Protecting Fire Fighters Exposed in Room Fires: Comparison of Results of Bench Scale Test for Thermal Protection and Conditions During Room Flashover

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Abstract

Heat flux conditions measured in seven room fires are discussed. The conditions varied from just below flashover in a sparsely furnished bedroom to flashover and severe postflashover fire in a typically furnished recreation room. These heat flux conditions are compared with the protection level provided by fire fighter turnout coats conforming to NFPA 1971, *Protective Clothing for Structural Fire Fighting*. This standard requires that the turnout coat or pants assembly must protect the wearer against second degree burns when a heat flux of 84 kW/m^2 (2 $cal/cm^2 \cdot s$) is applied to its outside surface for a minimum of 17.5 seconds ["thermal protective performance (TPP) of 35"]. The results imply that fire fighters have only ten seconds or less to escape under most flashover conditions. However, the turnout coats provide good protection in many other fire situations. Practical definitions for flashover are given, and possible means for making the TPP test more relevant for research and development work are discussed.

Introduction

This paper discusses heat conditions which occurred in a number of room fires conducted over several years at the Center for Fire Research (CFR) of the U.S. National Bureau of Standards. The fires ranged from just short of flashover through rapid buildup to considerable postflashover burning. These conditions are compared with the theoretical level of protection afforded by present-day fire fighters' turnout coats and pants.

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Key words: burn injury; escape time; fire fighters; flashover; heat flux; room fires; thermal protection; protective clothing; turnout coats.

The National Fire Protection Association (NFPA) standard 1971, *Standard on Protective Clothing for Structural Firefighting*[1] requires that, among numerous other protective features, turnout coats and pants provide a certain level of protection against heat flux. In earlier issues of this standard, the criterion for this insulating value was a minimum thickness of the assembly comprising the turnout coat shell fabric, vapor barrier, and inner liner of 4.4 mm (0.175 in.), measured at room conditions. Recently, the Thermal Protective Performance (TPP) test was substituted for thickness. It measures the insulation value of the assembly under an applied heat flux of 84 kW/m^2 (2.0 $cal/cm^2 \cdot s$). This test is much more realistic because it takes into account such heat-induced changes of the assembly as shrinking, charring, melting, breaking open, and intumescence.

The question arises whether heat flux/time data obtained in the room fires could be compared to similar data obtained in the TPP test to provide a rough estimate of the protection afforded by turnout garments conforming to the NFPA standard in actual fires, especially during and after flashover. (Obviously, heat exposure of the turnout garment and the consequent heat buildup in it can also occur before flashover. However, this paper is primarily directed toward the rapid increase in room heat flux during flashover, which presents a special hazard.) This question has been previously addressed by investigating the degree of damage sustained by protective garments in fire accidents, and simulating the effects in the laboratory under known heat flux conditions.[2] The present report uses a different approach: we compared TPP values with heat conditions characterized by heat flux/time curves obtained in room fires. Of the large number of room and room/corridor fires conducted at NBS over the last 20 years, seven experimental fires were selected as having been conducted and instrumented in a manner most relevant to the present purpose. The selected room fires present a range from barely not reaching flashover to postflashover situations.

The flashover fires described here extend to some of the more hazardous situations for fire fighters. Fire fighter exposure to flashover is infrequent because the time between fire detection and flashover is often short, and thus the fire fighters frequently arrive after flashover. However, occasionally a fire fighter on a search mission will encounter the conditions discussed in this report.

Several limitations to the present study are noted. First, only the hazard due to exposure to heat is considered here, while fire fighters also have to contend with exposure to toxic combustion products, greatly reduced visibility, collapse of structures, etc. Second, the CFR experiments were conducted in relatively small rooms with typical, but by no means maximum, fire loads in the form of furnishings and combustible walls and ceiling. Heat conditions could be more severe in fires in rooms with different fire loads or size, e.g., a warehouse or a flammable liquid fire. Third, all but one fire discussed herein were conducted with an open door; other room opening geometries would have resulted in different conditions. And fourth, heat flux conditions vary considerably throughout a room while we report only conditions measured by one heat flux meter.

