherm

Fig. ~~9~~ 12 Flame spread profiles for test 18 (plywood 2 walls, gypsum board ceiling, exposure A)

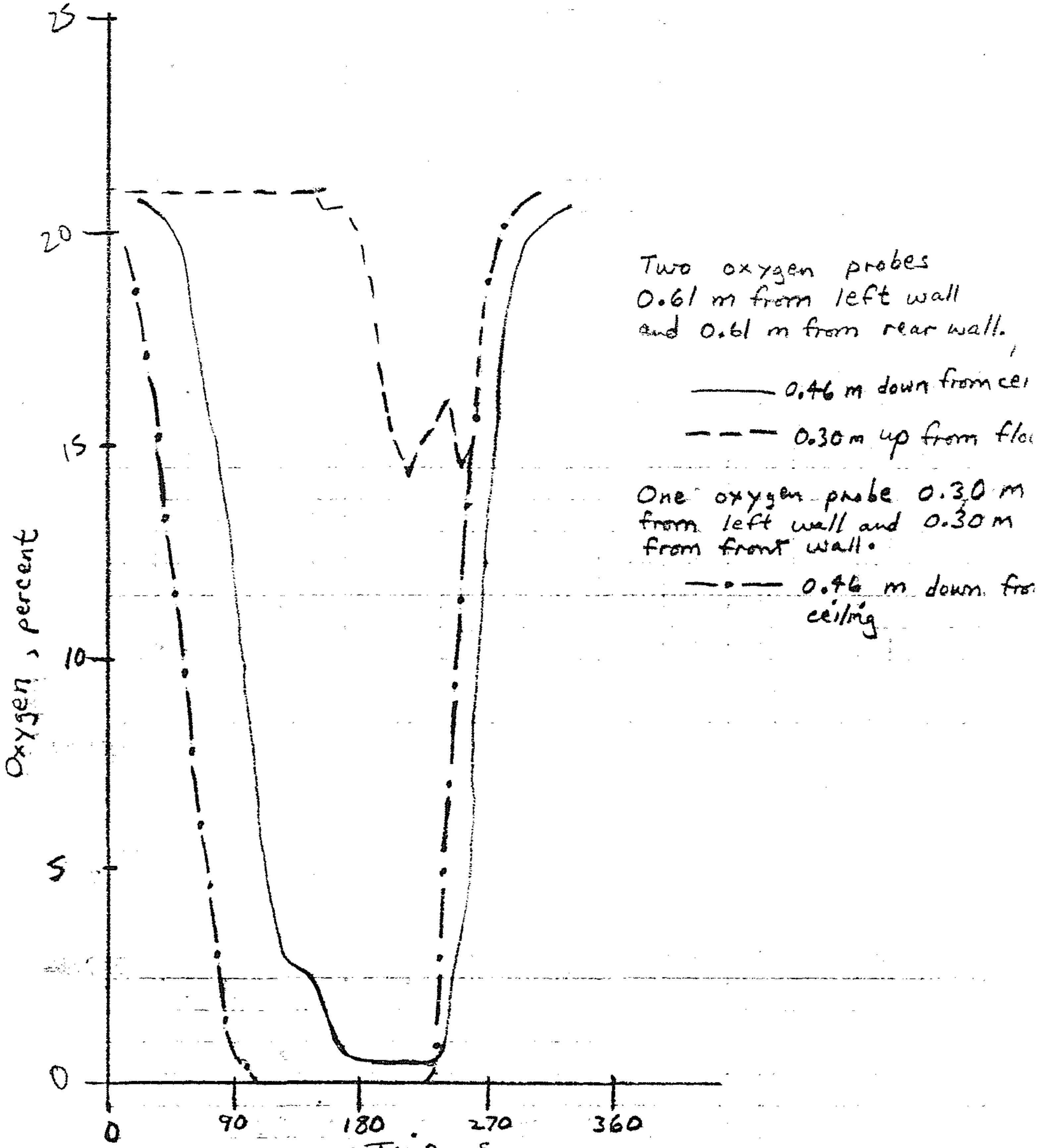


Fig. ~~10~~ #13. Oxygen concentrations in room for test 19 (plywood 2, exposure A

