DEVELOPMENT OF FIRE RESISTANCE RATINGS FOR SHELTER COMPONENTS

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Summary
of
Research Report

DEVELOPMENT OF FIRE RESISTANCE RATINGS FOR SHELTER COMPONENTS

by

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and

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OBJECTIVE AND SCOPE

The objective of this project is to begin verification experiments required for application of fire-rating techniques for shelter components. The scope of present effort covers the preliminary study of responses of shelter components to typical fire exposures.

PROBLEM DISCUSSION

An essential area of civil defense is the establishment of shelters in which large portions of the civilian population can be interned for the duration of dangerous nuclear radiation following an attack. Since fires will follow a nuclear attack, it is important to provide for the integrity of shelters when exposed not only to nuclear blast and/or fallout, but also to the effects of fire.

Present building fire resistance requirements, are used primarily to assure the safety of people within structures under peacetime situations. The ratings inherently presuppose that evacuation of the building is possible, that properly equipped professional fire fighters will soon arrive, and that an adequate water supply exists. Under nuclear attack conditions, however, the shelter occupants cannot leave the shelter area or building and outside fire fighting cannot be expected. Thus, fires within the shelter area must be controlled by the occupants and fires external to the shelter area must be withstood in their entirety by the structural barriers comprising the shelter envelope. In the case of the fallout shelter, the non-shelter portions of the structure must also be capable of withstanding unsuppressed burnout without endangering the shelter occupants.

The additional requirements imposed by the nuclear attack situation are reflected in a need for shelter-component fire resistance compatible with these requirements. In previous work (Contract No. OCD-PS-64-50), existing fire rating techniques were found to be generally applicable to the shelter envelope, and shelter building structure. However, means for proper assessment of test results in terms of real exposures were found lacking. To this end, experiments were performed to evaluate the responses of shelter components to typical fire exposures, in order to develop means for predicting these responses from the results of a minimum number of standardized tests.

DESCRIPTION OF EXPERIMENTS

In order to obtain a uniform, controlled exposure, an infrared lampbank was used. This lampbank consists of 72 sixteen-inch lamps (lighted length) mounted in a double bank array 24 inches high. The lamp system has an upper limit on output of 30-35 cal/cm^2-sec. Measurement of the radiant flux level is obtained with a Hi-Cal Asymptotic Calorimeter. The radiation intensity varied from 0.1 cal $cm^{-2}sec^{-1}$, (representing a low-level, long-duration debris fire) to about 8 cal cm^{-2} sec^{-1} (corresponding to an estimated maximum exposure from a mass fire).

The sample holder was mounted on a rack which allowed the holder to be moved in directions perpendicular and parallel to the lamps. Prior to each run a field calcrimter was placed at the front of the lamps and used to adjust the power output to the desired level. Subsequently, the sample was moved in front of the lamps.

The samples subjected to the varied exposures included:

1) Purely Conductive Material
    a) A-26 Insulating Fire Brick -- This material, properly conditioned, gives up no free or combined water up to 2600°F.
2) Moisture Bearing Material
    a) A-26 Brick with 10% water
    b) A-26 Brick with 25% water
    c) Plaster of Paris
3) Ablative Type Material
    a) Metal Clad Wood (A fire door type assembly which prevents the distilled combustibles from burning at the sample face).
4) Combustible Materials
    a) Wood (Pine, D-Select Lumber, the same as used in 3a)
    b) High Density Particle Board
    c) Low Density Fiberboard

Each sample was approximately 16-in. wide by 24-in. high by

2-in. thick. During exposure, samples were held in a frame made from steel angles.

Chromel-Alumel thermocouples were located near the center of each sample at various distances from the exposed face. Except for the plaster, thermocouples were located in 0.042-in. diameter holes, and were positioned to avoid conduction losses along the wires. The thermocouples were molded directly in the plaster samples.

RESULTS AND CONCLUSIONS

The study performed constitutes only the first step toward establishing absolute rating of shelter components. Toward this end, the study has brought to light several important findings which are summarized below.

1. Fire resistance of a barrier is considerably affected by the intensity of the exposure. Although this effect is a complicated function of various parameters, for homogeneous combustible materials it can be approximately expressed in terms of the area equivalence method suggested by Ingberg(1). For homogeneous non-combustible materials (containing free water) this method produced errors ranging from 10 to 31 percent. The error is substantially larger for materials containing both free and chemically-combined water, as in plaster. In the case of non-homogeneous material, the area equivalence concept introduced errors ranging from 62 to 86 percent.

2. A definite trend of data is indicated when fire resistance rating is plotted as the function of exposure intensity. Correlation is better at lower intensities.

3. Exposure intensities on the level of 0.1 cal/cm^2sec, which may be found in debris fires, do not appreciably affect the integrity of the barrier. However, the temperatures reached by the unexposed surface may still be too high for the environment of the shelter.

4. For moderate heating, (less than 1 $cal\ cm^{-2}sec^{-1}$), of materials containing relatively small amounts of moisture, heat-conduction theory predicts temperature distributions within 20 percent of those obtained from experiments. Agreement between theory and experiment becomes less satisfactory as either the moisture content or the heating intensity increase.

ABSTRACT

Experiments were performed to evaluate the responses of shelter components to typical fire exposures in order to develop means for predicting these responses from the results of a minimum number of standardized tests. Exposures were provided by an infrared lampbank. Irradiance levels used varied from 0.1 cal $cm^{-2}sec^{-1}$ (representing a low-level, long-duration debris fire exposure) to about 8 cal $cm^{-2}sec^{-1}$ (corresponding to an estimated maximum exposure intensity from a mass fire).

Samples included material of both high and low insulating qualities, inert materials, and those exhibiting ablative and dehydration processes. Each sample was approximately 16-in. wide, 24-in. high and 2-in. thick. Chromel-Alumel thermocouples were located near the center of each sample at various distances from the exposed surface.

Results indicate that fire resistance of a barrier is considerably affected by the intensity of exposure. For homogeneous combustible materials, this effect can be expressed approximately in terms of the area equivalence method suggested by Ingberg. For homogeneous non-combustible materials, containing free water this method produced errors ranging from 10 to 31 percent. This error is substantially larger for materials containing both free and chemically-combined water. In the case of non-homogeneous materials, the error ranged from 62 to 86 percent.

PREFACE

This is the final report on Contract No. N228 (64279) 65580, T.O. 64-200(29), OCD No. 1132A (IITRI Project No. M6125), "Development of Fire Resistance Ratings for Shelter Components." The program is sponsored by the Department of the Army, Office of the Secretary of the Army, Office of Civil Defense through the U. S. Naval Radiological Defense Laboratory. The objective of this effort is to begin verification experiments required for application of the shelter fire rating techniques developed under Contract No. OCD-PS-64-50. The present effort covers the preliminary study of homogeneous barrier materials.

The contract was initiated in May, 1965. All work accomplished on this program up to February, 1966 is reported herein.

Respectfully submitted

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I. INTRODUCTION

An essential area of civil defense is the establishment of shelters in which large portions of the civilian population can be interned for the duration of dangerous nuclear radiation levels following an attack. Since fires will follow a nuclear attack, it is important to provide for the integrity of shelters when exposed not only to nuclear blast and/or fallout, but also to the effects of fire.

Present building fire resistance requirements, which are used primarily to assure the safety of people within structures under peacetime situations, are designed to:

1) preserve life by providing time for safe egress from the building,
2) prevent conflagrations in built-up areas,
3) provide time for fire departments to save individual properties, and
4) provide a basis for fire insurance rating by estimating relative extent and degree of damage.

The ratings inherently presuppose that evacuation of the building is possible, that properly equipped professional fire fighters will soon arrive, and that an adequate water supply exists. Under nuclear attack conditions, however, the shelter occupants cannot reasonably flee the shelter area or building and outside fire fighting cannot be expected. Thus, fires within the shelter area must be controlled by the occupants and fires external to the shelter area must be withstood in their entirety by the structural barriers comprising the shelter envelope. In the case of the fallout shelter, the non-shelter portions of the structure must also be capable of withstanding unsuppressed burnout without endangering the shelter occupants.

The additional requirements imposed by the nuclear attack situation are reflected in a need for shelter component fire resistance compatible with these requirements. In previous work (Contract No. OCD-PS-64-50), existing fire rating techniques were found to be generally applicable to the shelter envelope, and shelter building structure. However, means for proper assessment of test results in terms of real exposures and, in fact, accurate definition of these exposures were found lacking. To this end, a series of verification studies were defined. The experiments are of three kinds, namely:

1) experiments to evaluate temperatures, pressures and gas concentrations which occur in the many possible fire situations,
2) experiments to evaluate the responses of shelter components to typical fire exposures, in order to develop means for predicting these responses from the results of a minimum number of standardized tests, and
3) experiments to verify the validity of certain peacetime fire test procedures (particularly

specimen restraint) which are applicable to rating shelter components.

The objective of the present program is to begin the experiments concerned with Item 2. The total scope of this item includes study of the effects on components of the duration and intensity of fire exposure for both constant and changing fire exposures with and without direct flame contact on the component. Homogeneous and heterogeneous components of high and low insulative qualities must be considered. Inert materials as well as those exhibiting ablative and dehydration processes should be included.

The preliminary study undertaken here is limited to one-dimensional heat flow through essentially homogeneous specimens of relatively small size with several constant heat input rates. Future study will treat full scale items or modules and will include heterogeneous materials such as reinforced, cellular, or block construction.

II. FIRE EXPOSURES

The ASTM methods of fire tests prescribe a standard exposing fire of controlled extent and severity, defined by a specific temperature-time relationship. Performance of an item under test is defined as the period of resistance to this standard exposure before the first critical point in behavior is observed. Results are presented as time periods such as "2-hr," "6-hr," "1/2-hr," etc. The test does not provide absolute values of fire resistance, but gives a measure or index by which to compare construction systems under one standard fire condition.

The standard time-perature furnace exposure curve described above is shown in Fig. 1 as taken from Ingberg[1]. Superimposed on the same graph, Ingberg shows the averge time-temperature curve from a full-scale experimental building fire, together with cooling curves obtained from temperature measurements of a fire test furnace.

According to Ingberg[1], the area under the time-temperature curve, above an appropriate base line, may be used as an approximate measure of severity of fire exposure. Two fires, having different time-temperature curves, are then said to be equally severe if this area is the same for both. Ingberg points out further that, in making comparisons, the minimum temperature that need be considered as an exposing temperature must be taken into account. That author suggests base line temperatures of 150°C (302°F) and 300°C (572°F), for exposure of combustible and non-combustible materials, respectively. In making a comparison of areas under two different time-temperature curves, Ingberg also includes the cooling portion of the curves for both fires. Accordingly, the severity of any fire is expressed in terms of a time of exposure to a fire having the standard time-temperature relation.

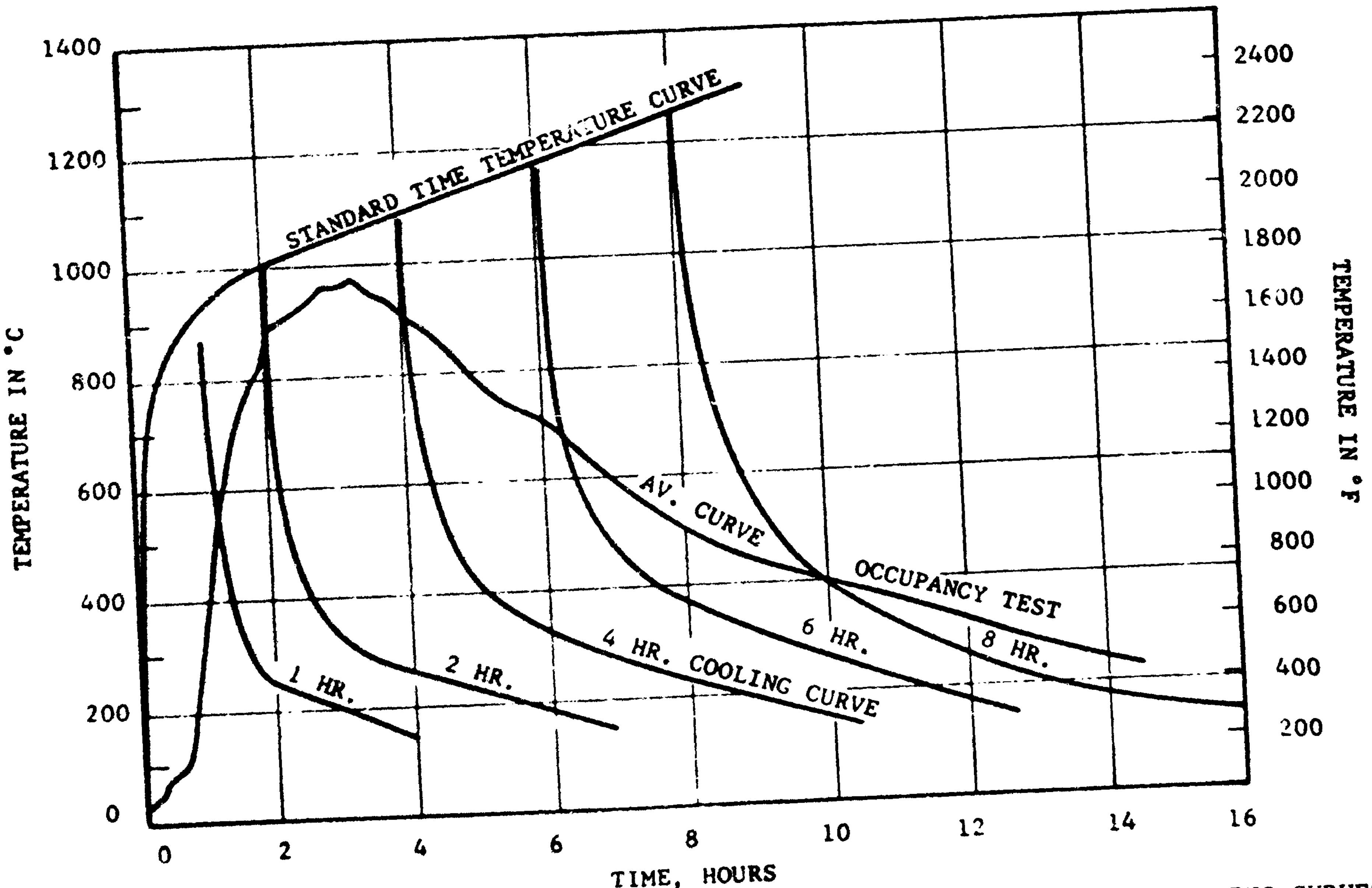


Fig. 1 STANDARD TIME TEMPERATURE CURVE USED IN FURNACE FIRE TESTS, COOLING CURVES, AND CURVE REPRESENTING THE TEMPERATURES IN A TYPICAL OCCUPANCY TEST

This method apparently stems from consideration of simple heat transfer. However, since the component loses heat by radiation and also the properties of the component may change with time (because of such things as thermal decomposition, moisture loss or structural cracking) there seems to be a question regarding the definition of fire severity in terms of area under the time-temperature curve, particularly where the temperature levels may differ significantly. In fact, the term "temperature level" may be in itself an inadequate description of the severity of exposure.