Thermal Protective Performance (TPP) Test

The TPP test arrangement is shown in Figure 1.[3] A horizontal specimen is exposed to a heat source, consisting of a radiant heat panel and two gas burners, adjusted so that the radiant and convective heat flux portions are each 42 kW/m^2.* A heat sensor above the specimen registers the heat transferred through the specimen. A typical heat/time curve obtained in this manner is shown as the solid curve in Figure 2. The broken line indicates the heat/time relationship at which an incipient second degree burn has been shown to occur.[4] As long as the measured (solid) heat/time curve is below the broken "injury" line, no burn injury would be expected; an incipient second degree or deeper burn would be expected on skin exposed to conditions above this line. It is evident from this injury line that not only the total amount of heat delivered to the skin, but also the rate at which it is delivered, determines whether a second degree burn occurs. Thus, if 50 kJ/m^2 were delivered over 3 s, a second degree burn would be expected; if this heat were delivered over 20 s, no injury would occur.

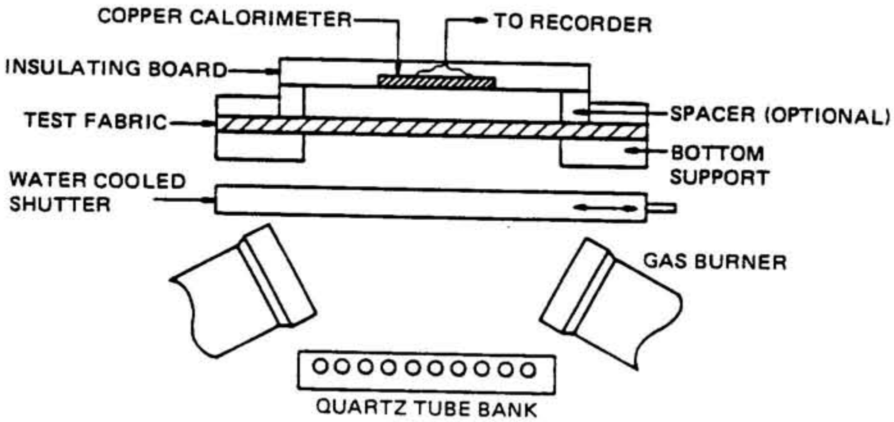

Figure 1. TPP apparatus.

The NFPA standard defines the TPP as twice the time at which the solid heat/time curve crosses the injury line (for a 2 cal/cm^2·s heat flux exposure). The higher the TPP of a protective garment, the greater the heat protection afforded to the wearer. A TPP of 35 is readily achievable by present-day technology. However, as with any effective turnout coat, there is a price in low comfort and substantial stress to the wearer, due to the weight, thickness, and lack of breathability of the coat.

*1 cal/cm^2·s = 42 kW/m^2 = 42 kJ/s·m^2. kW/m^2 and cal/cm^2·s are units of energy flux.

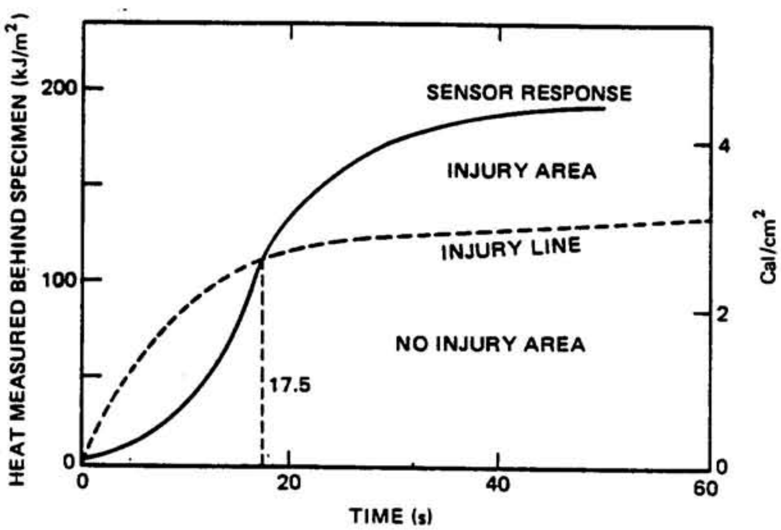

Figure 2. Heat injury and typical time/heat curves.