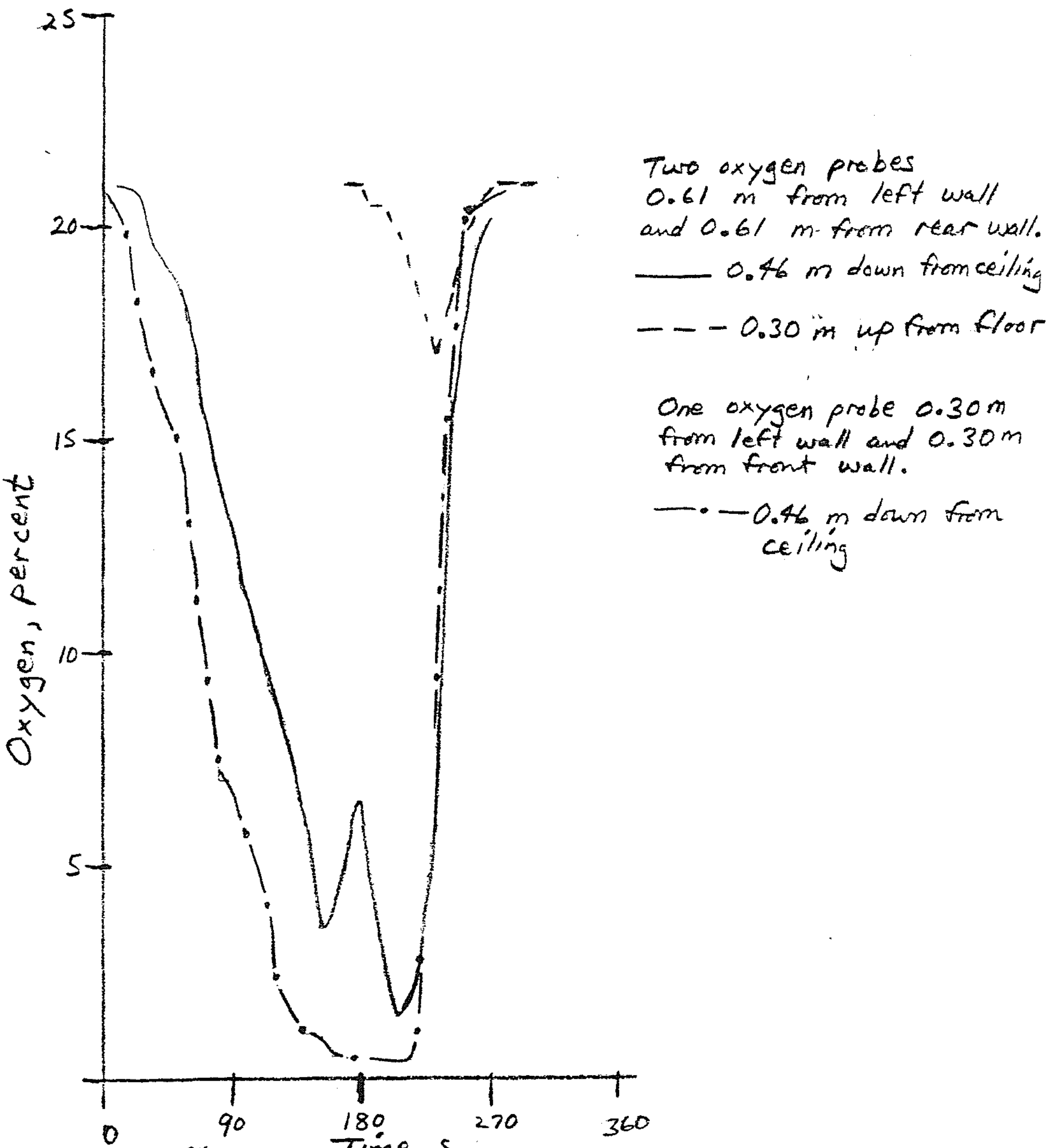


Fig. ~~12~~ 14. Oxygen concentrations in room for test 17 (plywood 2 walls, exposure A)

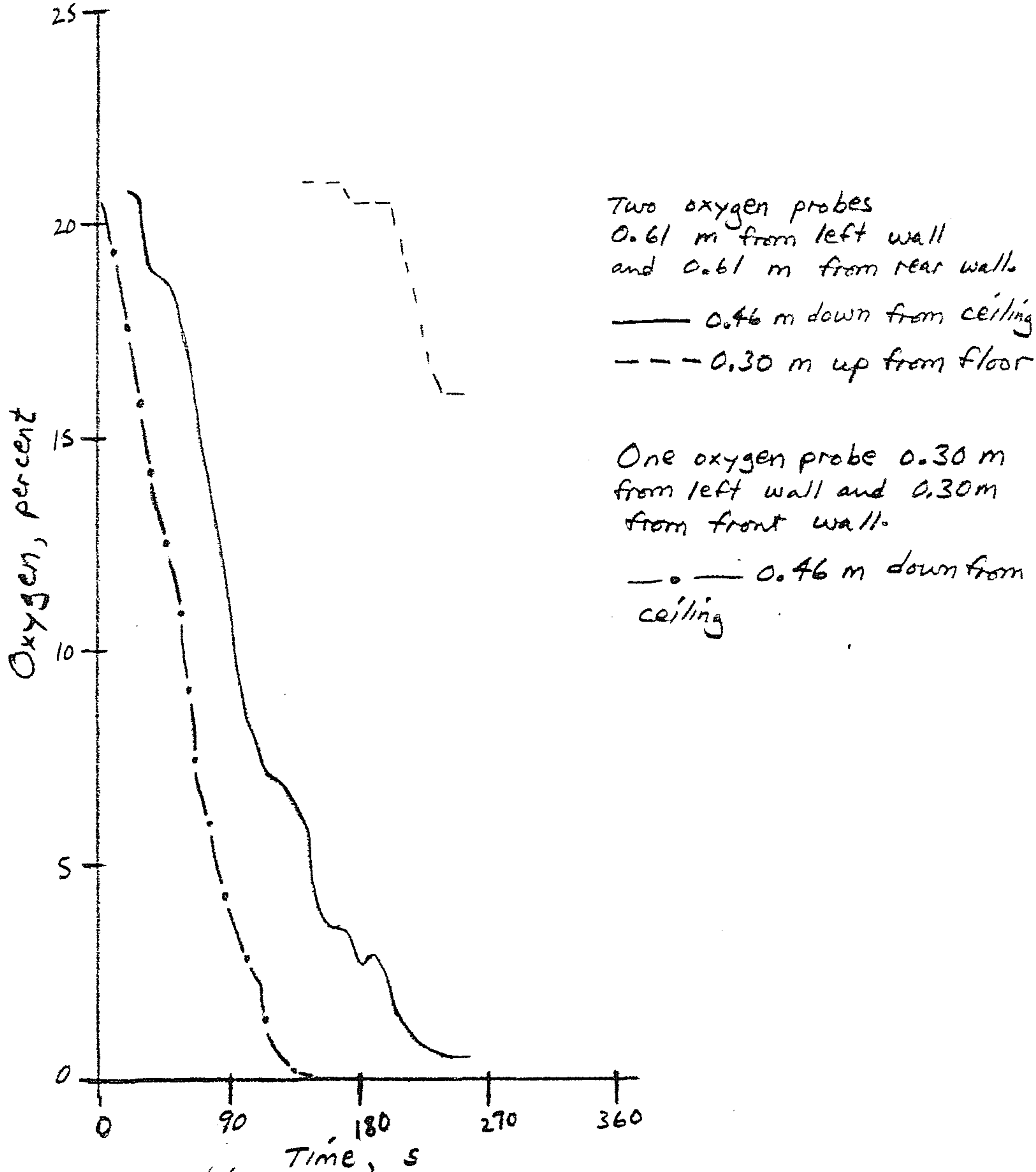


Fig. 15. Oxygen concentrations in room for test 18 (plywood 2 walls, exposure A)