Fire exposures for the rating of shelter components can be classified according to their characteristic modes of heat transfer, as:

(a) Distant Flame Exposures, characterized by transfer of heat to the shelter component primarily by the thermal radiation from a flame that does not contact the component,

(b) Impinging Flame Exposure, characterized by transfer of heat to the shelter component due to the combined effects of thermal radiation and convection from flame in contact with the component, and

(c) Debris Fire Exposure, characterized by conductive transfer of heat to the shelter component from a mass of hot or burning materials resting on or adjacent to the component.

The sources of exposure may be outlined and classified as follows:

1. Exposure from fire within the shelter building--
This type of fire exposure of shelter components

usually consists of direct contact with flame as a result of fire in a portion of building adjacent to a shelter in the same building. Accordingly, this type of exposure would normally classify as "impinging flame exposure."

2. Exposure from fire in individual nearby buildings-- This exposure divides more evenly into the two general types.

   a. The shelter building is separated from the exposing building by a fire wall. Where communicating openings between buildings are present, these are protected with standard fire doors. This type of exposure is similar to exposure from fire within the shelter building and would classify as "impinging flame exposure."

   b. The shelter building is separated from the exposing building by an open space, perhaps the width of a street or an alley. Since heat transfer from this exposure usually would be due only to thermal radiation, it would normally be classified as "distant flame exposure."

3. Exposure from mass fire-- This exposure would result from the merging of several separate fires into a single fire involving a large number of buildings. A mass fire with a stationary front is called a

"fire storm." A mass fire with a moving front is called a "conflagration." Depending upon location of the mass fire with respect to the shelter, this type of exposure may be classified as either "distant flame exposure" or "impinging flame exposure."

4. Exposure from debris fire-- The term "debris fire exposure" is intended as a unique classification. The debris fire has significant effect on that component which it covers or contacts directly. Exposure to a debris fire will produce heating of lower intensity than will the other exposures listed, but of much longer duration. It can conceivable follow an exposure of another type.

It is impractical to consider testing of shelter components by direct exposure to real fire conditions, such as a mass fire. Therefore, the effects of these exposures must be well enough understood to derive an equivalent shelter component rating by use of a practical fire exposure method.

Consider a non-combustible shelter component exposed to any source of heat. The ability of the component to endure the exposure until some predetermined test endpoint is reached depends upon the temperature distribution within the component as a function of time. Test endpoints may include a limit on the maximum or average temperature on the unexposed side of the component; or a limit on component deformation resulting in a crack size and length sufficient to exceed a maximum flow rate of fire gases per unit wall area. At any instant, the temperature gradient from point-to-point within the component determines the distribution of forces due to thermal expansion responsible for component deformation. The temperature distribution as a function of time can, therefore, be used as a basis for comparison of the various types of fire exposures. For this purpose it may be stated that equivalent fire exposures produce identical time-variant temperature distributions within identical components, regardless of the mode (or modes) of heat transfer involved. Comparison of fire exposures by means of the temperature distribution produced within components is a useful concept, but somewhat idealized with respect to application. The specification of fire exposure in terms of the time variable heat flux which attacks the barrier surface is, however, a useable means of severity comparison.

Determination of the way materials respond to various levels of exposures was the objective of the experiments discussed in this report. For these small scale experiments, the following heat fluxes have been chosen:

1) 8 cal/cm^{2}sec, representative of the radiant flux from a source at approximately 2350°F filling the field of view. This level is expected to represent the approximate maximum exposure intensity from mass fires.

2) 5 cal/cm^{2}sec, (2035°F source), indicative of a maximum exposure level from non-mass fires.

3) 1 cal/cm^{2}sec, (1210°F source), typical of ventilation-controlled fires in buildings, will produce spontaneous ignition of most cellulosic materials.

4) 0.5 cal/cm^{2}sec, (945° source), representative of a distant flame exposure sufficient to produce pilot ignition of most cellulosic materials, and

5) 0.1 cal/cm^{2}sec, (500°F source), an approximate lower limit, possibly representing a low-level, long-duration debris fire exposure.

III. EXPERIMENTS

A. Sample Materials

As mentioned previously, the samples subjected to the varied exposures should include materials of both high and low insulating qualities, inert materials, and those exhibiting ablative and dehydration processes. The following were selected for these purposes:

1) Purely Conductive Material

   a) A-26 Insulating Fire Brick -- When properly conditioned this material gives up no free moisture or combined water up to 2600°F.

2) Moisture Bearing Materials

   a) A-26 Brick with 10% water

b) A-26 Brick with 25% water

c) Plaster of Paris

3) Ablative Type Material

a) Metal Clad Wood

(A fire door type assembly which prevents the distilled combustible from burning at the sample face.)

4) Combustible Materials

a) Wood (Pine, D - Select Lumber)

(The same as that used in 3a)

b) High Density Particle Board

c) Low Density Fiberboard

Some properties of the materials are listed in Table 1. Each sample was approximately 16 inches wide by 24 inches high by 2 inches thick; and during exposure, it was held in a frame made from steel angles. To provide surface similarity and increase heat absorption, the exposed surface of each non-combustible sample was coated with ferric oxide. Several other "blacker" coatings were tried and discarded due to problems of surface adhesion or lack or high temperature stability. Fe_2O_3 is available as a fine powder which can readily be applied either dry or as a water or alcohol suspension.

The samples were conditioned for several weeks in a controlled atmosphere chamber at 75°F and 30-35 percent relative humidity. Conditions of 10 and 25 percent water content in

Table 1. Properties of Exposed Materials

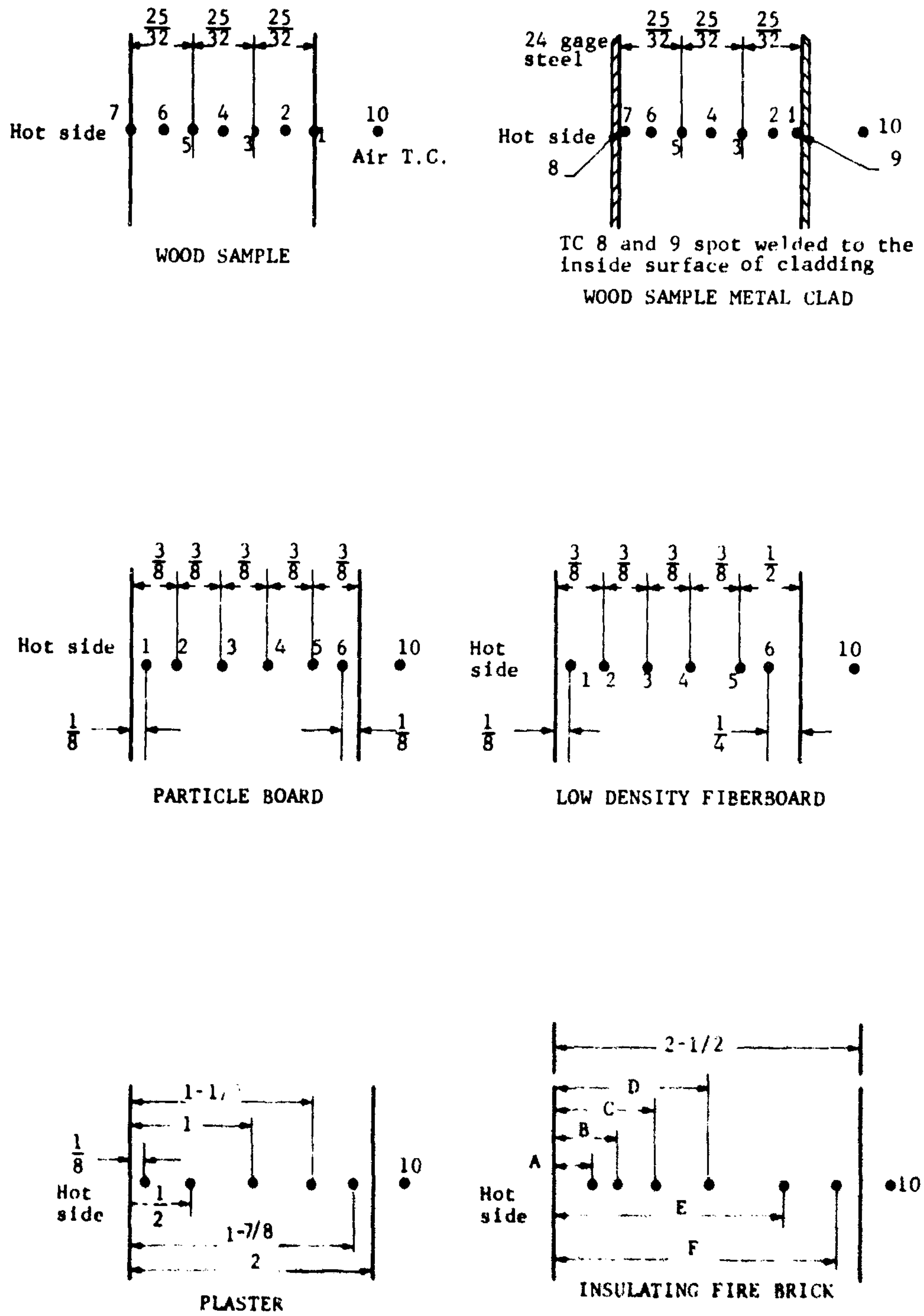
Material	Density lb/ft^3	Conductivity B-in/hrft^{2}F	Specific Heat B/lbF	Thermal Diffusivity ft^2/hr
Insulating Fire Brick	46.5	2.1	0.23	0.0164
Plaster	69.6	1.8	0.25	0.00862
Wood	27.6	2.1	0.34	0.0187
Particle Board	41.0	1.5	0.42	0.00726
Fiberboard	13.7	0.6	0.45	0.00811

the firebricks were achieved by adding the appropriate weight of water to each brick and allowing the assembly to set for several days in a plastic bag.

Chromel-alumel thermocouples were located near the center of each sample at various distances from the exposed face. Except for the plaster, thermocouples were located in 0.042 in. diameter holes, and were positioned to avoid conduction losses along the wires. The thermocouples were molded directly in the plaster samples. Locations of the thermocouples in the samples are shown in Fig. 2.

B. Experimental Apparatus

In order to obtain a uniform, controlled exposure, an infra-red lampbank was used.[2] This lampbank consists of 72 sixteen-inch lamps (lighted length) mounted in a double bank array 24 inches high. The lamps are nominally rated at 200 watts/inch at 300 volts. They can be operated at over-voltages and the present system has an upper limit of providing 30-35 cal/cm^2-sec. Regulation is obtained by an Ignitron power regulator, the control signal being provided by a Research Incorporated Model TC5192 Thermac Controller. The control signal is modified by a Research Inc. Model FGE5110 Data-Trak-curve - following programmer. Measurement of the flux level and feedback to the controller are obtained with two Hi-Cal Asymptotic Calorimeters.



BRICK	1	2	3	4
A	3/16	7/32	7/32	17/64
B	1/2	19/32	17/32	1/2
C	13/16	31/32	1-3/64	7/8
D	1-19/64	1-35/64	1-21/32	1-1/2
E	1-7/8	1-11/16	2-7/64	1-15/16
F	2-17/64	2-11/32	2-9/32	2-9/32

Fig. 2 LOCATION OF THERMOCOUPLES

The sample holder was mounted on a rack which allowed the holder to be moved in directions perpendicular and parallel to the lamps. Prior to each run a field calorimeter was placed at the front of the lamps to establish that the power output was at the desired level. Subsequently, the sample was moved in front of the lamps. After each sample exposure, the field calorimeter was again moved in front of the lamps and the exposure intensity checked before the lamps were turned off. Radiation that is emitted by the exposed sample surface when heated to high temperatures or (diffusively) reflected from it and then reflected from the lamp bank, is not present when the field calorimeter is used in the absence of the sample. However, since the controller uses the signal from a monitoring calorimeter, placement of this calorimeter near one edge of the lampbank permitted it to also receive a major portion of this "re-reflected" irradiance and accordingly to compensate by reducing the power to the lamps. Several experiments with the field calorimeter placed in a hole in the center of one of the dry brick samples showed the radiation level with the sample in place to be only 10% higher than that indicated by the bare calorimeter at a distance of 9 inches from the lamps (closest distance used). The correction became 12% at 24 inches from the lamps (the largest distance used) and was not sensitive to flux level. This correction, particularly since it was consistant, was considered insignificant. Figures 3a and 3b show the front and the back view of the sample holder and the rack, respectively.

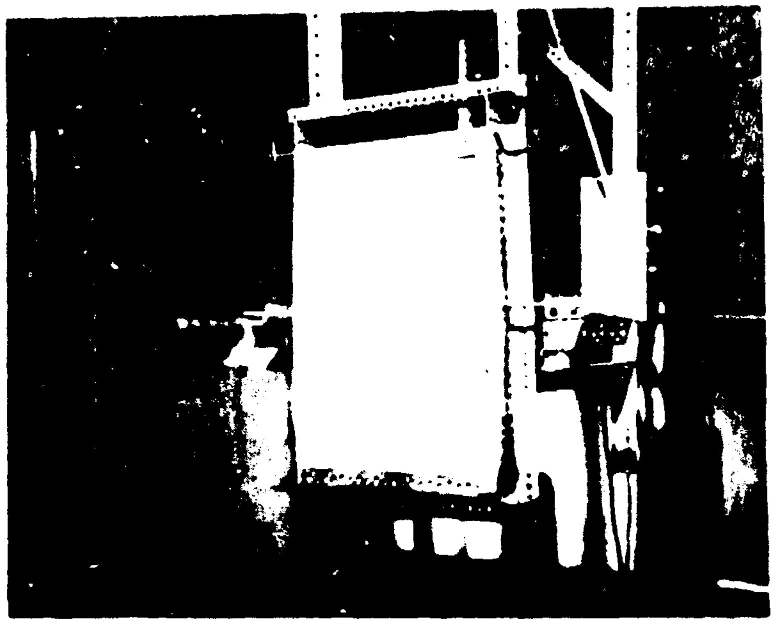


Fig. 3a FRONT VIEW OF SAMPLE HOLDER

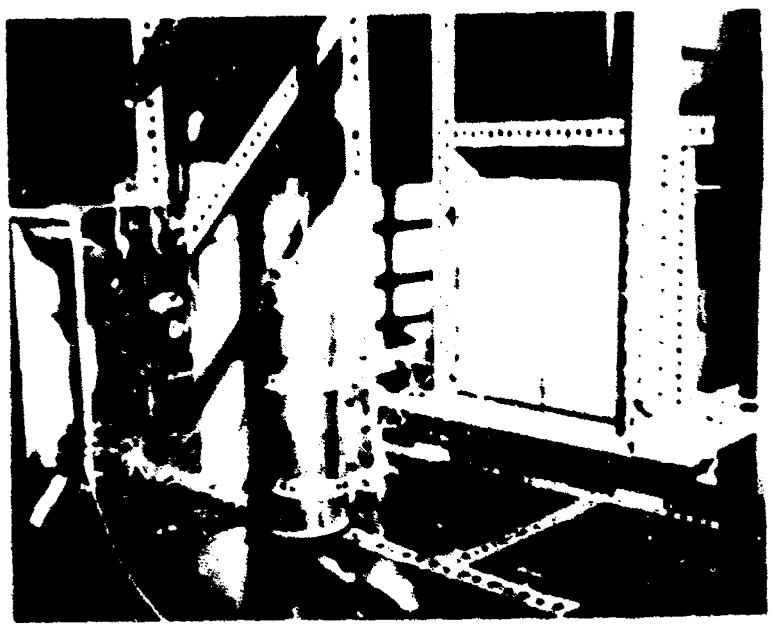


Fig. 3b BACK VIEW OF SAMPLE HOLDER

In Figure 3a the sample holder is moved to the side and the calorimeter is measuring the exposure level. Thermocouple wires leaving the material are visible in Figure 3b. Also visible in this figure is the thermocouple used to measure the ambient air temperature at the back of the sample. This thermocouple was located one-inch from the center of the back face. Aluminum foil shielded the ambient air thermocouple from the back surface of the sample.