An American Society for Testing and Materials (ASTM) standard, ASTM D 4108, employs a different version of this test, using only one gas burner and no radiant panel.[5] Specimen exposure is also specified as 84 kW/m² (2.0 cal/cm²·s), and the heat flux ratio is reported to be about 30/70 radiant/convective. It has been shown that the results obtained with the 50/50 heat exposure prescribed by NFPA 1971 correlated well with those of the ASTM test, except above TPP 25 and at longer exposures,[6,7] when the NFPA test was more severe.

The actual radiant/convective ratio to which a fire fighter may be exposed varies widely, and depends on the presence of drafts, contact with hot floors, etc. However, the most critical exposure may be that due to radiant heat resulting from sudden flashover.

Flashover

"Flashover" is an important fire term, but has no single standard definition. It is, first of all, not a condition of a fire, but the boundary between two conditions. One completely subjective description might be: "On arrival at a house fire the officer reports that 'the chair is on fire'—flashover has not yet occurred; or he reports that 'the living room is fully involved'—flashover has occurred." An alternative, subjective definition is the transition between the burning of a single object in a room and the nearly simultaneous involvement of all the combustibles in the room. More quantitative indicators, which, while differing slightly, are essentially equivalent are:

1. The point in a fire development when light fuels (such as crumpled newspaper), displayed in the open on the floor, ignite by radiation from the flames and smoke layer.

   The ignition of light fuels causes a further, rapid increase in the intensity of the fire and is usually followed closely by the involvement of all the remaining fuel.
2. The point in a fire development when flames first come out an open door or window. This often is synonymous with the ignition of light fuels but is not quite equivalent to the above. Flames out the door have been observed without flashover, if, for example, the object burning is close to the opening.
3. The point in the fire development when the average temperature of the gases in the upper part of the room reaches about 600°C (1100°F).
4. The point in a fire development when an upward-facing total heat flux sensor at floor level registers 20 kW/m^2. (Crumpled newsprint has been found to ignite at about this heat flux.)

Where the necessary instrumentation has been used, definition 4 is probably the most precise, although not necessarily the most accurate. In less fully instrumented tests, methods 2 or 3 have to be used.

Description of Room Fires

As will be shown below, the heat flux conditions before and after flashover can vary widely, from a slow buildup to just short of flashover to rapid heat buildup and finally to prolonged postflashover high heat flux, as all combustible materials in a room are consumed. For the present report, heat flux results from a large number of room fires conducted by the Center for Fire Research were examined.[8–12] From these, several fires from three series of simulated bedroom and recreation room fires were chosen. They were believed to present a fairly representative range of flashover severity. The fire loads are described in Table 1.

Test Condition 1[8,9]

In these experiments, the only combustible materials were "twin size" polyurethane foam mattresses, resting on a metal frame, made up with the same set of bedding in all cases. Ignition was from a wastebasket, with a standardized load of burning trash, placed so as to ignite the bedding. Some of the mattresses were sufficiently fire-retardant treated that no significant fire developed. Others led to room flashover conditions and would have ignited other fuels had they been present. Two mattress tests, one that burned marginally and one that resulted in flashover conditions, are included in this study. This first set of tests represented the least severe conditions considered in this paper.

Table 1. Fire loads in room fires.

Test Condition 1

Test room: 3.5 x 3.4 x 2.4 m, door 2.1 x 0.9 m.

Walls and ceiling: noncombustible.

Bedding, both fires: two polyester/cotton sheets, one cotton sheet, one polyester/cotton pillow case, one polyester/cotton bedspread, one shredded polyurethane (PU) pillow.