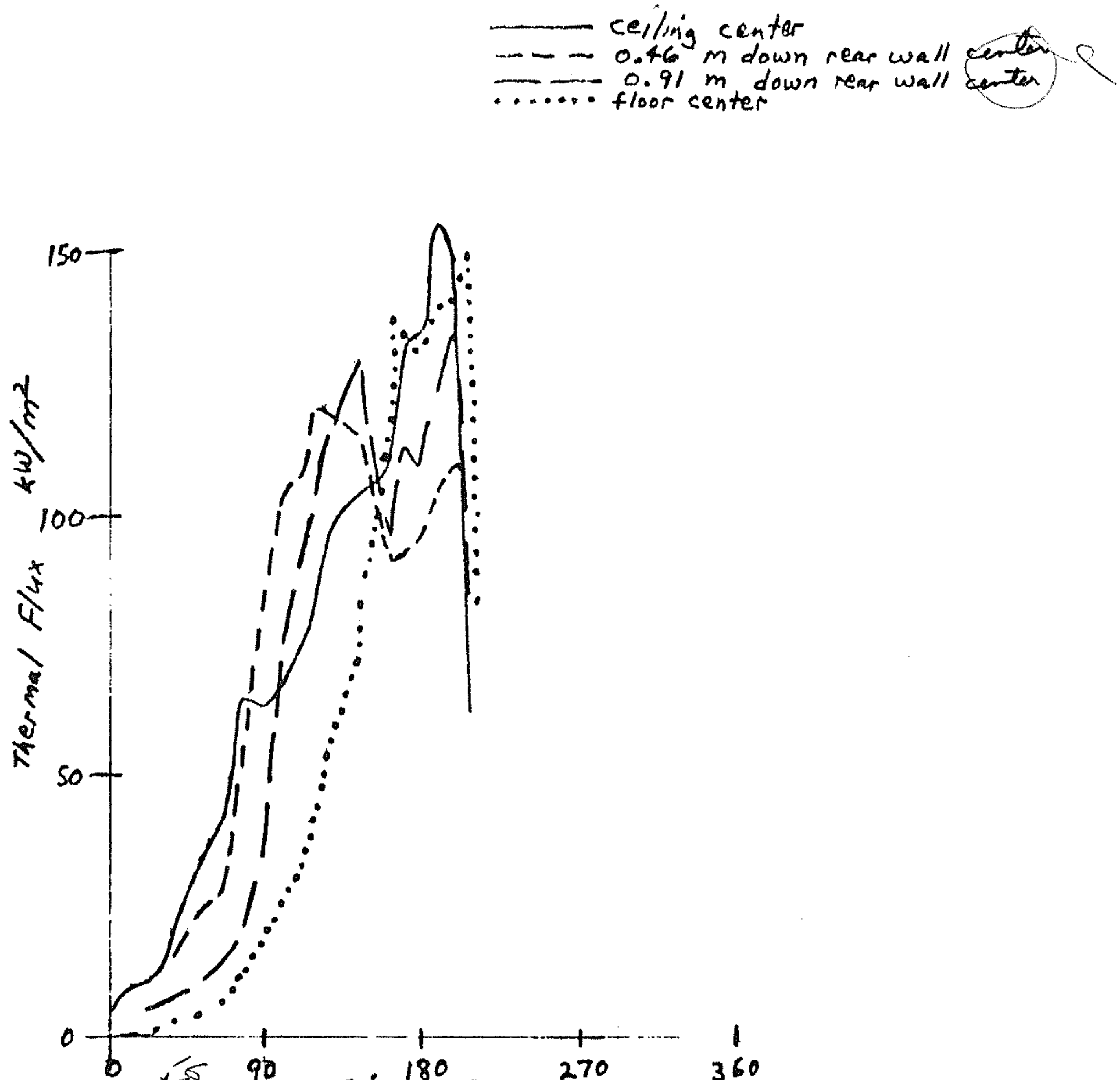


Fig. ~~13~~ 16. Flux levels in room for

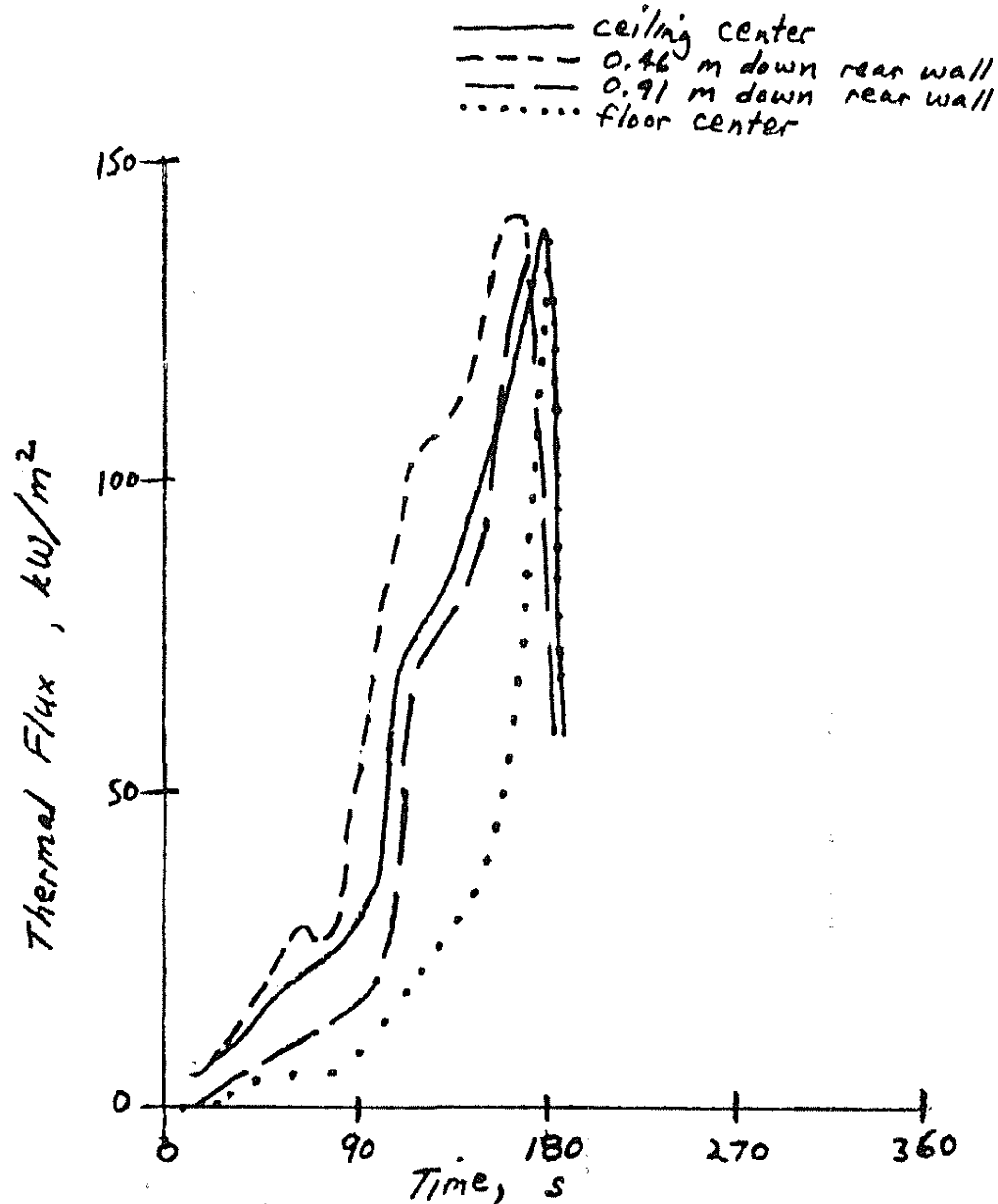


Fig. ~~14~~ 15 17. Flux levels in room for