IV. RESULTS

A. General Remarks

As indicated in the discussion of previous sections, the objective of this effort is to increase understanding of the material behavior under various heating conditions. For this purpose, both combustible and incombustible materials have been exposed to heat inputs ranging from very low values (0.1 cal $cm^{-2}sec^{-1}$), such as might be encountered from smoldering debris fires, up to very high values (8 cal $cm^{-2}sec^{-1}$) such as those thought possible in a mass fire. The materials have been selected to provide wide representations of physical properties. To reduce the number of parameters to be considered, only constant heat input has been used in these initial studies. Exposures considered with each material are indicated in Table 2.

For determination of fire resistance ratings, two aspects are of main interest; namely, the integrity of the material and the temperature of the back surface. Both criteria

Table 2 Summary of Experiments

Exp. No.	Material	Exposure Flux cal $cm^{-2}sec^{-1}$	Exp. No.	Material	Exposure Flux cal $cm^{-2}sec^{-1}$
14	Particle Board	0.11	19	Brick (1)*-Dry	0.54
9	Particle Board	0.49	21	Brick (1)-Dry	1.04
8	Particle Board	0.51	28	Brick (1)-Dry	4.7
3	Particle Board	1.00	30	Brick (1)-Dry	4.7
4	Particle Board	1.04	29	Brick (3)-Dry	4.77
36	Particle Board	4.80	41	Brick (1)-Dry	6.61
15	Wood	0.11	24	Brick (3)-10%	0.51
10	Wood	0.47	27	Brick (3)-10%	1.03
11	Wood	0.49	31	Brick (2)-10%	4.8
6	Wood	1.01			
5	Wood	1.05			
35	Wood	4.8			
18	Metal Clad Wood	0.52	26	Brick (1)-25%	0.51
17	Metal Clad Wood	1.00	45	Brick (3)-25%	0.506
34	Metal Clad Wood	4.8	46	Brick (3)-25%	0.50
44	Metal Clad Wood	7.6	47	Brick (3)-25%	0.53
			25	Brick (2)-25%	1.02
			32	Brick (3)-25%	4.91
16	Fiberboard	0.11	23	Plaster	0.51
13	Fiberboard	0.50	22	Plaster	1.00
12	Fiberboard	0.51	20	Plaster	1.02
7	Fiberboard	1.05	33	Plaster	4.9
37	Fiberboard	4.76	42	Plaster	8.04
38	Fiberboard	4.80			

* Number in parenthesis as in BRICK (1) refers to thermocouple location shown in Fig. 2; percentage refers to the moisture, and "dry" to conditioning at 30-35% RH

were evaluated in the experiments. However, in these experiments, the sample was held by a steel frame in a different manner than that used in standard fire resistance tests. Therefore, only measured back-surface temperatures and visible burn-through provide information about the effect of heating rate on the standard fire-resistance rating. The variations with time of these temperatures are shown in Figs. 4a, 5a, 6a, 7a, 8a, 8b, and 9a*. Also, the time variations of the exposed surface are shown in Figs. 4b, 5b, 6b, 7b, 8c, 8d, 9b and 9c. It must be noted, however, that except for the back surface of the wood samples, the temperatures shown were measured at some distance below the surfaces (see Fig. 2). For this reason the actual temperatures of the back surface are lower and of the front surfaces higher than the temperatures indicated. This means that the customary allowable maximum temperature rise of 250°F for the back surface would have been reached at somewhat later times than shown by the data. Since the main objective of the experiments is to study the effect of exposure level and moisture content on the temperature within the materials, the reference points used are of no consequence.

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* Figures 4 through 9 are shown in Appendix A.

B. <u>Temperatures Near the Surfaces of Irradiated Materials</u>

1. Particle Board

Particle board is the most dense combustible material considered. For exposures less than 0.5 cal/cm^{2}sec the material distilled without visible charring. Pilot ignition was possible after 1.5 minutes of exposure to 1.04 cal/cm^{2}sec. When irradiated with 4.8 cal/cm^{2}sec particle board flamed spontaneously after 11 seconds.

The temperature distributions as functions of time at 1/8-inch distances from the unexposed and exposed surface are shown in Fig. 4a and 4b, respectively. The lowest exposure level, 0.11 cal cm^{-2}sec^{-1}, produced a gradual temperature rise at the back surface to about 160°F. For the irradiance levels of 0.51 and 1.04 cal cm^{-2}sec^{-1}, however, plateaus occured in the time-temperature curves between 180° and 200°F. Such plateaus are characteristic of materials with moisture evaporating at the back surface. This phenomenon is much more apparent in the data shown later for the insulating brick. In the case of the particle board, the moisture was apparently driven to the unexposed surface where it evaporated. However, at the highest irradiance level (4.8 cal cm^{-2}sec^{-1}), the amount of heat transmitted was so large that any cooling due to moisture evaporation had only negligible effect on the temperature.

2. Wood

Wood samples were exposed to energies ranging from 0.11 to 4.8 cal/cm^{2}sec. For exposures of 0.49 cal/cm^2-sec pilot ignition occured after 3 min. 40 sec. Irradiance levels of 0.47 cal/cm^2-sec produced spontaneous ignition after 57 minutes. When the exposure intensity was increased to 1.05 cal/cm^2-sec spontaneous ignition took place after 3 min. 40 sec. At 4.8 cal/cm^2-sec only seven seconds were required to ignite the wood. These times agree well with those reported in the literature.

In wood, the temperature distribution may be affected by decomposition and burning at irradiation levels greater than about 0.4 cal cm^{-2}sec^{-1}. Such effects are seen in Fig. 5a and 5b for experiments with 0.47 and 0.49 cal cm^{-2} sec^{-1} exposures. The markedly higher temperatures attained with 0.49 cal cm^{-2}sec^{-1} irradiant energy can be attributed to the actual flaming of the wood, whereas at 0.47 cal cm^{-2} sec^{-1} the material was smoldering only. Nevertheless, since similar behavior may occur in actual structures, the temperatures shown give a representative range of expected values.

For the radiation level of 0.11 cal cm^{-2} sec^{-1} the temperature of the unexposed surface reached 131°F after 180 minutes, and this temperature seems to correspond to nearly steady-state conditions. It agrees well with the temperature of 135°F which one calculates assuming that distillation and moisture migration do not occur.

At a radiation level of 4.8 cal cm^{-2} sec^{-1}, (Fig. 5a) the back-surface temperature was 260°F after about 27 minutes, and the wood was also penetrated by the fire after 28 minutes.

Loss of wood integrity occurred prior to the unexposed surface reaching 250°F at the lower irradiance levels. If the burning rate follows the equation R = 0.09 $lb/ft^2 min$*, the time required for the sample to be consumed by the fire is 60 minutes. This is approximately the average time required for disintegration of wood when exposed to 0.49 and 1.05 cal $cm^{-2} sec^{-1}$.

3. Metal Clad Wood

The metal clad wood was used since it resembles fire door construction and provides a sample with distillation but no cumbustion at the hot face. At any particular location the temperature rose gradually until active distillation or burning took place. Similar situations existed during the exposure of unclad wood. For this reason, prior to the penetration of unclad wood by fire the temperatures (Fig. 6a) of the unexposed surfaces do not differ greatly for wood with and without cladding. The main difference is in the time at which the sample loses its integrity.

4. Low Density Fiberboard

The fiberboard has the lowest density and thermal conductivity of the materials used. When exposed to 0.51 cal/cm^2-sec the front surface charred completely within 6 minutes. For energies of 1.05 cal/cm^2- sec spontaneous ignition occurred after 26 seconds, and at 4.8 cal/cm^2-sec after five seconds.

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* This burning rate is typical of wood barriers exposed to well ventilated room-fires.

The temperature of the exposed surface rose very rapidly for exposures above 0.5 cal cm^{-2} sec^{-1} (see Fig. 7b). This steep temperature rise was also sensed by the unexposed surface as can be seen from Fig. 7a. At 4.8 cal cm^{-2} sec^{-1}, the time when the unexposed surface rose 250°F above the ambient temperature was about the same as the time when the material was penetrated by the fire.

5. Insulating Fire Brick

Figure 8a shows the time-temperature curves for the unexposed surface of brick conditioned at 30 percent relative humidity. The temperature profiles are essentially those which would be expected from theoretical consideration of heat conduction with no migration of moisutre.

The effect of moisture content of the brick is shown in Figs. 8a and 8b. All samples containing 10 and 25 percent water have shown characteristic plateaus in the temperature histories of the unexposed surface. The extent and the temperature level of the plateaus seem to be functions of the moisture content and of the exposure intensity.

It is of interest to note from Fig. 8b that back-face temperatures of bricks containing a large quantity of moisture may even decrease with time during a portion of the exposure. This can be attributed to the moisture being driven toward the back surface where it evaporates and cools the surface. This hypothesis was verified by experiments in which the moisture loss at the back face was prevented by an aluminum-foil vapor barrier. With the vapor-barrier present, the temperature of the back face never underwent a decrease with time.

6. Plaster

Temperature histories near the unexposed surfaces of plaster show characteristics similar to those obtained with insulating fire bricks containing 10 and 25 percent of moisture. In the case of plaster, however, as may be noted from Fig. 9a, more than one plateau can occur in each time-temperature curve. This probably comes about because plaster contains chemically combined water as well as free moisture.

C. Theoretical Calculations

The temperature distributions within the materials were calculated assuming that: 1) the physical properties remain constant, 2) no heat generation or absorption takes place and 3) materials are not transparent. Since the change in physical properties with the temperature can be substantial, the calculations must be considered to give approximate values only. The problem has been formulated by postulating one dimensional heat flow through a slab exposed on one side to a constant radiative souce Q (cal cm^{-2} sec^{-1}) and losing heat on both sides by both radiative and convective processes. Because the radiative boundary condition is nonlinear the problem could not be solved analytically and a finite difference method was used. Computation wer performed using the IBM 7094 computer.

Comparison between the calculated and measured temperatures of the unexposed surface of the dry brick is given in Fig. 10. The agreement is better for lower values of Q, which indicates only that the values of thermal properties used in the analysis were most appropriate for the lower temperatures. The same order of agreement between calculated and measured temperatures was also obtained for the particle board, wood, and fiberboard exposed to 0.11 $cal/cm^2 sec$.

An attempt was made to determine which of the constant fluxes used in the experiments would produce temperatures near the unexposed surface similar to those produced by a furnace programmed to follow the standard time-temperature curve. The standard time-temperature curve may be expressed as follows[3]:

$$T = 400 \cdot \log [313.8 (t - 4)], \quad t < 2 \text{ hr} \qquad (1)$$

$$T = 1.25 \cdot t + 1700 \qquad t > 2 \text{ hr} \qquad (2)$$

where T is temperature in °F and t is time in minutes. The heat input to brick exposed to a standard E 119 furnace test was calculated from Eqs. 1 and 2 under the assumption that the gas flame has an emittance of 0.2 and transfers energy to the

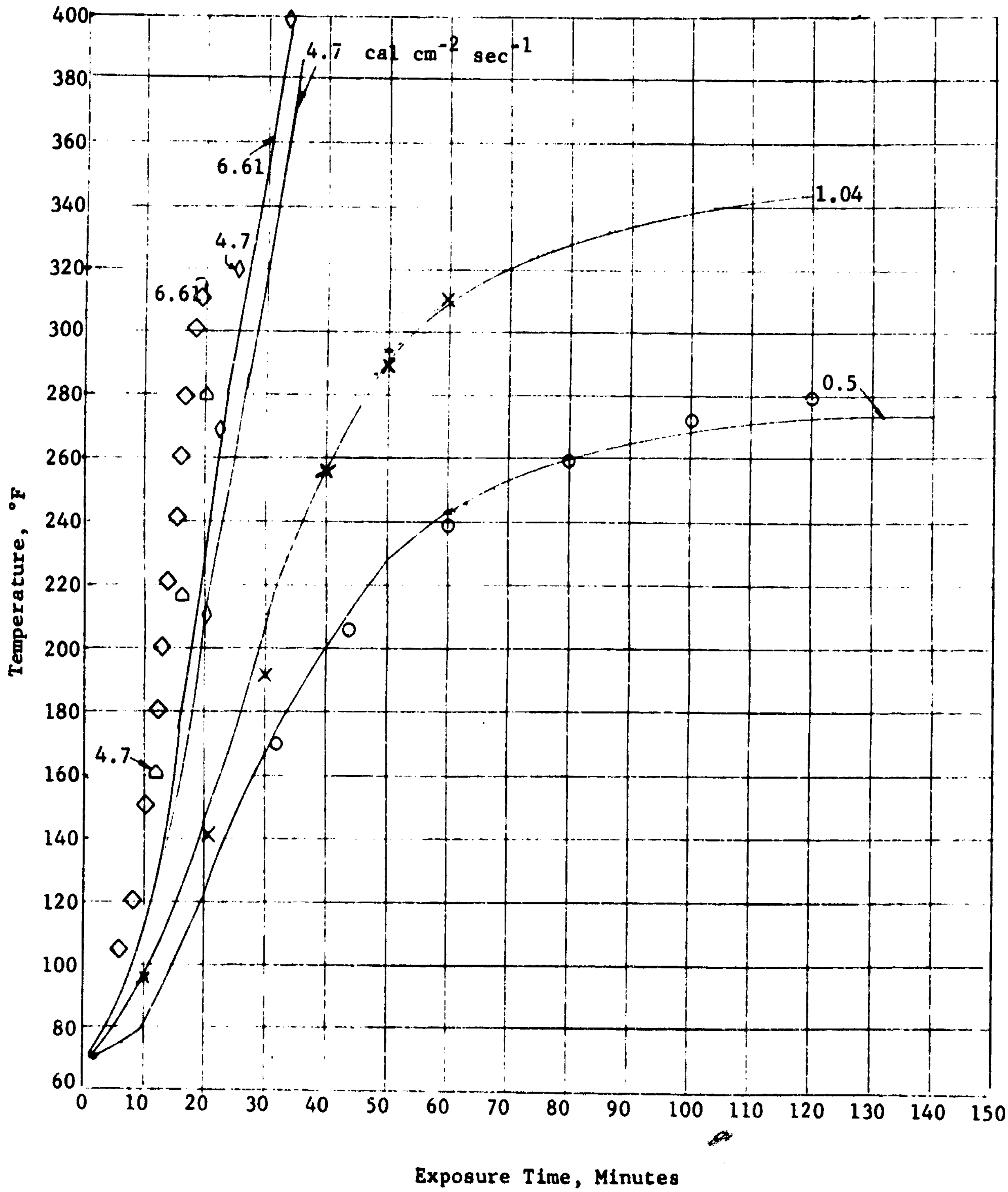

Fig. 10 INSULATING BRICK - THEORETICAL CURVES AND EXPERIMENTAL POINTS FOR TEMPERATURES NEAR UNEXPOSED SURFACE

brick by radiation and free convection. This heating rate was then used to calculate the time-temperature history of brick exposed to furnace conditions. Temperatures of the unheated surface of the brick thus calculated agreed well with the experimental data obtained with a heat input of 0.5 cal/cm^{2}sec for the first hour, as shown in Fig. 11. The agreement was not as good for the temperatures near the exposed surface. This probably results from changes in physical properties of the material due to the elevated temperatures near the exposed surface.