Ignition source: polyethylene wastebasket with 443 g assorted paper items.

Mattress 1: hospital mattress, 1.88 x 0.95 x 0.3 m, 6 kg, solid PU with low-level fire retardant treatment, fire retardant PVC ticking.

Mattress 2: commercial 2.3 x 0.89 x 0.17 m, 14 kg, solid PU foam, ticking: two layers rayon fabric with PU foam interlayer.

Test Condition 2

Test Room: 3.66 x 2.44 x 2.44 m, door 2.03 x 0.76 m.

Walls and ceiling: walls gypsum board and plywood over gypsum board, ceiling gypsum board.

Total combustible furnishings: 54 kg; plywood walls: 88 kg.

Furnishings:

Frames: double bed, 1.91 x 1.37 x 0.53 m, headboard 2.39 x 0.89 m, night table 0.63 x 0.41 m, all made from 12.7 mm plywood.

Bedding: acrylic blanket, two polyester/cotton sheets, two polyester/cotton pillow cases, two pillows consisting of polyester fiberfill with polyolefin ticking.

Mattress: polyester quilt cover, 6.4 mm PU layer, flame retardant cotton felt, cotton felt, mixed fiber pad.

Box spring: polyester ticking, cotton felt, cellulosic fiber pad, wood frame with wire springs.

Ignition source: polyethylene waste basket, 0.41 kg assorted cellulosic items.

Test Condition 3

Test Room: Room dimensions and furniture arrangement shown in Figure 3.

Walls and ceiling: gypsum board.

Furnishings:

Sofa, loveseat, chair, ottoman: polyolefin cover fabrics, PU padding except cotton batting in side arms reinforced with cardboard, wood frames; total weight 148 kg.

Coffee table and end table: veneer top and sides laminated on hardwood, 33 kg.

Bookcase: wood particle board, melamine finish, 42 kg.

Carpet: low-level olefin loop pile, foam rubber backing, 20 kg.

Ignition source: 400 g newspaper placed along back and seat, at center of sofa, supported by a steel frame.

Test Condition 2[10,11]

Bedrooms with a higher fire load than in test condition 1 were constructed: furnishings consisted of a larger, "full size" mattress, made up with bedding, and placed on a box spring on a metal bed frame to which was attached a wooden headboard. A wooden side table was placed near the bed. Rooms with both combustible (plywood) and noncombustible (plasterboard) walls were included. Ignition was by a standard wastebasket producing 5 to 10 kW, igniting the bedding. Four representative tests from this series were included in this study. They represent a second step in the graded series chosen.

Test Condition 3[12]

A series of still more severe tests was also conducted of a room furnished to simulate a basement recreation room (see Table 1). The wall linings were varied: plasterboard was used alone in some tests, and plasterboard covered with plywood in others. In addition to the furniture, draperies were hung from the wall, simulating window dressings, and the floor had various coverings. In those tests, the room was driven to flashover by the sofa fire (started by burning newspaper on the seat of the sofa) which was roughly equivalent to a twin size mattress fire in amount of combustible and surface area. But, after flashover, there were a number of other, noncontiguous items that became involved. These tests exhibited behavior close to what is to be expected in a fully furnished room. Results from one of these tests in which a flashover occurred are included in this study. Figure 3 is a floor plan showing the location of the only vent, a door, and the disposition of the furniture.

Test Results

Test Condition 1 — Twin-Size Mattresses

Figure 4 shows the total heat flux registered at the floor, away from the burning mattress. This heat flux exposure may be similar to that experienced by a fire fighter lying on the floor. This fire did not quite reach flashover conditions: the upper gas layer temperature was approximately 550°C. The heat flux to the floor peaked at about 13 kW/m^2 and the newspaper targets on the floor did not ignite. Thus this test is an example of a room fire under near-flashover conditions.