test 17 (plywood 2 walls, exposure A)

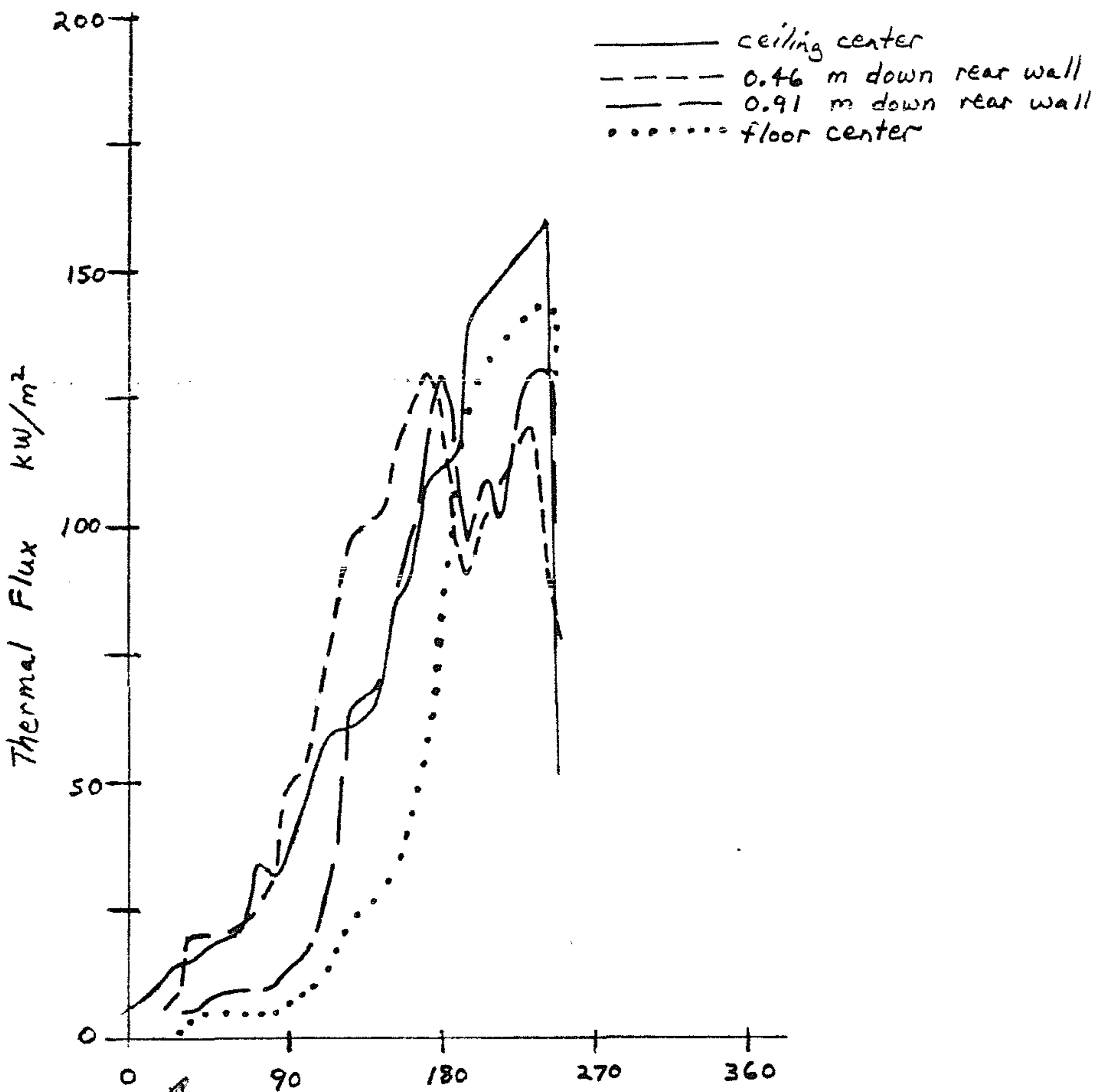


Fig. ~~15~~ ~~16~~ 18. Flux levels in room for test 18
(plywood 2 walls, exposure A)