D. Discussion of Results

The objective of the performed experiments is to determine the relationship between fire resistance ratings corresponding to different fire exposure. In this discussion, the fire resistance rating refers to the time when the temperature of the unexposed surface rises 250°F above the ambient temperature. For combustible materials the experiments have indicated that this time is about the same as when fire penetration takes place.

There are several possible approaches which come to mind to reach the goal outlined above, i. e. to express the fire resistance as a function of exposure intensity. It seems logical, however, to investigate first whether the exposure equivalence concept proposed by Ingberg[(1)] could be utilized. According to

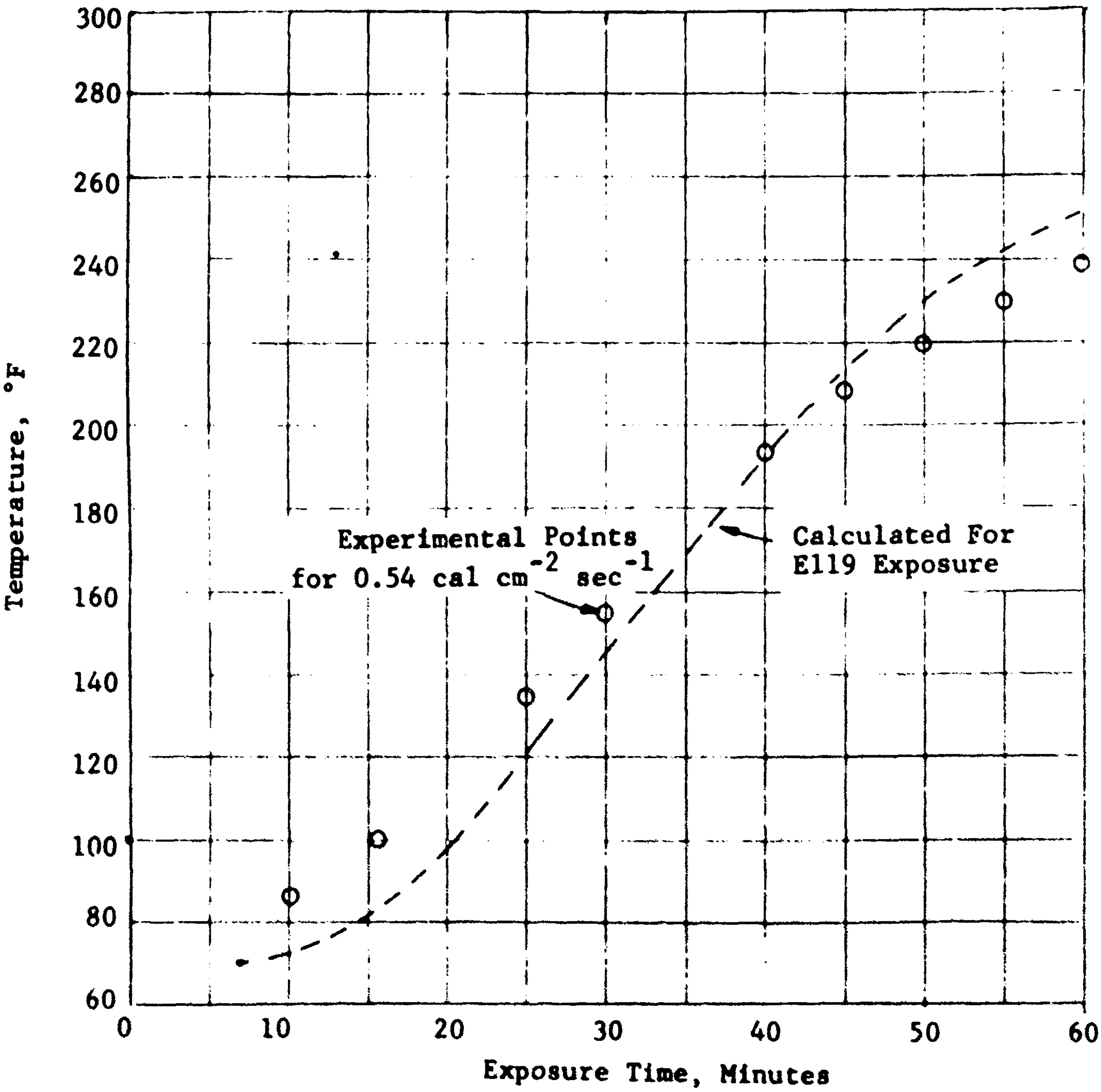

Fig. 11 INSULATING BRICK - TEMPERATURE NEAR UNEXPOSED SURFACE FOR EXPOSURE TO HEATING ACCORDING TO THE STANDARD TIME TEMPERATURE CURVE

this concept, the area under the time-temperature curve is indicative of the exposure severity. Based on this assumption the fire resistance ratings for any exposure can be determined by equating the area under the standard time-temperature curve to that of the exposure considered.

The simplicity of this procedure makes the area equivalence concept very attractive for general use. However, as already pointed out by Ingberg, theoretical considerations suggest that the expression of fire severity in terms of the area under time-temperature relationship is an approximation only. How accurate the method is can be determined from the analysis of experimental data obtained. Individual steps of the performed analysis are indicated in Table 3.

First, corresponding to each exposure (q) considered, the equivalent temperature (t) is calculated assuming that the exposure is from a radiating black body. Second, using these equivalent temperatures (Column 2) and the experimentally determined fire resistance ratings (t, Column 3), the areas under the time-temperature curve above a base of 68°F are evaluated (Column 4).

The areas under the time-temperature curve above base lines suggested by Ingberg (302°F for combustible samples and 572°F for non-combustible samples) are listed in Column 5. For the equivalent area concept to be applicable, the values shown in Column 5 (or Column 4 if 68°F base is assumed correct)

Table 3 AREA UNDER THE TIME TEMPERATURE CURVE

Column	1	2	3	4	5	6	7	8
Material	Exposure, q, cal/cm^2-sec	Equivalent Exposure Temperature, T, °F	Actual Fire Resistance Rating, t, min	$\int_0^t (T(t)-68) \cdot dt$ °F · min	$\int_0^t (T(t)-A^*) \cdot dt$ °F · min	$\frac{(T-A)t-(T-A)_1 t_1}{(T-A)_1 t_1}$	$\frac{qt - q_1 t_1}{q_1 t_1}$	$\frac{t-t_1}{t_1}$
						(Subscript 1 refers to values of $q = 1$ cal/cm^2-sec)		
Particle Board	0.51	952	60	53,040	39,000	-0.02	-0.30	+0.36
	1.00	1,210	44	50,248	39,952	0	0	0
	4.80	2,010	21	40,782	35,868	-0.10	+1.29	-0.52
Wood	0.49	937	77	66,913	48,895	+0.05	-0.28	+0.54
	1.05	1,231	50	58,150	46,450	0	0	0
	4.80	2,010	28	54,376	47,824	+0.03	+1.56	-0.44
Fiber Board	0.51	952	32	28,288	20,800	-0.07	-0.35	+0.33
	1.05	1,231	24	27,912	22,296	0	0	0
	4.80	2,010	10	19,420	17,080	-0.23	+0.90	-0.58
Steel Clad Wood	0.52	962	Over 280	--	--	--	--	--
	1.00	1,210	138	157,596	125,304	0	0	0
	4.80	2,010	28	54,376	47,824	-0.62	-0.03	-0.80
	7.60	2,310	9	20,176	18,072	-0.86	-0.50	-0.93
Brick - Dry	0.54	972	Over 180	--	--	--	--	--
	1.04	1,225	73	84,461	47,369	0	0	0
	4.70	1,998	25	48,250	35,650	-0.25	+0.55	-0.66
	6.61	2,215	20	42,940	32,860	-0.31	+0.74	-0.73
10% H_2O	0.51	952	Over 180	--	-	--	--	--
	1.03	1,222	116	133,864	75,400	0	0	0
	4.80	2,010	37	71,854	53,206	-0.29	+0.49	-0.68
25% H_2O	0.51	912	Over 180	--	--	--	--	--
	1.02	1,218	120	138,000	77,520	0	0	0
	4.91	2,025	48	93,936	69,744	-0.10	+0.93	-0.60
Plaster	0.51	952	Over 420	--	--	--	--	--
	1.00	1,210	Over 300	--	--	--	--	--
	4.90	2,023	134	261,970	194,434	--	--	--
	8.04	2,350	12	27,384	21,336	--	--	--

* Combustible Samples: A = 302°F
Non-Combustible Samples: A = 572°F

should be the same for each material considered. Deviations obtained in Column 5 are shown in Column 6. As indicated by Column 6, the area under the curve concept appears reasonable for combustible samples but produces errors ranging from about 10 to 30 percent for non-combustible samples containing free moisture. The errors are considerably larger when materials contain both free and chemically-combined water. This is exemplified by the vast differences between areas under the time-temperature curve for plaster shown in Column 5 of Table 3. Metal cladding presents situations beyond the prediction capabilities of the area equivalence concept which shows errors ranging from 62 to 86 percent.

Substantial discrepancies are obtained when the attempt is made to correlate the data using the heat fluxes. Column 7 lists a set of differences for this type of data reduction.

Since a sufficient number of experiments was not possible within the scope of this program to evaluate the effects of all pertinent parameters, the data has been reduced in the form of time differences obtained. This correlation is plotted in Fig. 12. Agreement for the various materials is quite good at lower values of exposure intensity. The exposure of 4.8 cal/cm^2sec seems to have the same effect on the fire resistance of insulating brick regardless of the moisture content. The data for combustible materials at this irradiance level show considerable scatter which can in part

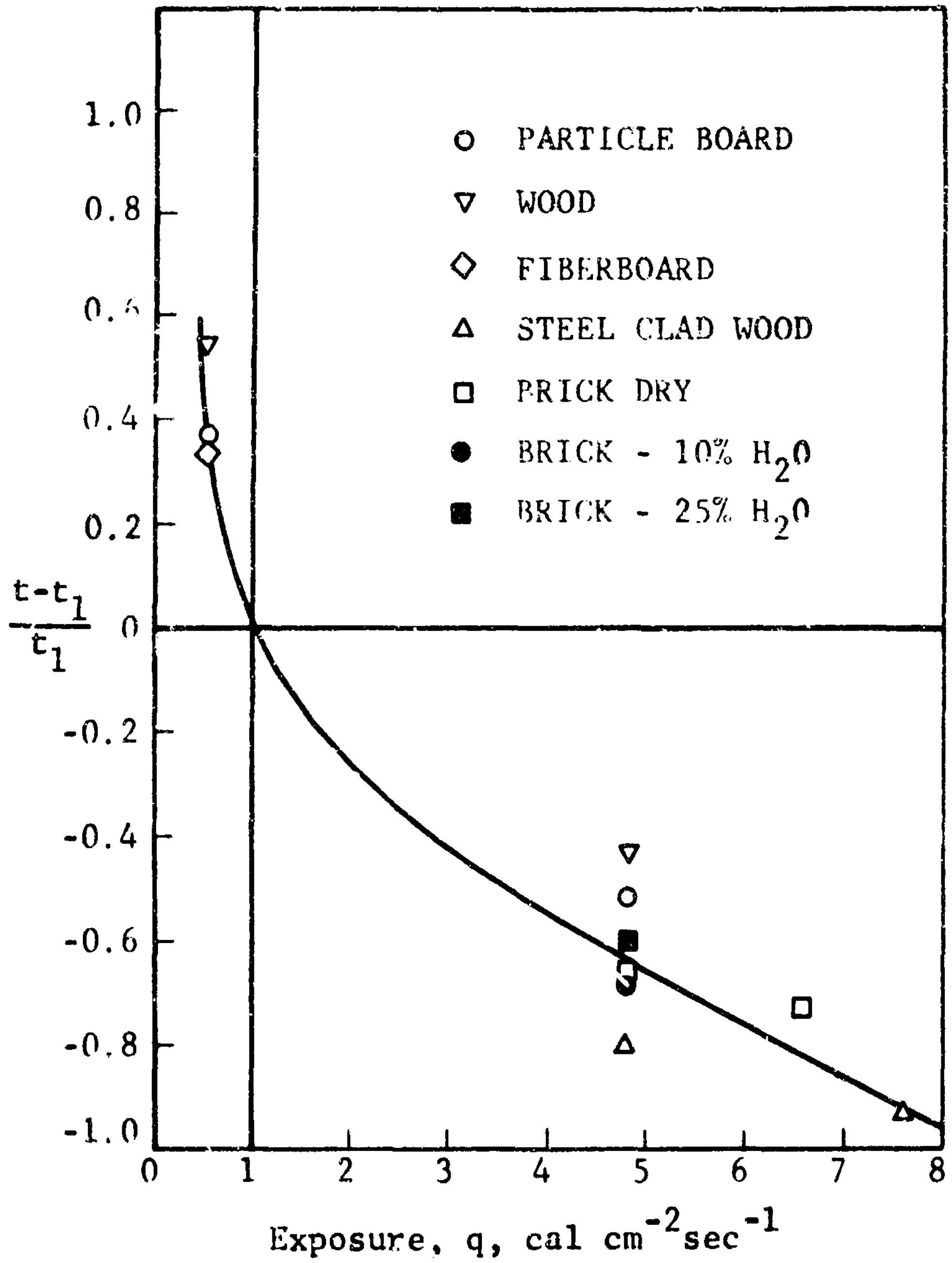

Fig. 12. EFFECT OR EXPOSURE INTENSITY (q) ON THE FIRE RESISTANCE RATING TO THE BASE OF $q = 1$ cal $cm^{-2}sec^{-1}$

be explained by the changes in integrity of the exposed surface which may have occurred. It is realized, however, that this scatter is probably also due to other parameters which cannot be evaluated at this point. Nevertheless, the graph of Fig. 12 does provide the general expected trend of the effect of exposure intensities on the fire resistance rating of various materials.

V. CONCLUSIONS

As stated previously the study performed constitutes only the first step toward establishing absolute rating of shelter components. Toward this end the study has brought to light several important findings which are summarized below:

1. Fire resistance of a barrier is considerably affected by the intensity of the exposure. Although this effect is a complicated function of various parameters, for homogeneous combustible materials it can be approximately expressed in terms of the area equivalence method suggested by Ingberg(1). For homogeneous non-combustible materials (containing free water) this method produced errors ranging from 10 to 31 percent. The error is substantially larger for materials containing both free and chemically-combined water, as in plaster. In the case of non-homogeneous material, the area equivalence concept introduced errors ranging from 62 to 86 percent.

2. A definite trend of data is indicated when fire

resistance rating is plotted as the function of exposure intensity. Correlation is better at lower intensities.

3. Exposure intensities on the level of 0.1 cal/cm^2sec, which may be found in debris fires, do not appreciably affect the integrity of the barrier. However, the temperatures reached by the unexposed surface may still be too high for the environment of the shelter.