Superimposed on the floor heat flux-time curve (solid line) is a rectangle 84 kW/m^2 by 17.5 s wide (dotted line). This represents the heat flux incident on the turnout coat test specimen as prescribed in the NFPA standard test; i.e., a TPP rating of 35. The mattress fire lasted over several hundred seconds but it produced a much lower peak heat flux than that which is applied to a turnout

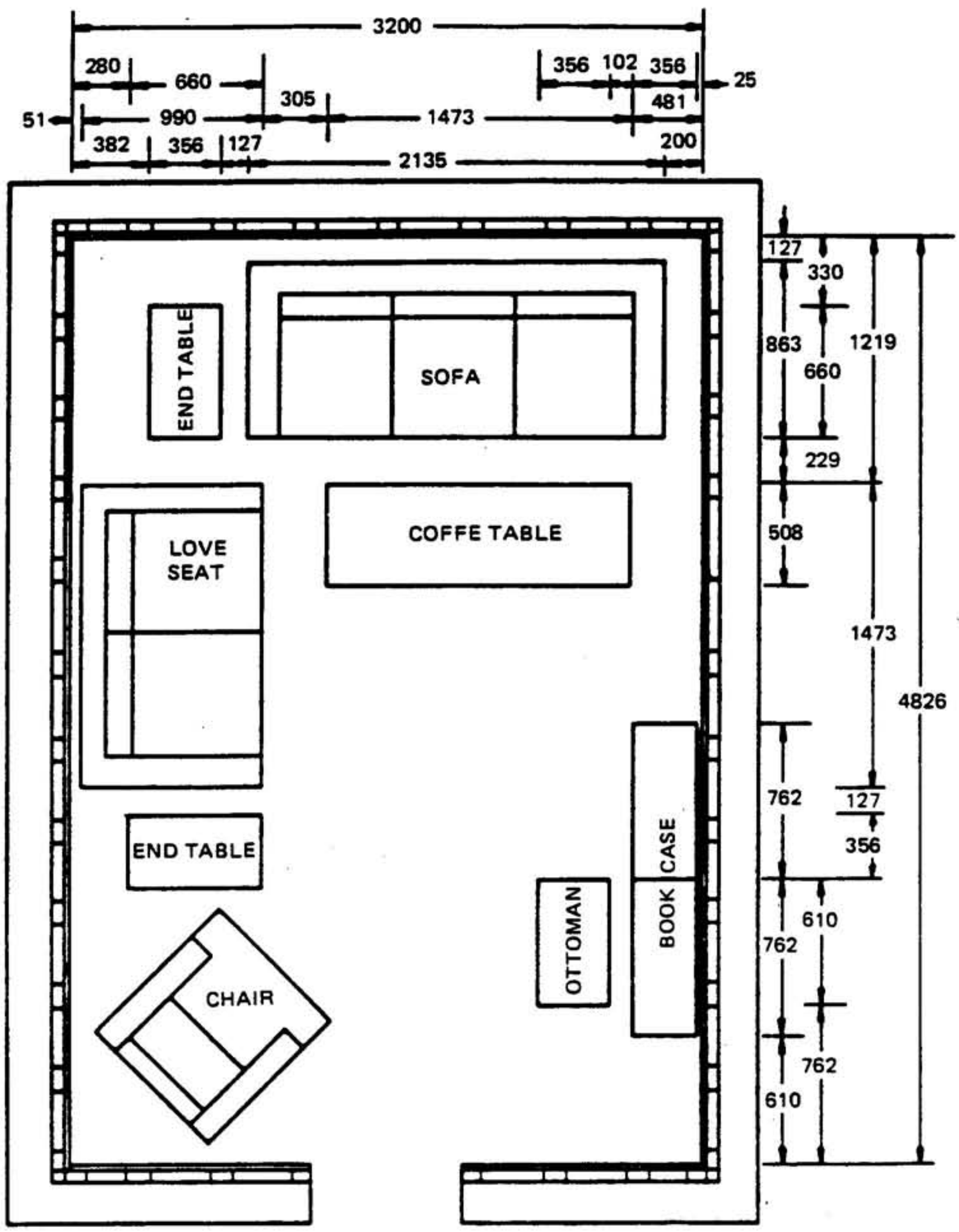

Figure 3. Floor plan of recreation room. All dimensions in mm.