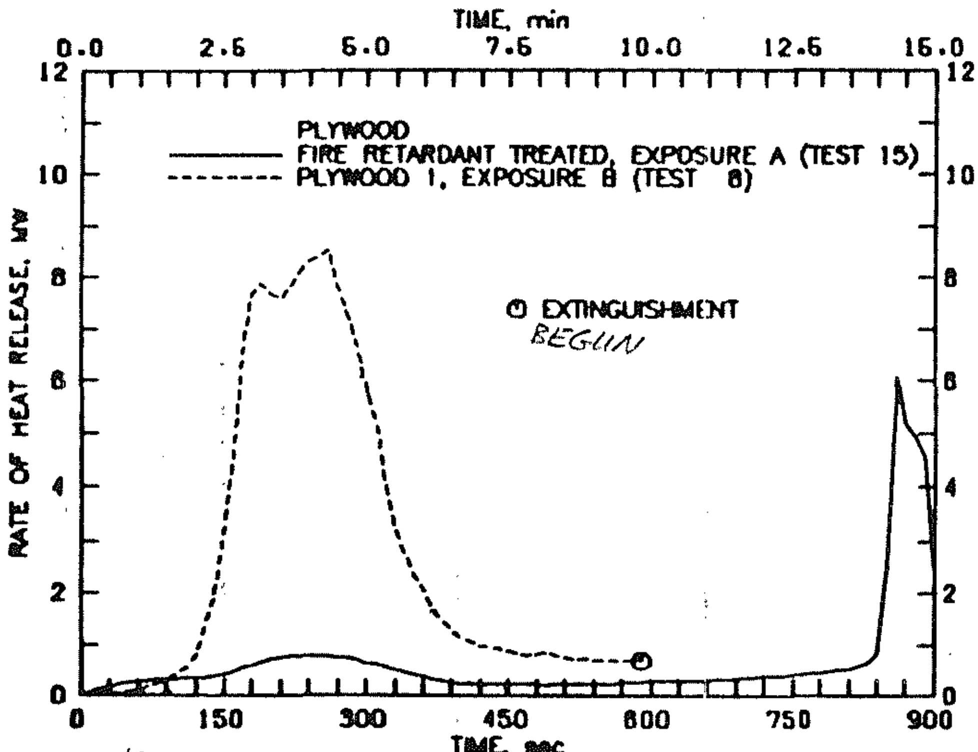


Figure ~~16.~~ #7 19 Rate of heat release histories for test 8 (plywood 1, exposure B) and test 15 (fire-retarded plywood, exposure A)

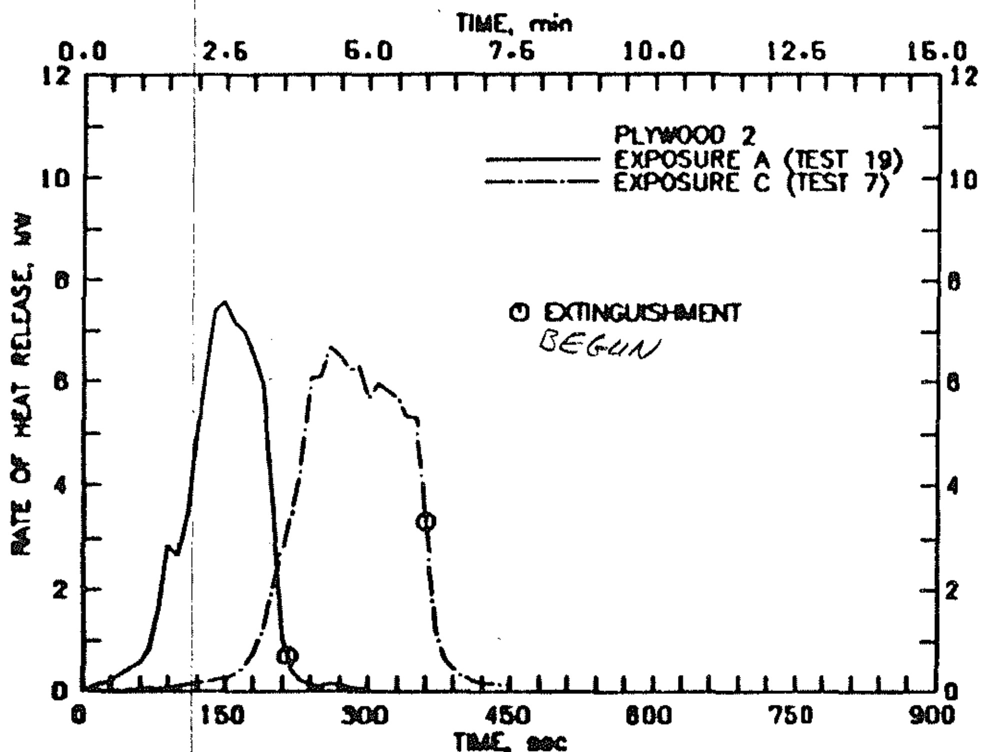


Figure ~~17.~~ 20 Comparison of rate of heat release histories for plywood 2 (tests 7 and 19)