4. For moderate heating, (less than 1 can $cm^{-2}sec^{-1}$), of materials containing relatively small amounts of moisture, heat-conduction theory predicts temperature distributions within 20 percent of those obtained from experiments. Agreement between theory and experiment becomes less satisfactory as either the moisture content or the heating intensity increases.

VI. RECOMMENDATION FOR FUTURE WORK

The results of the performed experiments indicate the need for expressing the fire resistance rating of materials in terms of pertinent parameters. To reach this objective, it is proposed that experiments be conducted using a limited number of materials whose properties and exposures can be systematically varied.

The incremental variation in the sample properties could be obtained by employing synthesized materials manufactured in the laboratory. Such materials may be produced by using combustible and incombustible constituents, for example, wood shaving and alumina. By proportioning these constituents, desired incremental variations in material properties can be achieved.

At low exposure levels, the existing lamp facility seems to be appropriate. The frequent required replacement of the lamps at high exposure levels suggests the use of a more economical source such as Globars. Since both sources produce radiative heating only, the gas type exposure will be necessary to evaluate the effect of the convective heat input to the sample materials.

The proposed systematic evaluation of the parameters and the processes affecting the temperature distribution within the materials, will provide the necessary basis for developing an absolute fire resistance rating. The knowledge obtained will also indicate the relationship between existing standard ratings and those of actual fire. This information is needed for evaluating the fire protection provided by shelter components under various fire exposures which may result from a nuclear attack.

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3. "Standard Methods of Fire Tests of Building Construction and Materials", NFPA No. 251, 1963 National Fire Codes, Vol. 4, 1963-64.