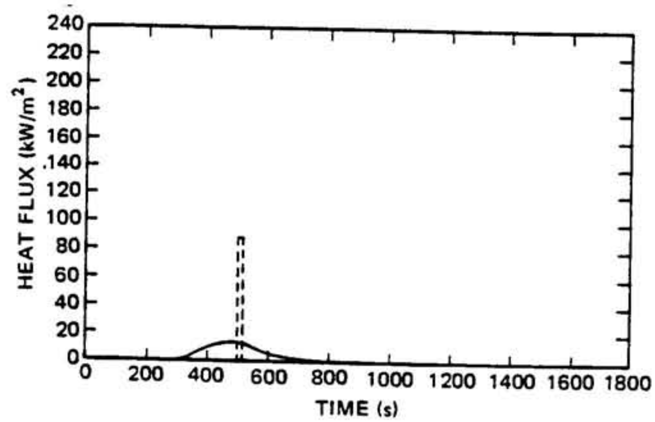

Figure 4. Mattress test 1. Solid line: heat flux meter output; dashed line: TPP = 35.

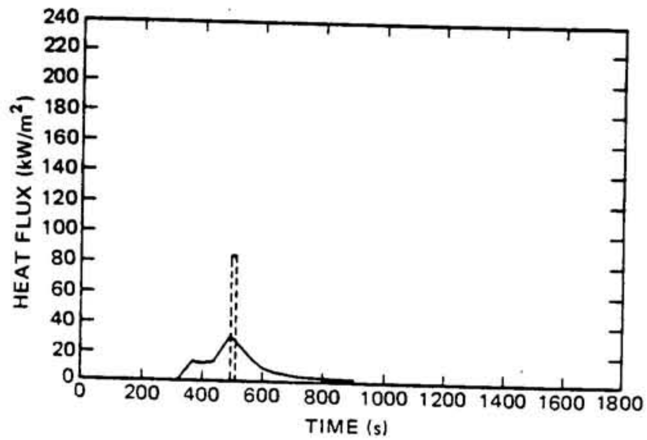

Figure 5. Mattress test 2. See Figure 4 for legend.

coat specimen in the TPP test protocol. In this situation, the fire fighter would presumably have ample warning of heat buildup in the coat.

Figure 5 shows a similar pair of curves for a slightly more severe mattress test and the TPP. This test met all the flashover conditions: flames came out the open doorway; the upper gas temperature exceeded 600°C (peak 1000°C, average peak upper gas temperature over the room 760°C); the floor heat flux exceeded 20 kW/m^2 (peak 31 kW/m^2); and the newspaper targets ignited.

Test Condition 2—Double Bed Fires with Noncombustible and Combustible Walls

Figure 6 shows the result of the double bed fire in a room with plasterboard walls and ceiling. Here, in contrast to Figures 4 and 5, the heat flux data plotted is from a sensor on the room wall 0.64 m (about 2 feet) above the floor, perhaps resembling the conditions encountered by a crouching fire fighter. The sensor shows a sharp peak just after 200 seconds which, by 300 seconds, had subsided. During this peak, flashover, as defined by all the criteria given above, occurred. This peak was caused by the rapid development of fire on the bedding (determined from visual observation) and the probable burning of the paper on the surface of the gypsum board on the ceiling. Flames came out the top of the room door briefly during this time period. At about 700 seconds the fire built up to a second, more severe and sustained peak associated with the burning of the mattress and the wooden articles of the bed frame, headboard, and side table. Again, a rectangle representing the TPP exposure has been superimposed on the heat flux plot. Its location was arbitrarily selected to make its top left corner tangent to the second peak of the heat flux curve. One could surmise that the fire fighter perhaps could survive the first peak without major injury. However, the occurrence of two peak conditions indicates that extreme care must be taken in entering a room even if the fire appears to have subsided: there is very little escape time in the situation represented by the second peak, even if the turnout coat had not been preheated by the earlier heat load.