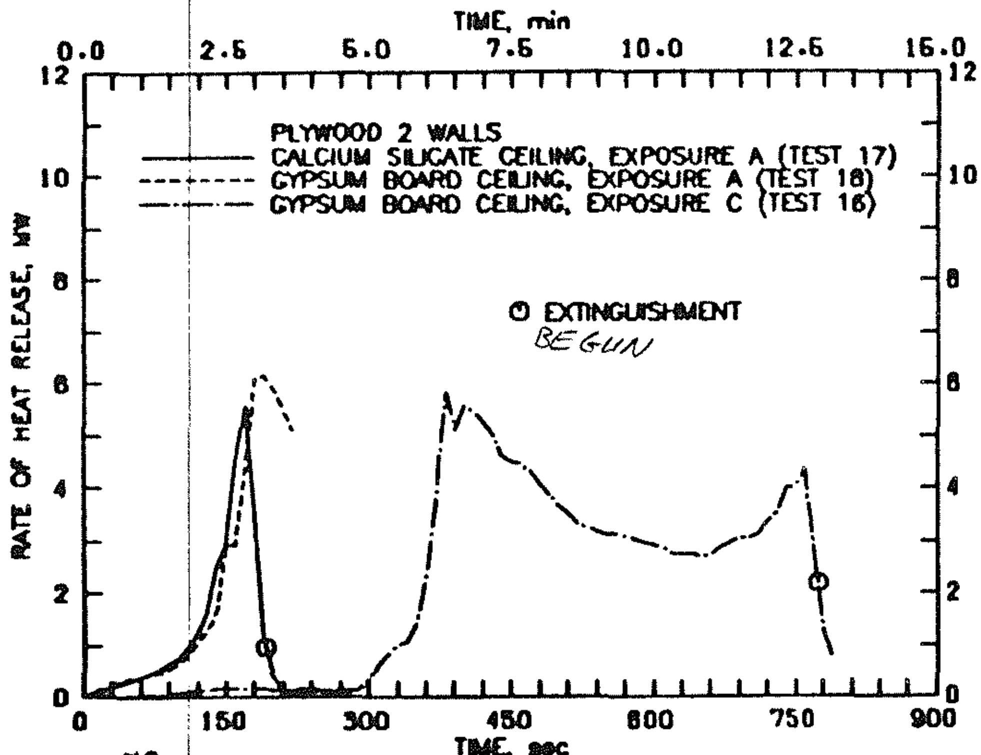


Figure ~~18.~~ 19 Comparison of rate of heat release histories for plywood 2 (tests 16, 17, and 18)

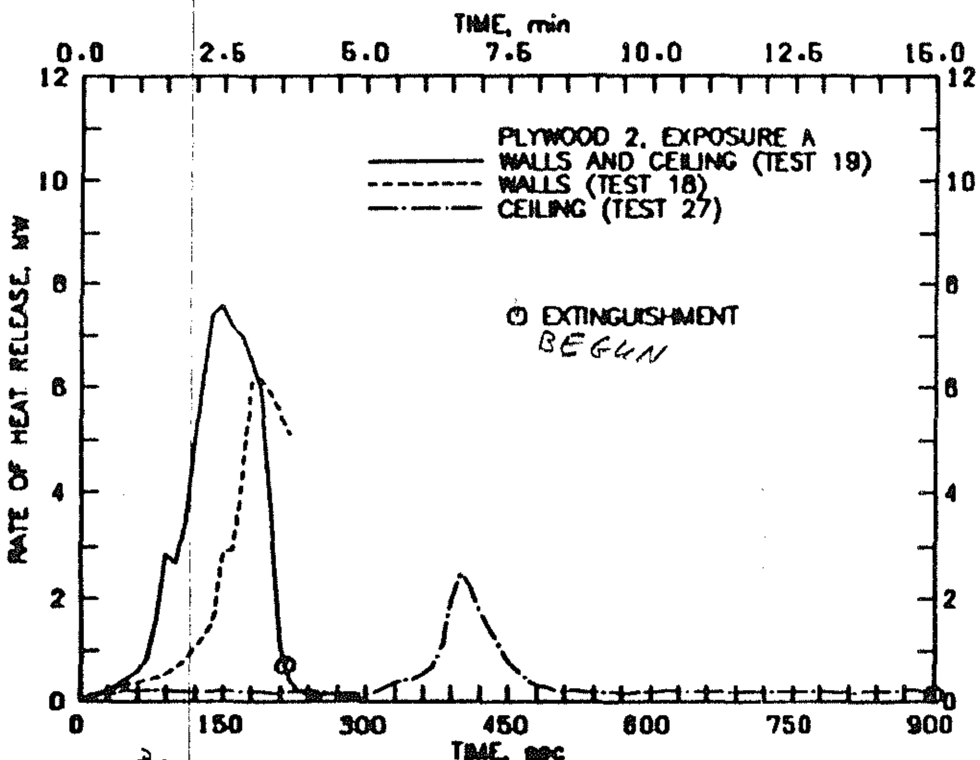


Figure ~~19.~~ 22 Comparison of rate of heat release histories for plywood 2 (tests 18, 19, and 27)

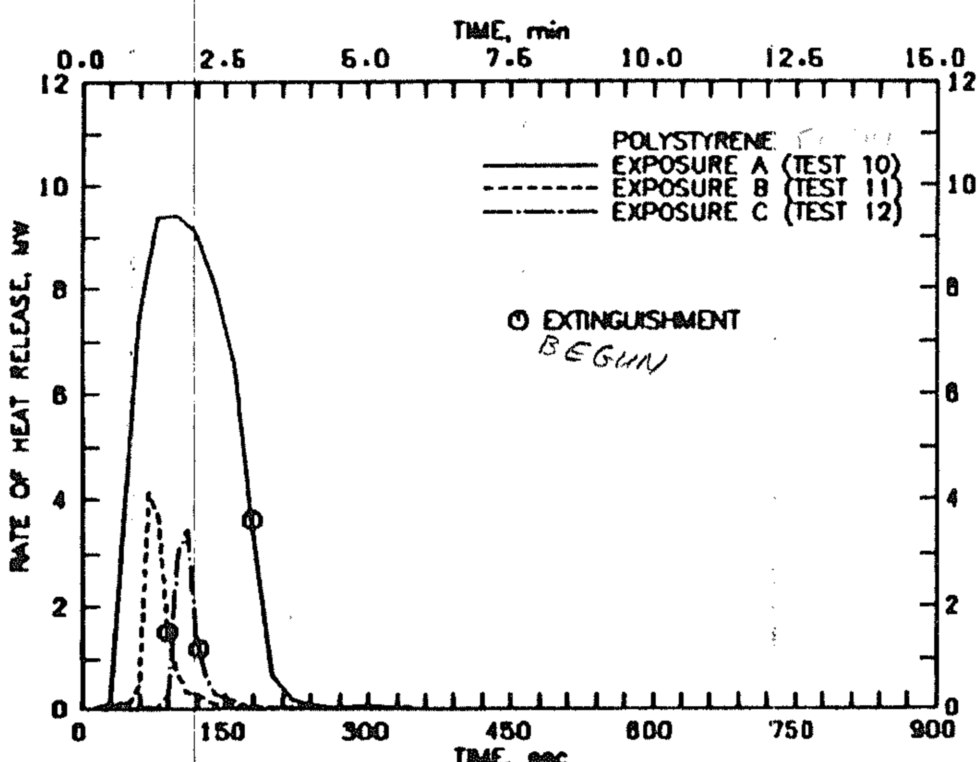


Figure ~~20~~ 23. Comparison of rate of heat release histories for polystyrene (tests 10, 11, and 12)