APPENDIX A

Figures 4a Through 9c

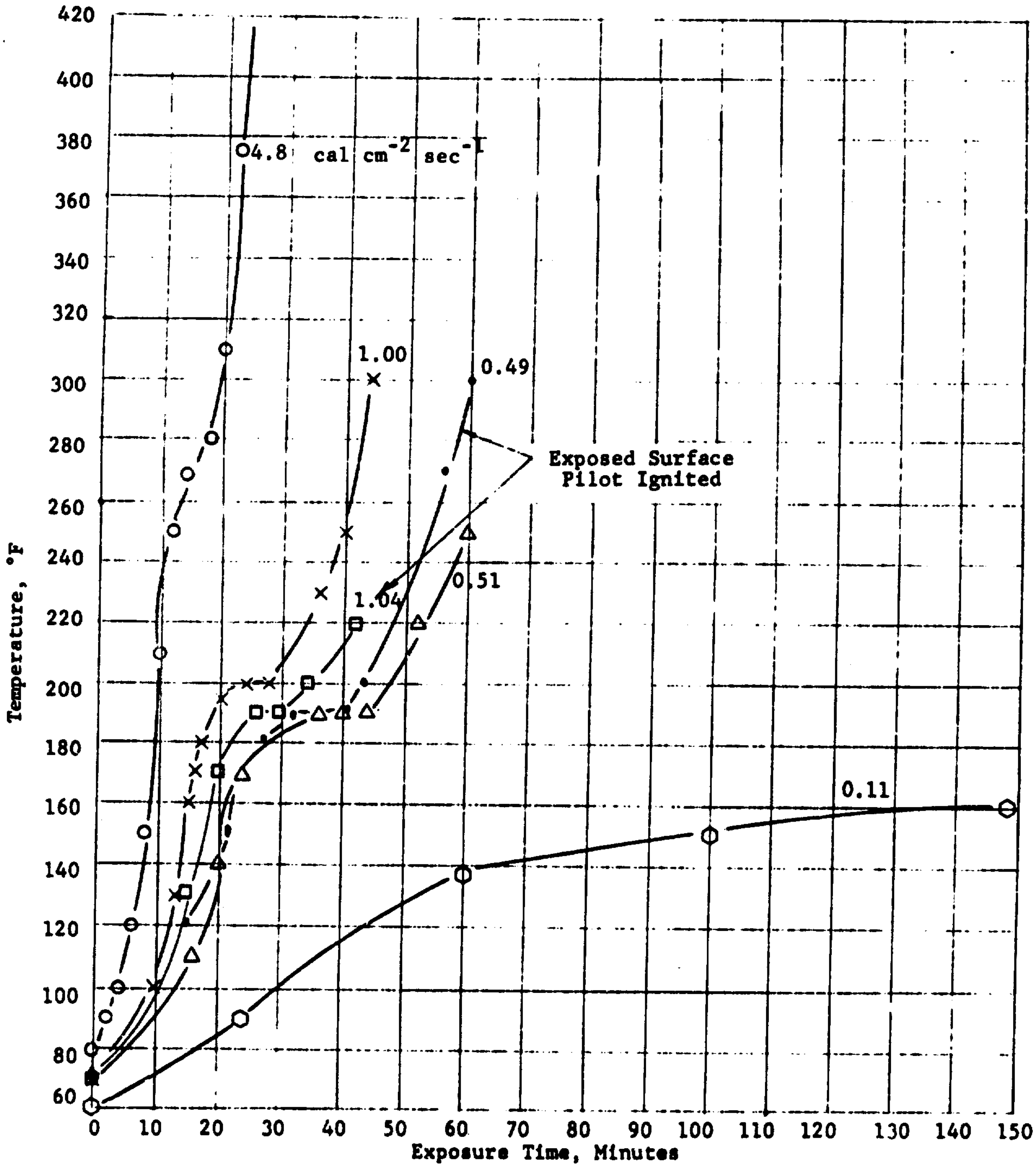

Fig. 4a PARTICLE BOARD - TEMPERATURES 1/8-in. FROM UNEXPOSED SURFACE

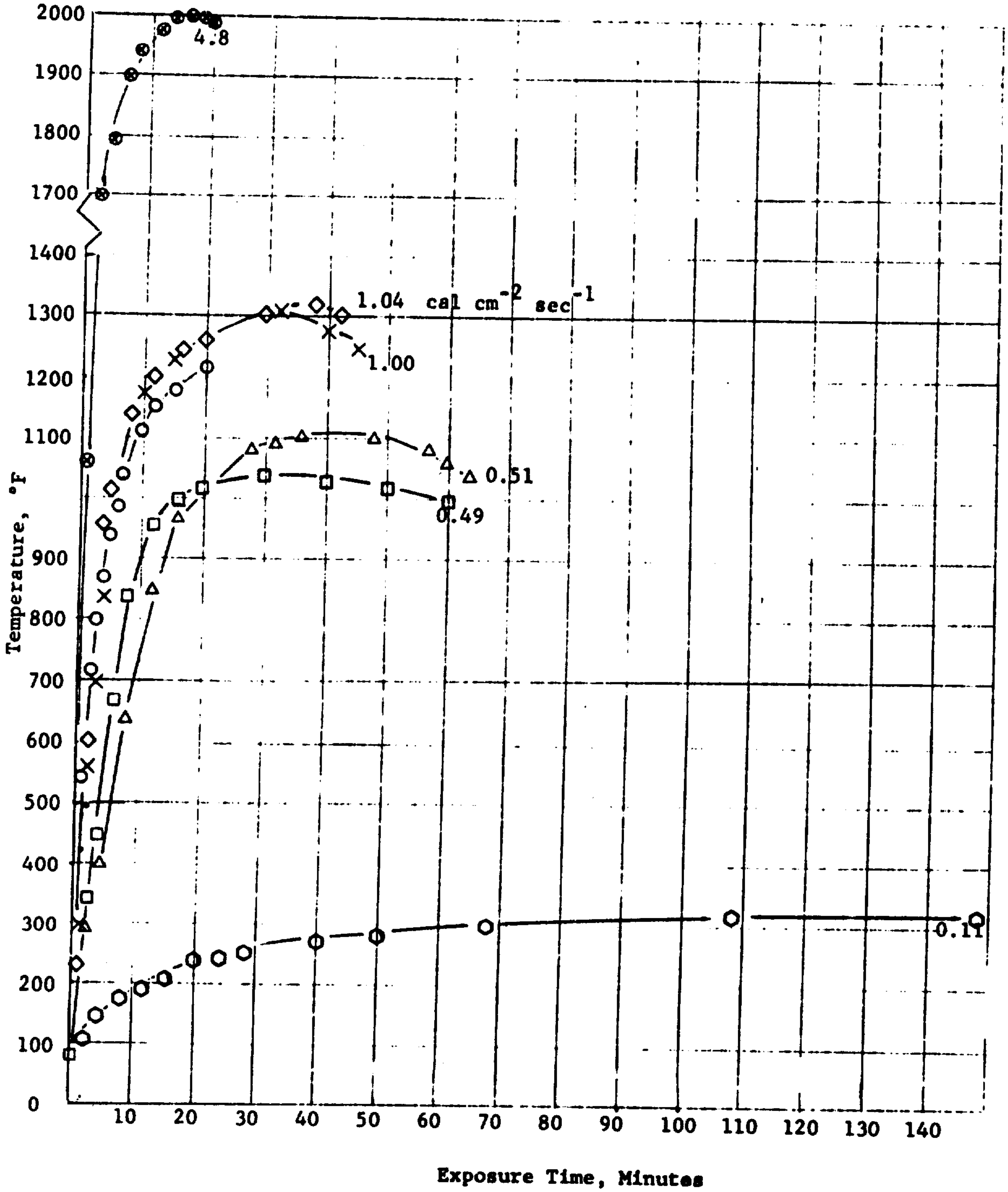

Fig. 4b PARTICLE BOARD - TEMPERATURES 1/8-in. FROM EXPOSED SURFACE

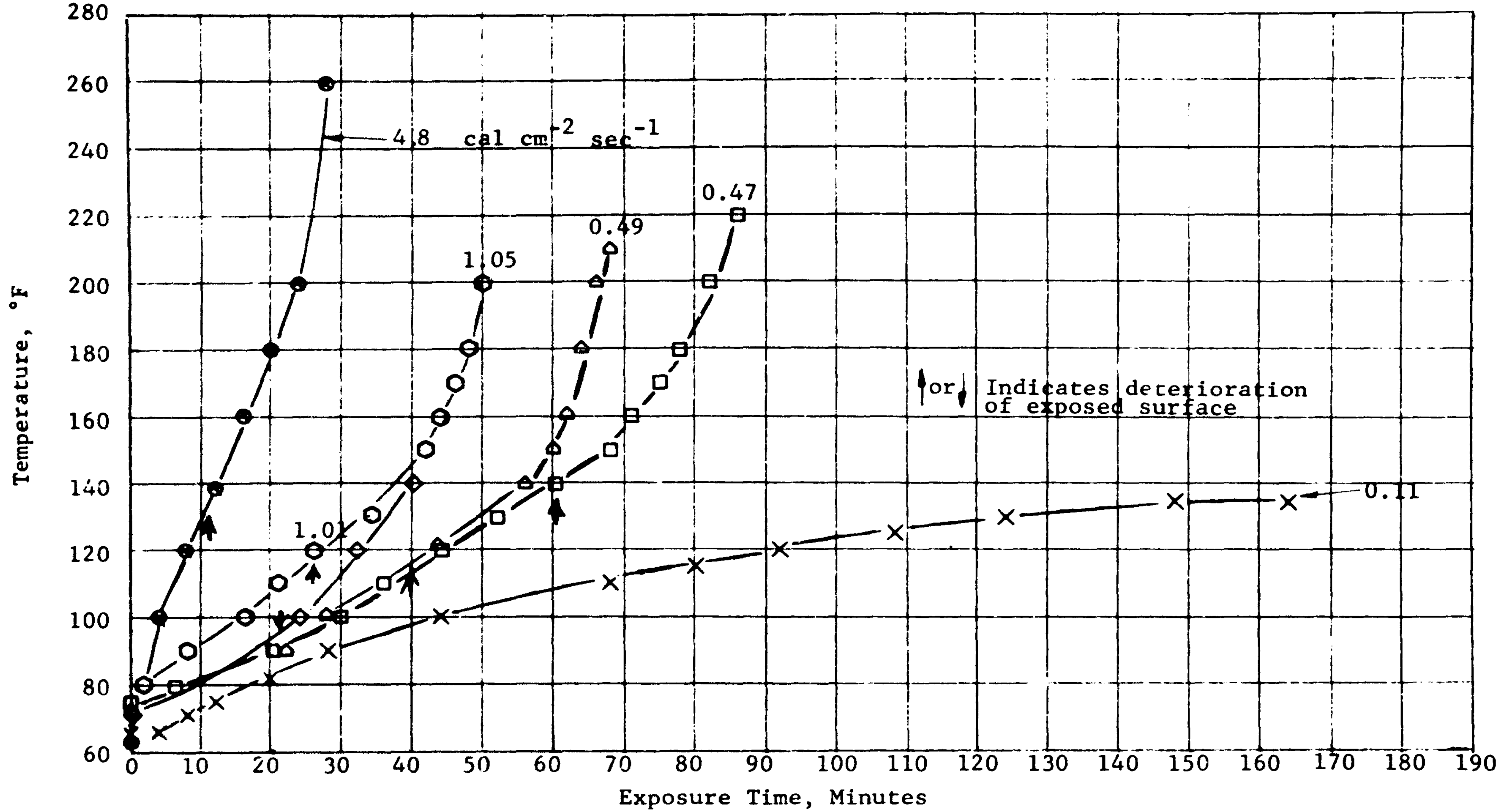

Fig. 5a WOOD SAMPLE - TEMPERATURES OF THE UNEXPOSED SURFACE

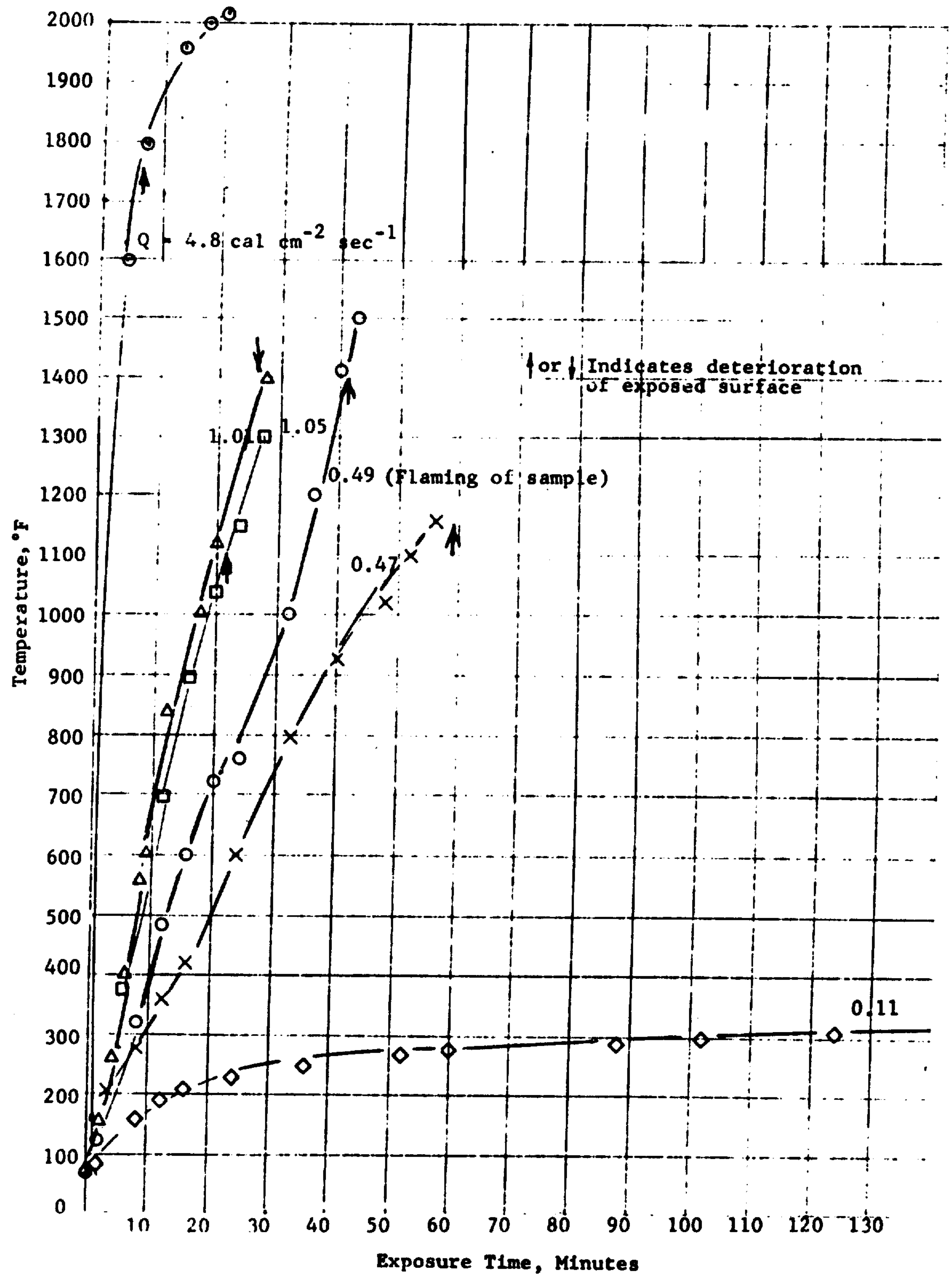

Fig. 5b WOOD SAMPLE - TEMPERATURES 25/64-in. FROM THE EXPOSED SURFACE

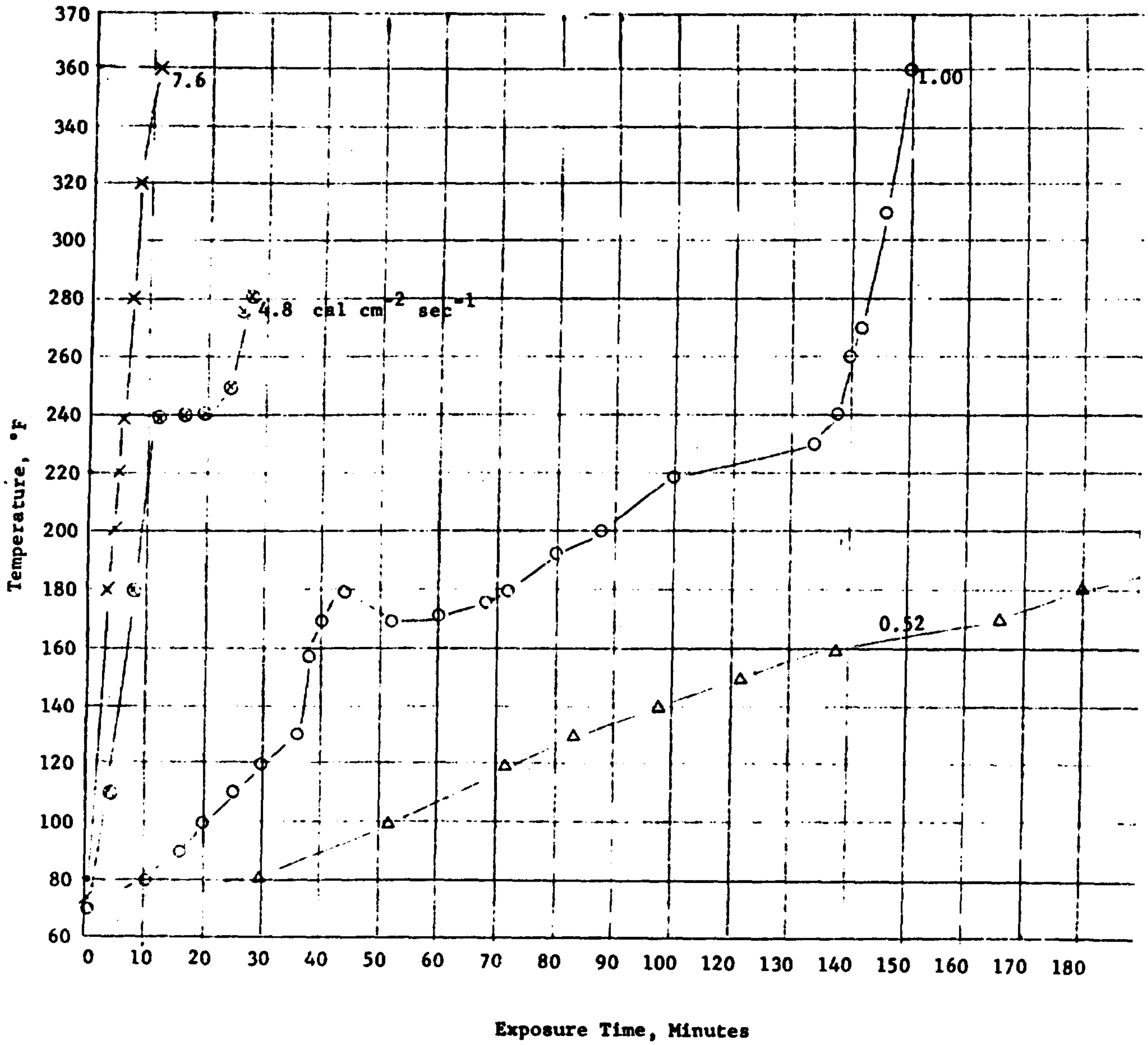

Fig. 6a SHEET METAL CLAD WOOD - TEMPERATURES OF UNEXPOSED SURFACE

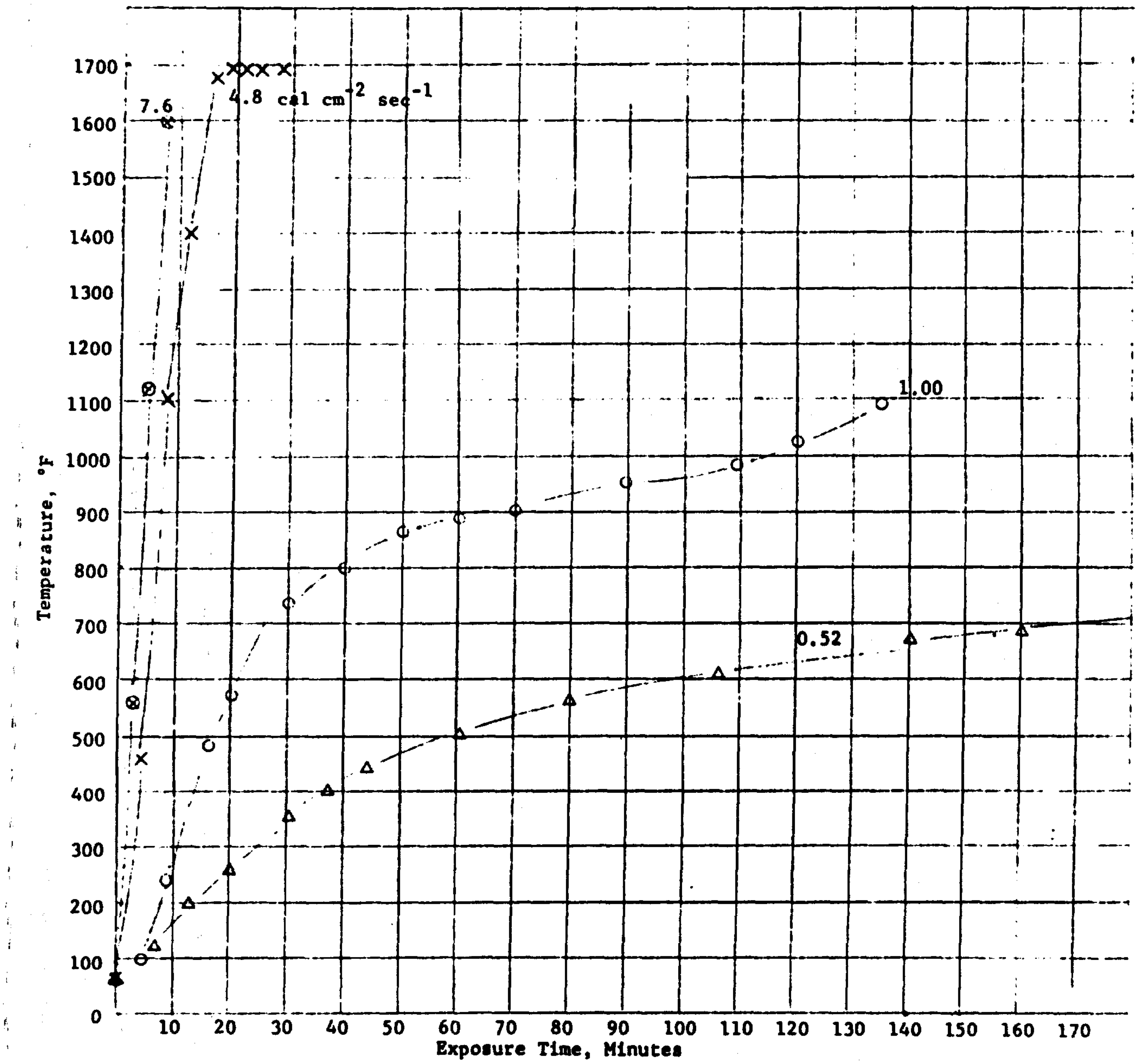

Fig. 6b SHEET METAL CLAD WOOD - TEMPERATURES OF EXPOSED SURFACE

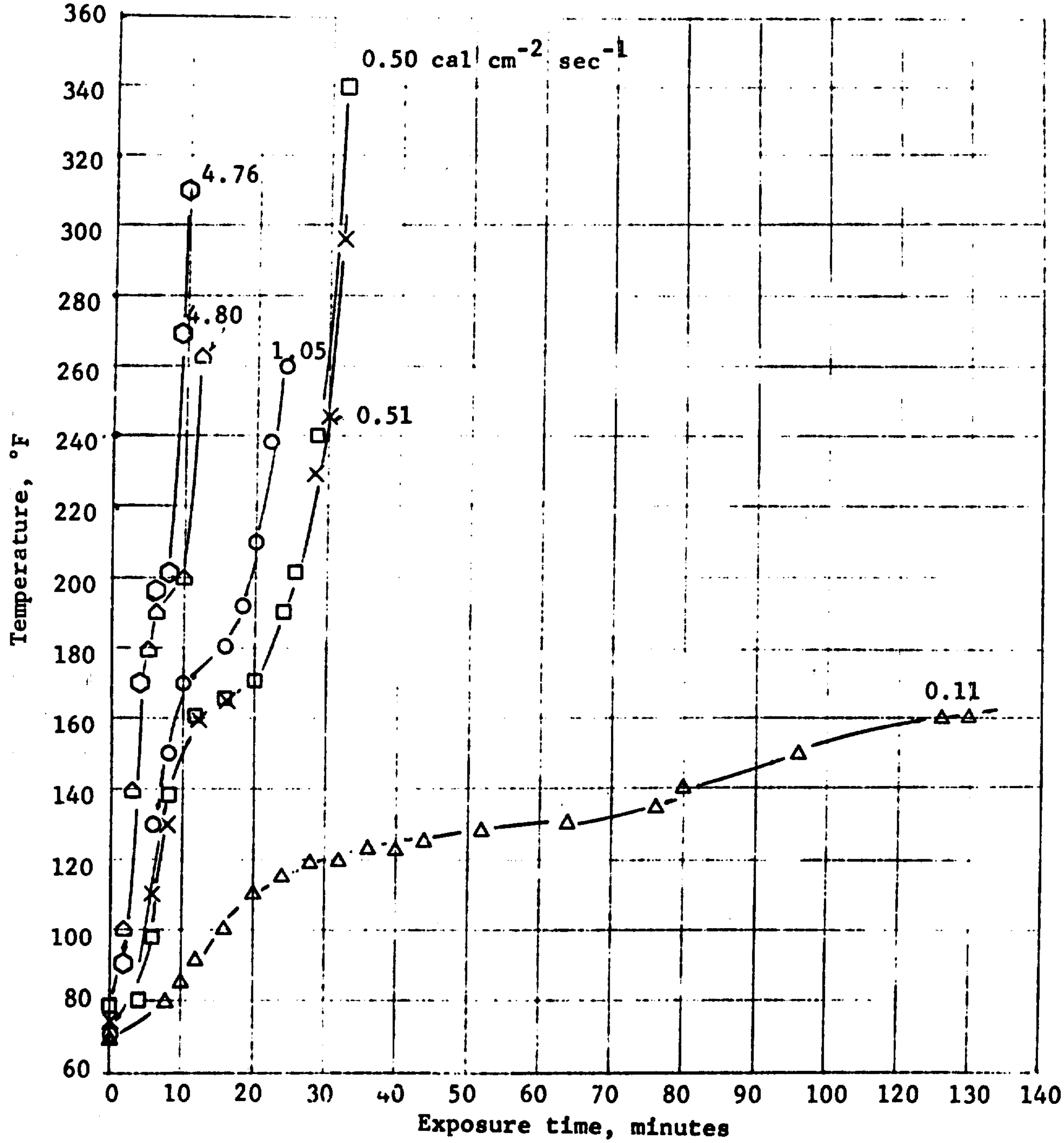

Fig. 7a LOW DENSITY FIBERBOARD - TEMPERATURES 1/4-in. FROM THE UNEXPOSED SURFACE

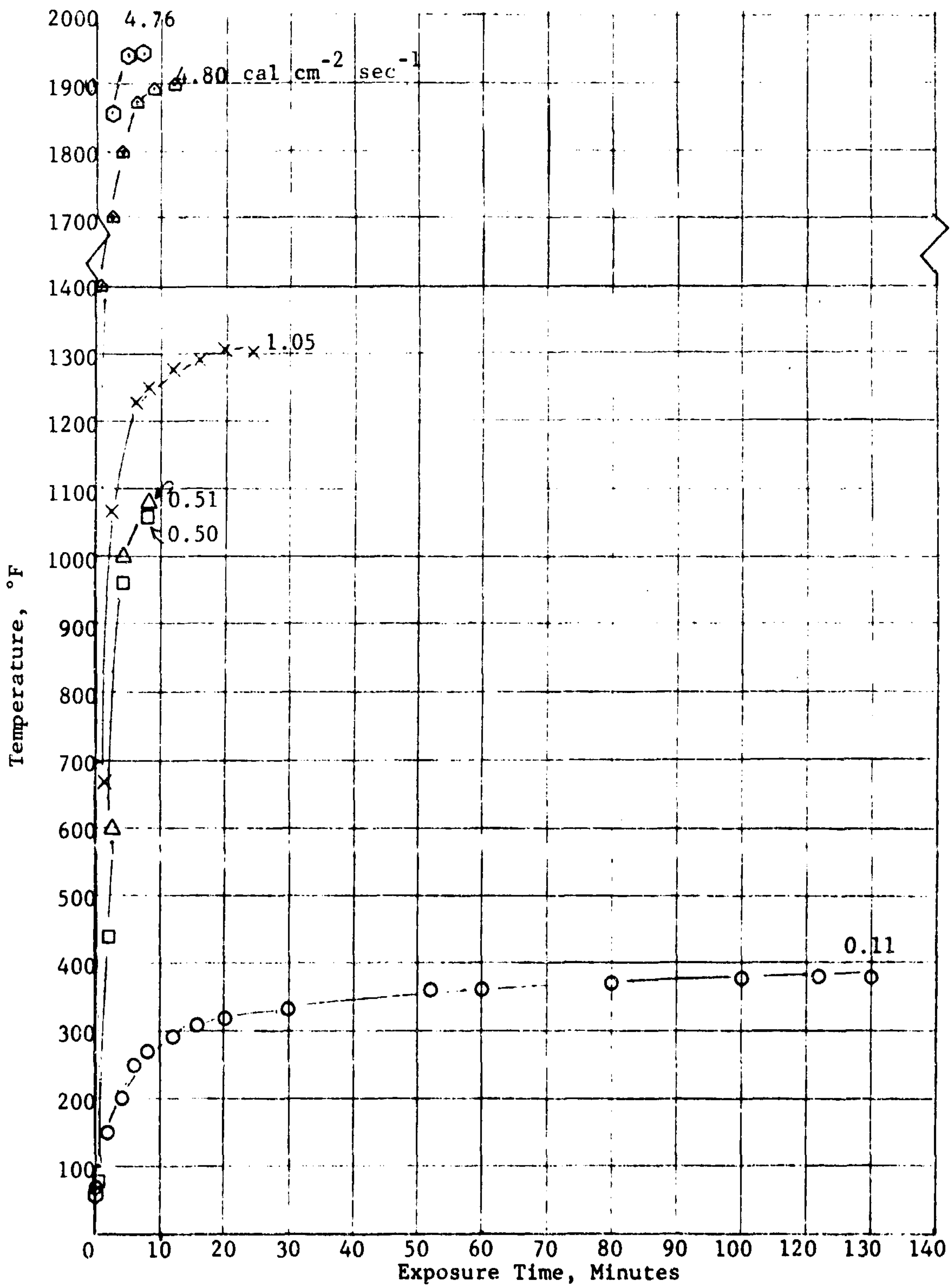

Fig. 7b LOW DENSITY FIBERBOARD - TEMPERATURES AT 1/8-in. FROM THE EXPOSED SURFACE

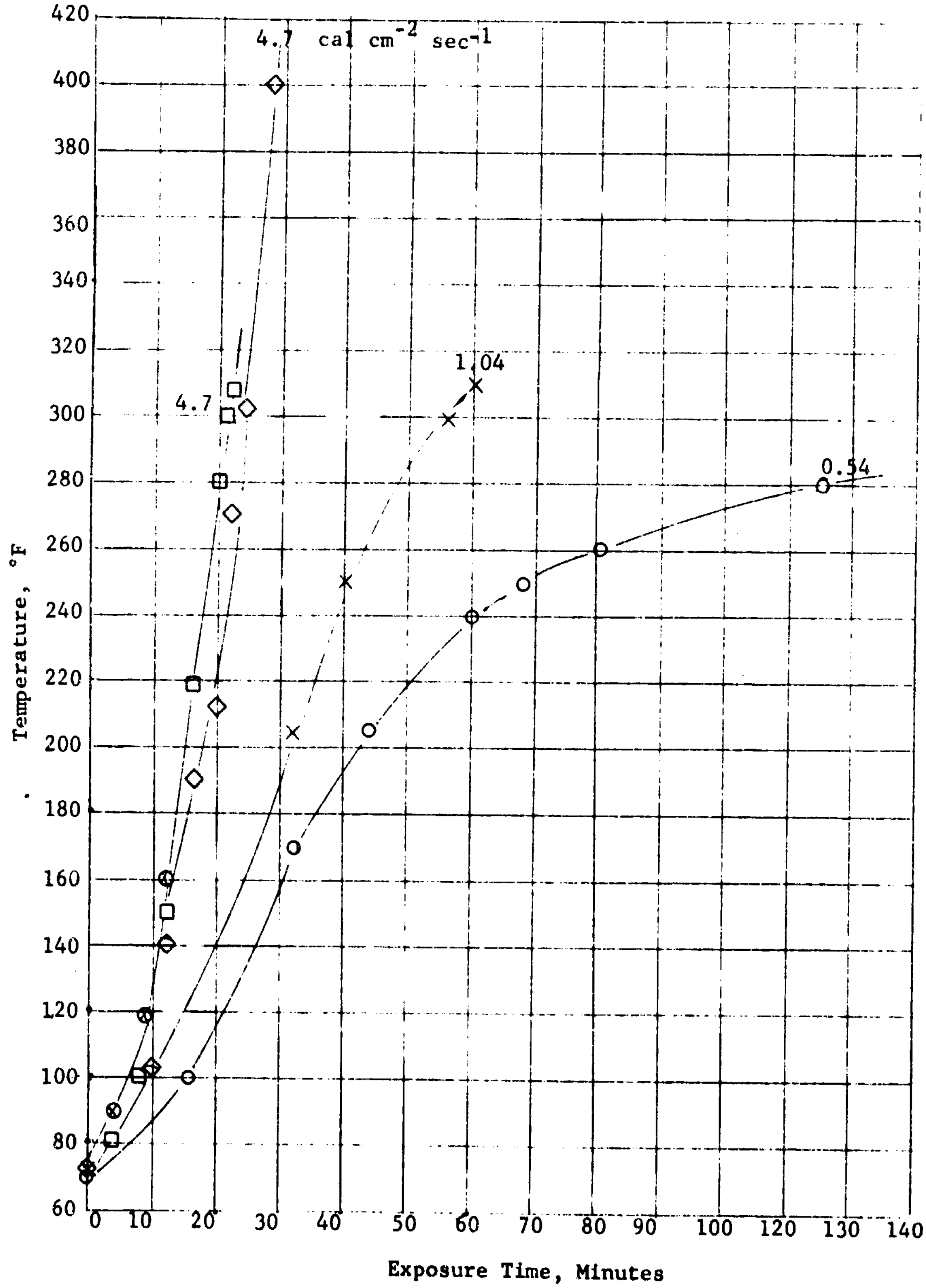