Figure 7 shows the result of a repeat of this test. The course of the fire was somewhat different from the first one, indicating that even quite closely controlled room tests produce a considerable range of results. There is a small peak at about 200 seconds followed by a larger one between 600 and 700

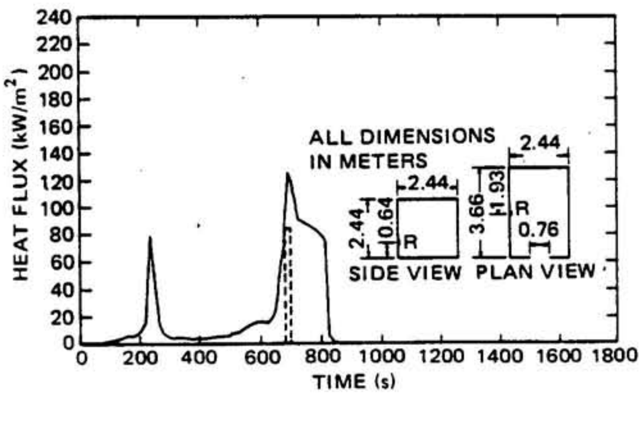

Figure 6. Bedroom test with gypsum board walls. Solid line: heat flux meter output; dashed line: TPP = 35; R: heat flux meter location.

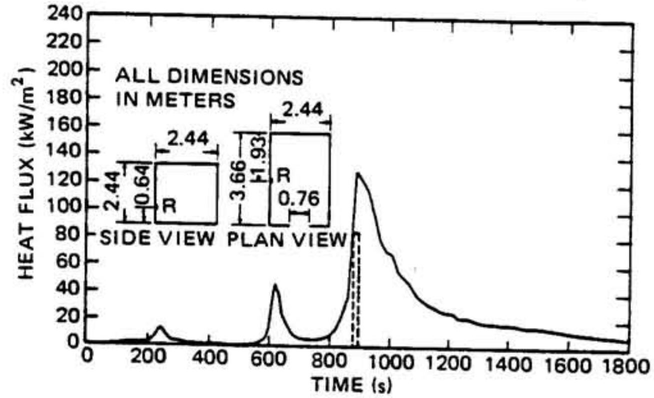

Figure 7. Bedroom test with gypsum board walls (repeat). See Figure 6 for legend.

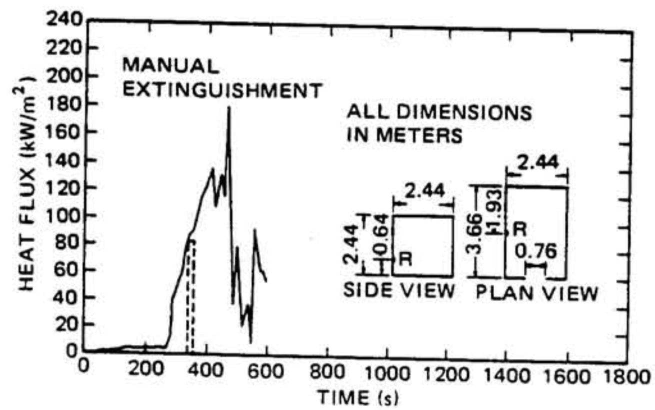

Figure 8. Bedroom test with plywood walls. See Figure 6 for legend.

seconds. Observation of the test suggests that these two peaks comprised burning of the same group of materials that produced the single, stronger peak at 200 seconds in the test shown in Figure 6. Although flames came out the door briefly during the 600 second peak and the heat flux exceeded 20 kW/m^2, ignition of the newspaper targets on the floor did not occur. The final peak, which begins at about 800 seconds, corresponds to that beginning at about 625 seconds during the prior test shown in Figure 5. The TPP is represented, arbitrarily, at this peak. Again, turnout coats with TPP of 35 would be expected to provide protection only during the very first part of the fire, the incidental fires involving parts of the bedding, but not the fire of the mattress or the large items of furniture.