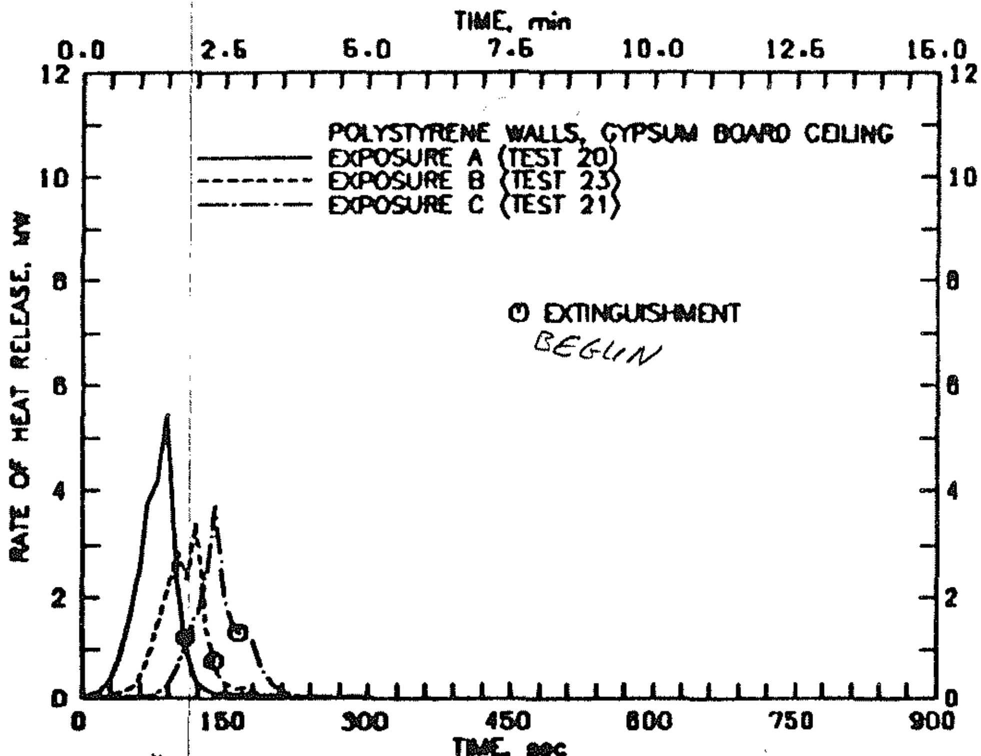


Figure ~~21~~ 22. Comparison of rate of heat release histories for polystyrene (tests 20, 21, and 23)

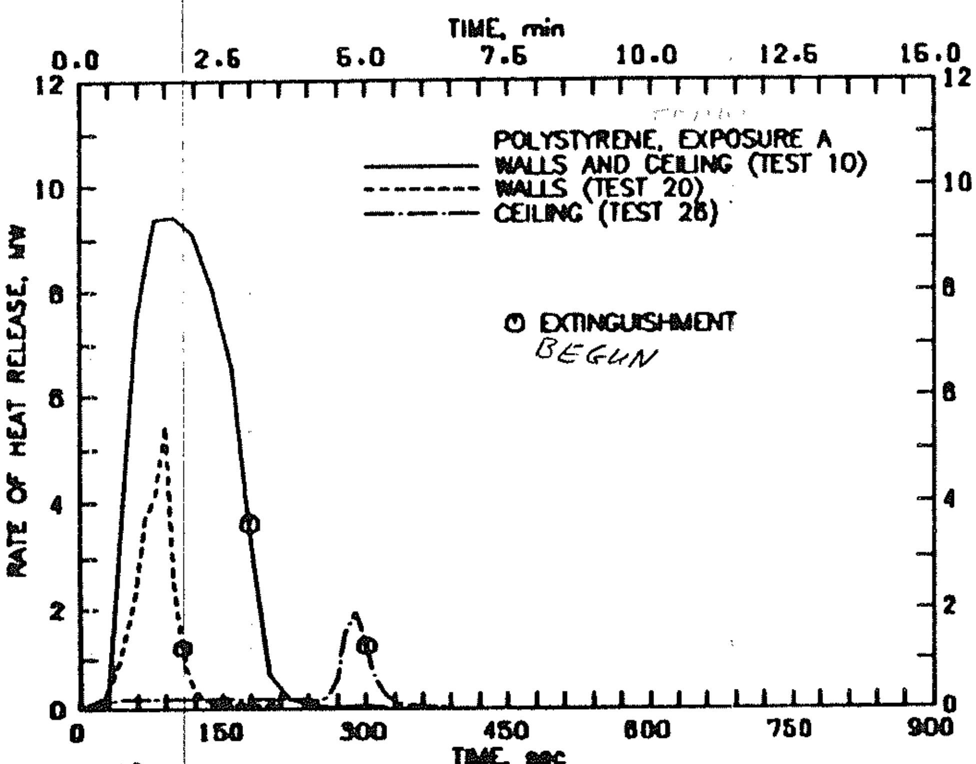


Figure ~~22~~ 25. Comparison of rate of heat release histories for polystyrene (tests 10, 20, and 26)

Clearly the fire didn't go out immediately
Fix wording here + in other figures. O-K