Fig. 8a INSULATING FIRE BRICK - TEMPERATURES NEAR THE UNEXPOSED SURFACE

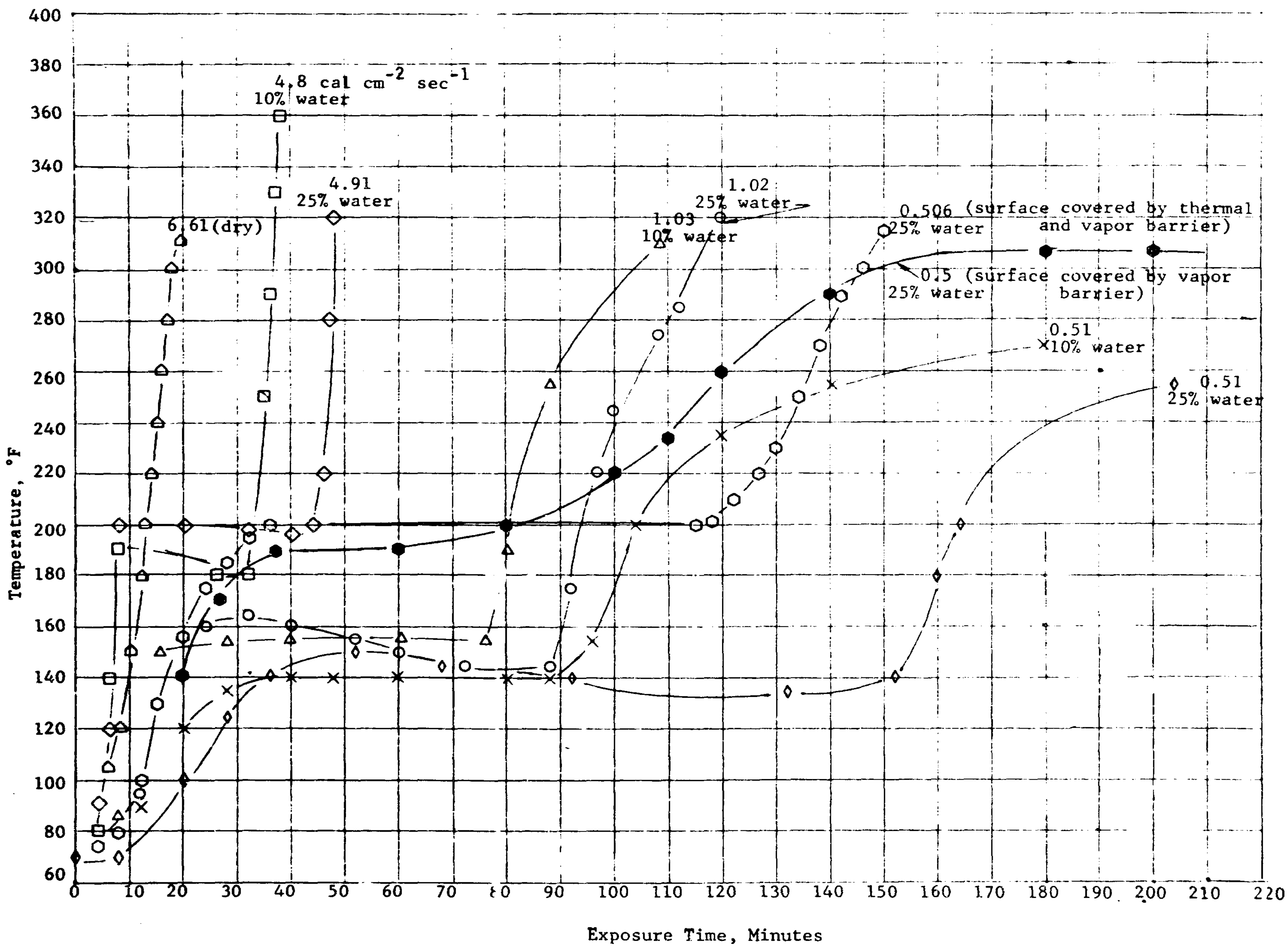

Fig. 8b INSULATING FIRE BRICK - TEMPERATURES NEAR THE UNEXPOSED SURFACE

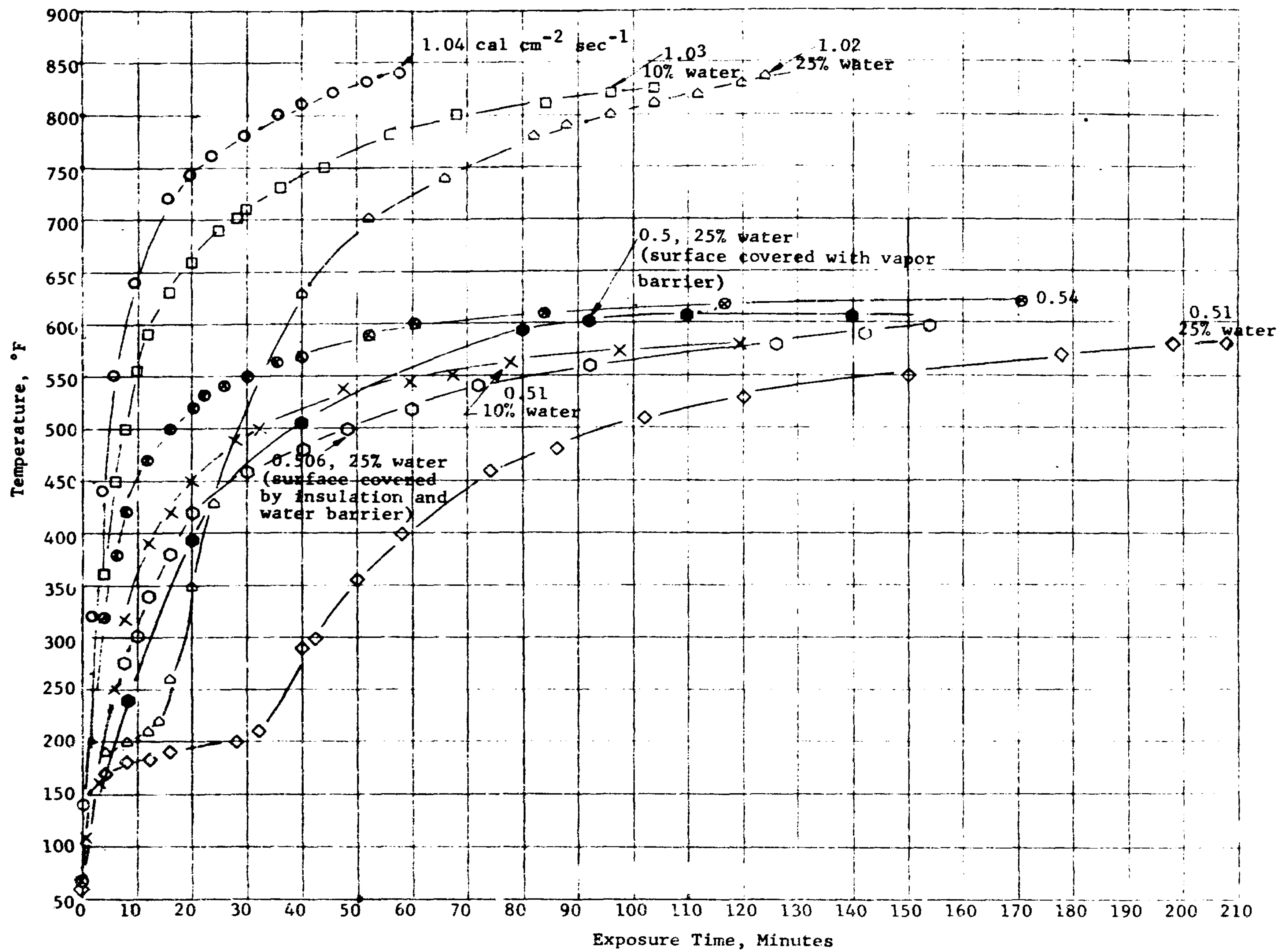

Fig. 8c INSULATING FIRE BRICK - TEMPERATURES NEAR THE EXPOSED SURFACE

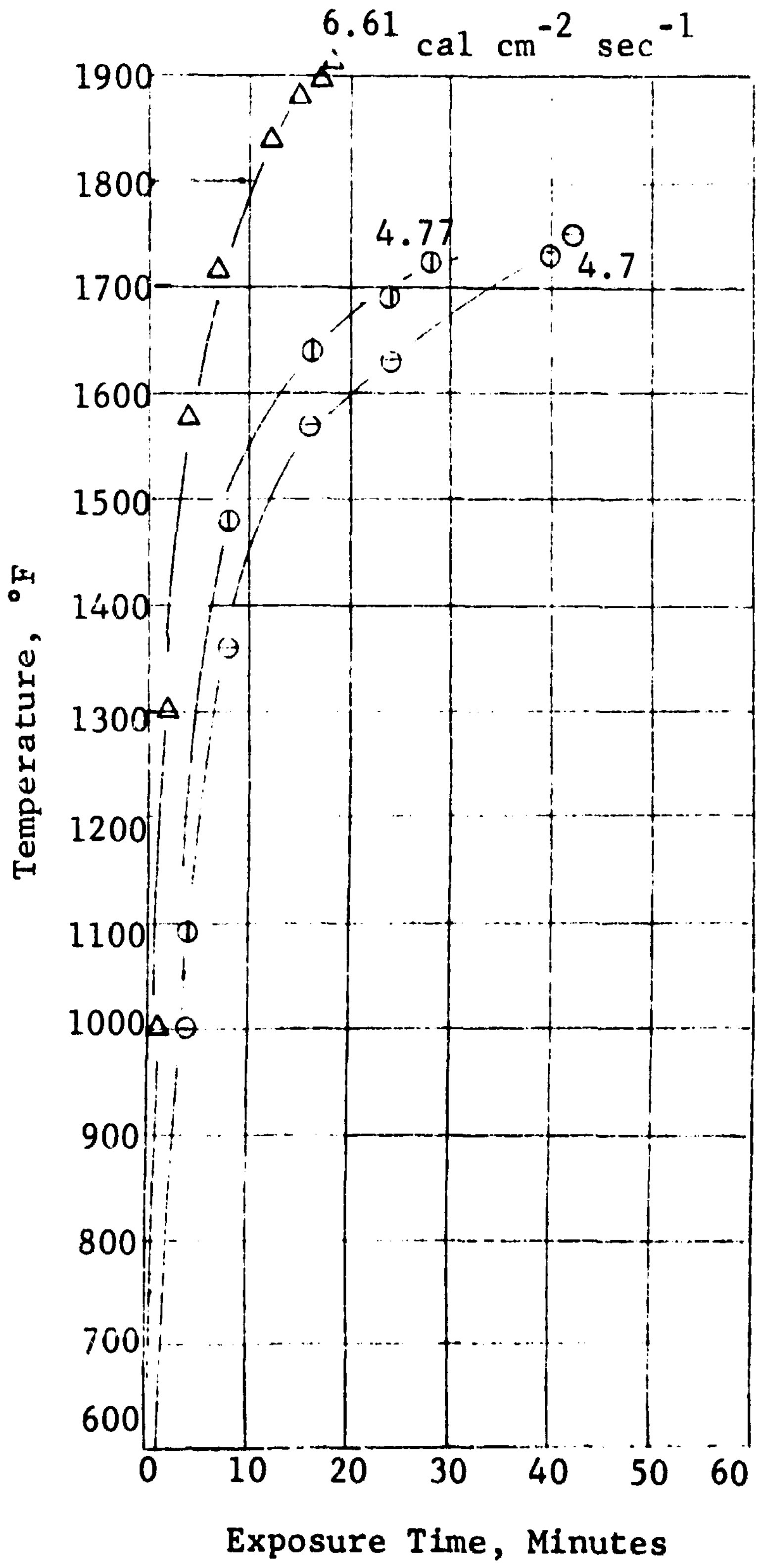

Fig. 8d INSULATING FIRE BRICK - TEMPERATURES NEAR THE EXPOSED SURFACE

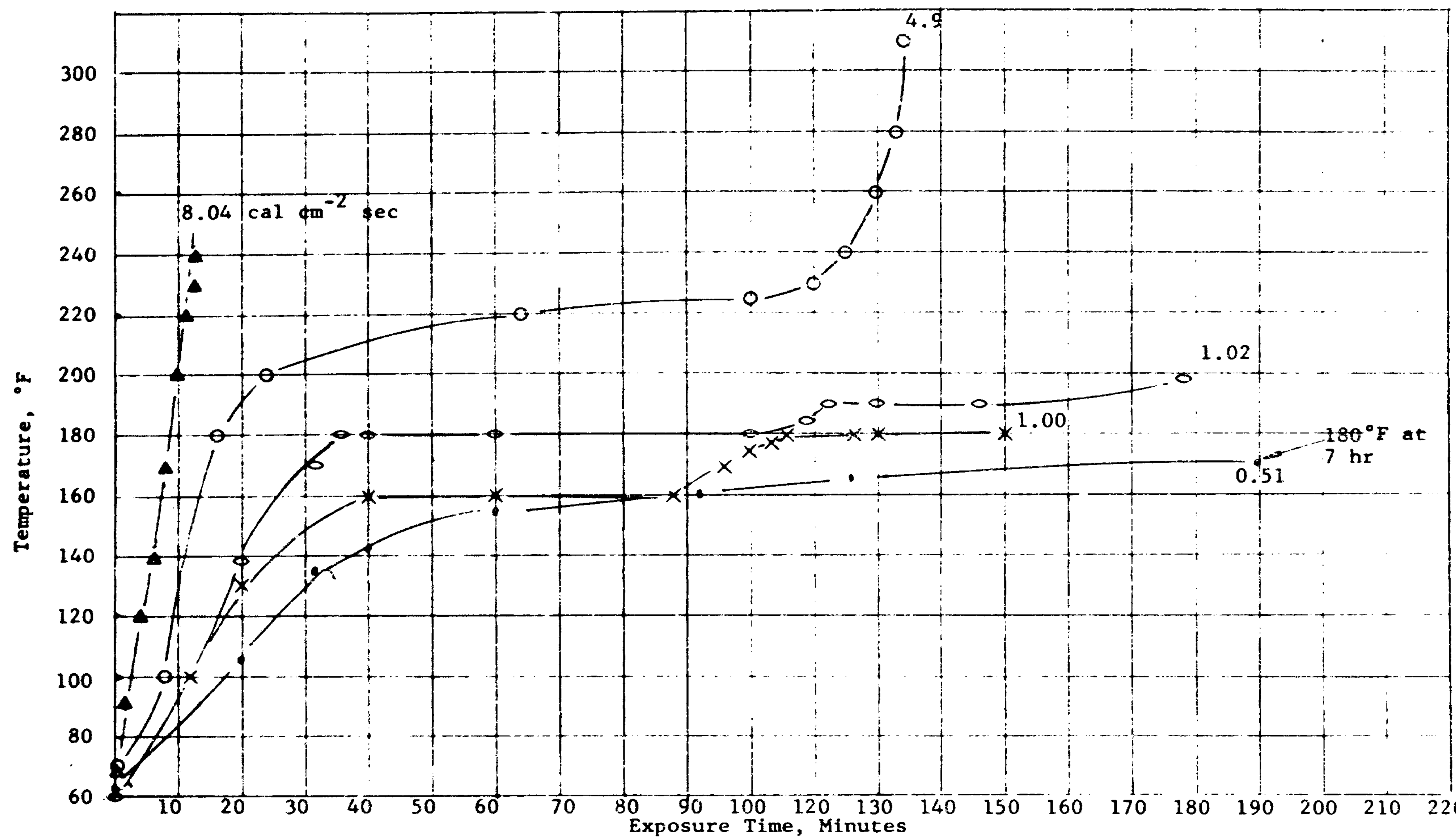

Fig. 9a PLASTER - TEMPERATURES 1/8-IN. FROM THE UNEXPOSED SURFACE

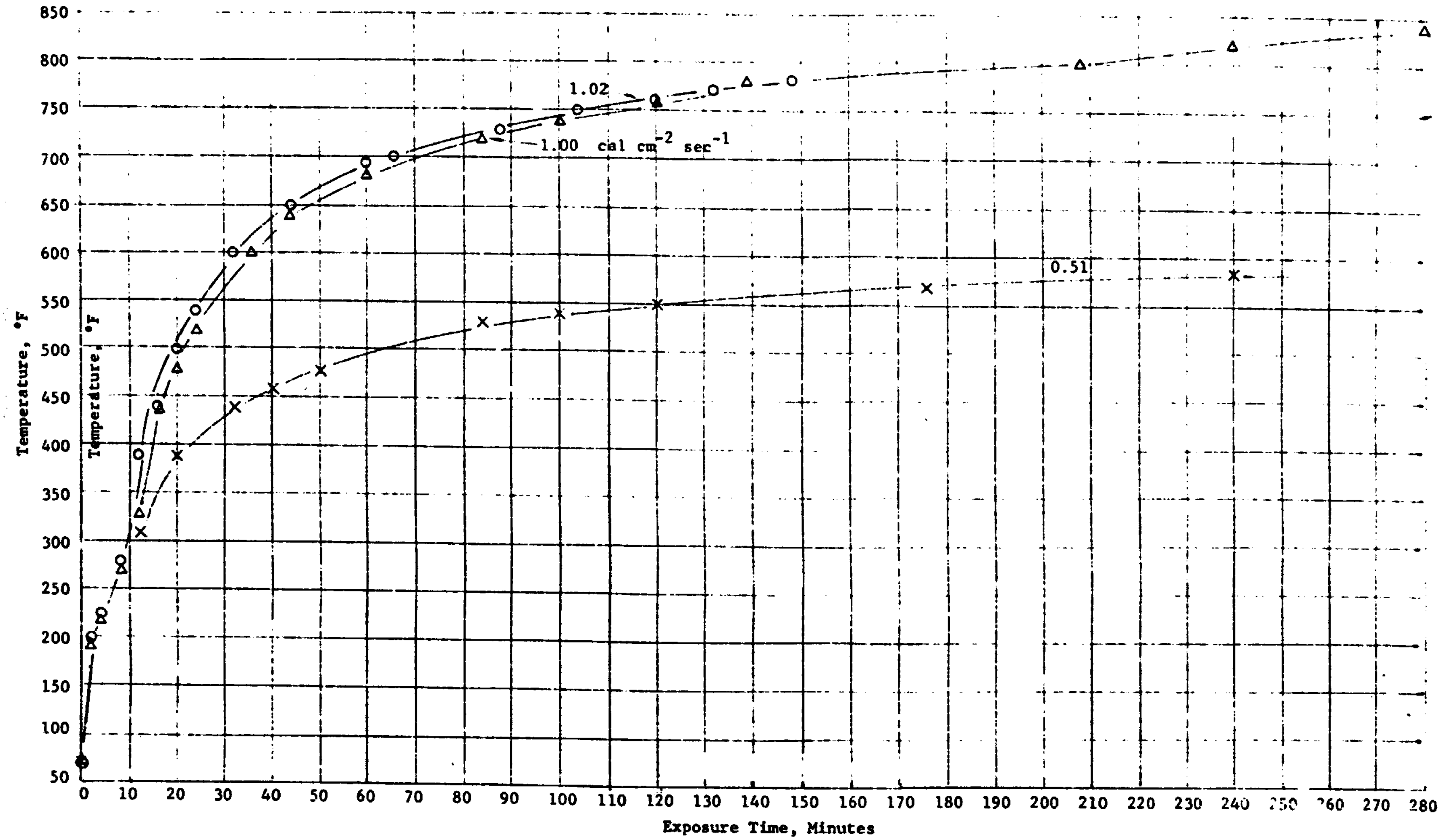

Fig. 9b PLASTER - TEMPERATURES 1/8-IN. FROM THE EXPOSED SURFACE

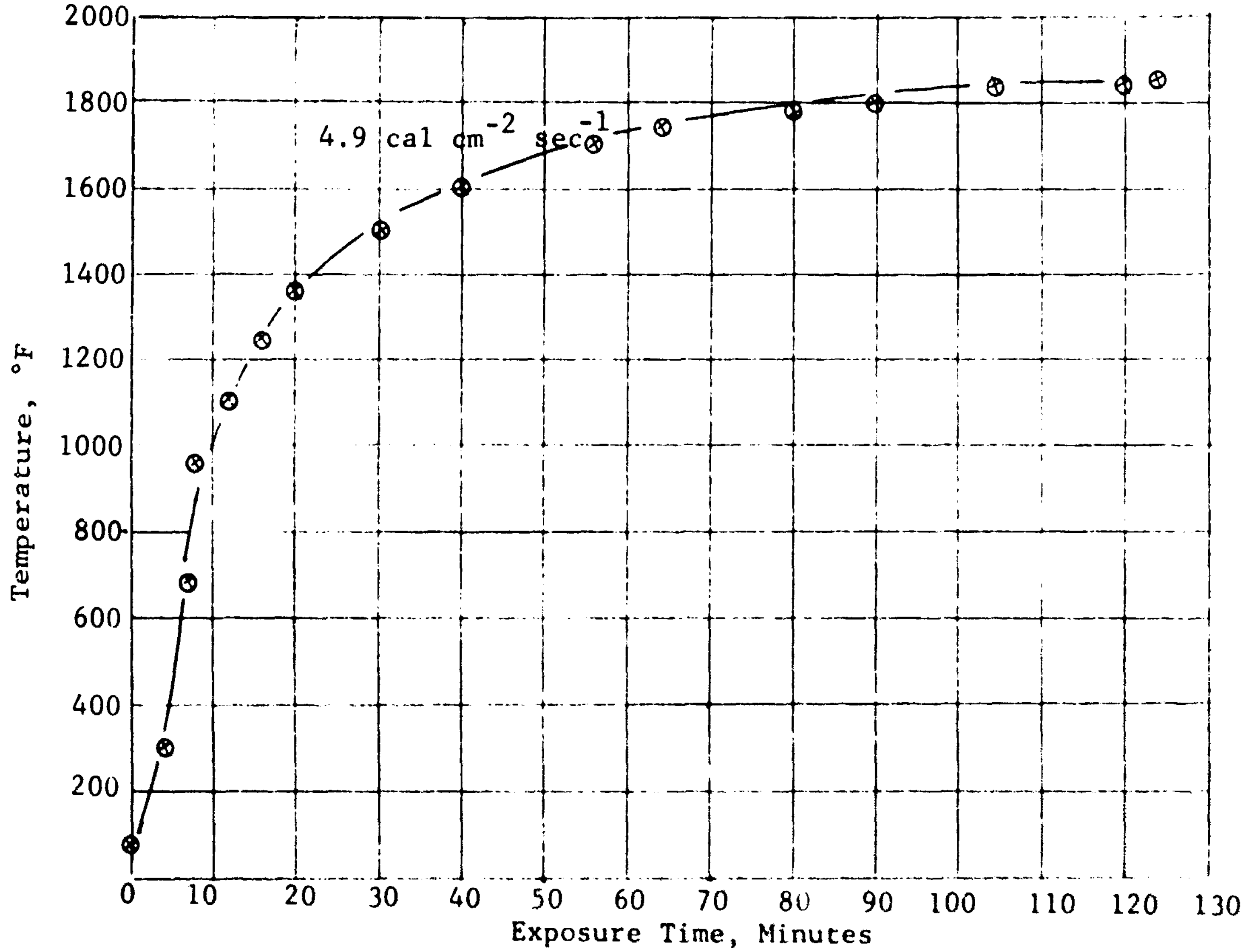

Fig. 9c PLASTER - TEMPERATURE 1/8-IN. FROM THE EXPOSED SURFACE

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13 ABSTRACT

Experiments were performed to evaluate the responses of shelter components to typical fire exposures in order to develop means for predicting these responses from the results of a minimum number of standardized tests. Exposures were provided by an infrared lampbank.

Samples included material of both high and low insulating qualities, inert materials, and those exhibiting ablative and dehydration processes. Each sample was approximately 16-in. wide, 24-in. high and 2-in. thick.

Results indicate that fire resistance of a barrier is considerably affected by the intensity of exposure. For homogeneous combustible materials, this effect can be expressed approximately in terms of the area equivalence method suggested by Ingberg. For homogeneous non-combustible materials, containing free water, this method produced errors ranging from 10 to 31 percent. This error is substantially larger for materials containing both free and chemically-combined water. In the case of non-homogeneous materials, the error ranged from 62 to 86 percent.

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2. Fire Resistance Rating						
3. Radiative Heating of Materials						

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