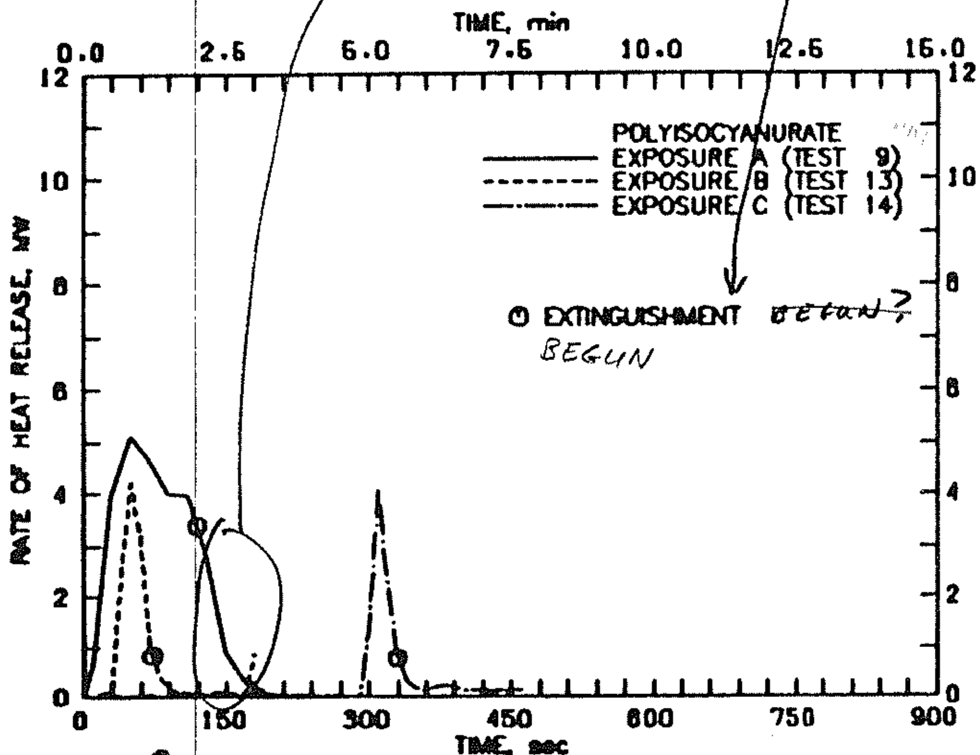


Figure ~~23.~~ 26 Comparison of rate of heat release histories for polyisocyanurate (tests 9, 13, and 14)

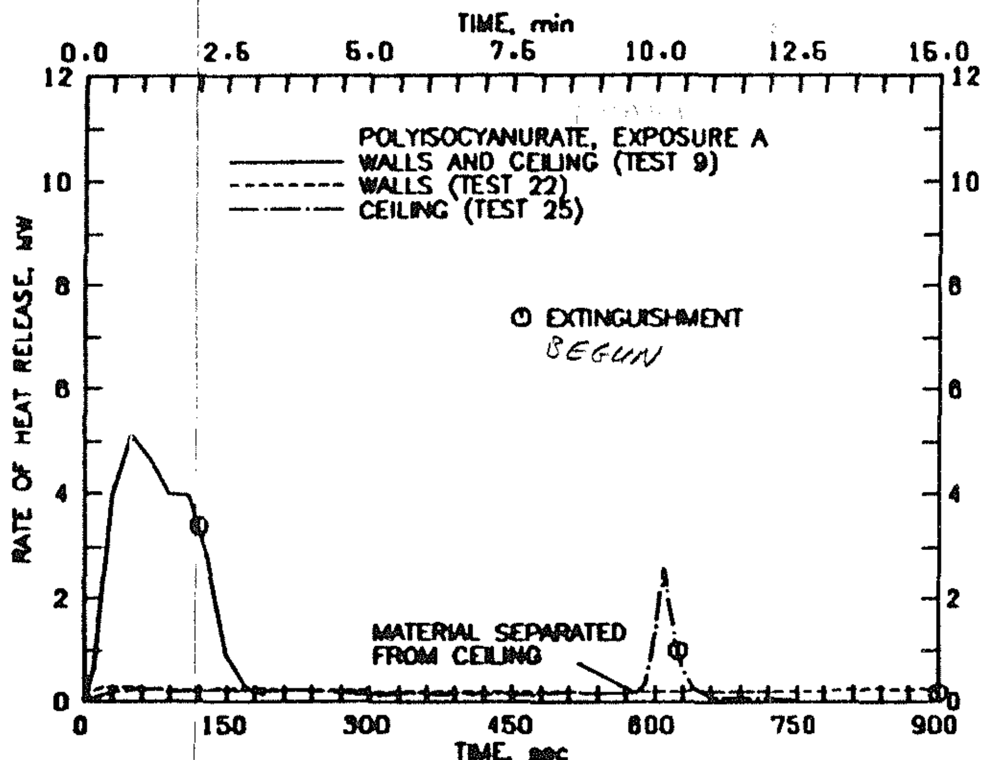


Figure 23. Comparison of rate of heat release histories for polyisocyanurate (tests 9, 22, and 25)

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

Research results with the proposed ASTM standard room fire test for interior finish materials are presented. The materials selected for the study were two untreated plywoods, a fire-retarded plywood, polystyrene, polyisocyanurate, and gypsum board. Three 900 s duration test scenarios were considered. Scenario A is a constant nominal 160 kW ignition source exposure. Scenario B achieves the same maximum exposure after three intervals of 30 s each in which the heat release rate is increased in equal steps of 40 kW. Scenario C evaluates a material over a 300 s exposure at a nominal 40 kW, with another 300 s exposure at a nominal 160 kW, followed by 300 s at zero exposure. This zero exposure allows the material to be screened for self-burning properties afterwards. The study demonstrated that all three scenarios could adequately differentiate material fire behavior, in terms of the maximum degree of fire buildup attained and the time to reach the maximum, for the materials selected. However, scenario C would allow a more comprehensive evaluation of materials. Thermal radiation incident on the floor and room and doorway air temperatures were found to be suitable parameters for determining room fire buildup including room flashover. Surface flame spread and rate of heat release are discussed for the room fires. Unit-area bench-scale rate of heat release data from the cone calorimeter were predictive of the full-scale data when melting and dripping (which changes the active burning area) or very slow to ignite fire retarded materials (whose retardants may be baked out) are not involved. Further full-scale testing is desirable to establish more confidence and delineate the limits of validity.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

fire growth; fire test method; flame spread; heat release; interior finish; room fire

13. AVAILABILITY

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