Figure 8 shows the results of a test with the same furnishings in a room with 6.4 mm thick plywood over the gypsum board on the two side and rear walls.

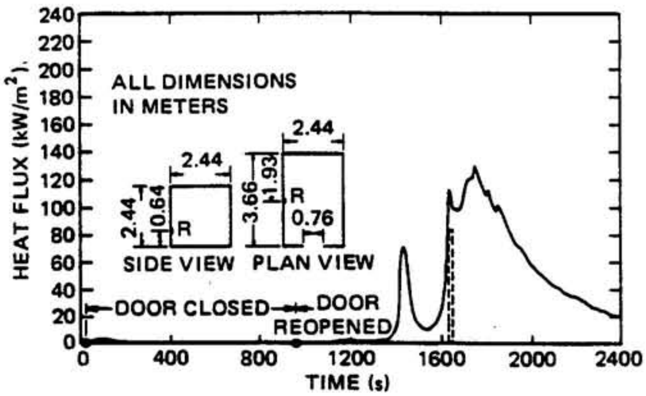

Figure 9. Bedroom test with gypsum board walls, door closed, then opened. See Figure 6 for legend.

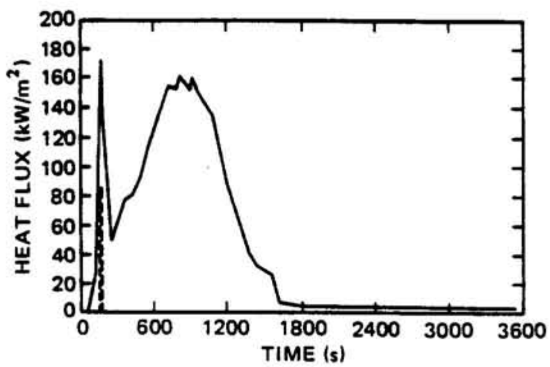

Figure 10. Recreation room test. See Figure 4 for legend.

The ceiling was the same as in the other tests. Here only a single burning period was observed.

The test shown in Figure 9 had, again, the same furnishings and the gypsum walls of the tests shown in Figures 6 and 7. However, in this case, immediately after ignition of the waste basket, the room door was closed. The door was reopened at about 900 seconds. The burning behavior after the door was opened is similar to that shown in Figure 6, but displaced in time.

Test Condition 3 — Recreation Room Tests

The test described in this report—one of sixteen recreation room tests—involved a much larger fire load than the previous ones, a fully furnished recreation room. The heat flux measured at the floor near the center of the room is shown in Figure 10. The spike near 200 seconds is associated with the ignition of the sofa upholstery fabric and the draperies. After briefly subsiding, the fire grew to involve all the furnishings, resulting in a peak near 1000 seconds and finally burning out after 1800 seconds.

Discussion

The test data indicate that once flashover occurs, a room rapidly becomes intolerable for a fire fighter using protective clothing meeting, or even considerably surpassing, the present TPP test requirement. The data also suggest that turnout garments that meet this requirement only allow a short time for escape. From the figures, one could estimate that this time may be less than 10 seconds, depending on the fire.

Factors other than heat conditions after flashover affecting the protective performance of turnout garments are: (1) lengthy exposure to less than 20 kW/m^2, i.e. preflashover conditions, causes the inside of the turnout garment to get hot before (and even without) a flashover; (2) heat stored in the garments continues to be delivered to the wearer even after escape unless the gear can be removed immediately;[13] (3) the presence of moisture in the turnout garments may adversely affect protection because of lower insulation value of wet rather than dry materials and possible steam formation;[14] and (4) on the positive side, the turnout garments contact the wearer only in very limited areas, so that more insulative space than provided in the TPP test can be assumed to exist in at least part of the body.

There can be little doubt that the TPP value is a better measure of protection provided by turnout garments than the previously used thickness specification. The TPP test measures insulative value of the materials under more realistic conditions than the thickness test, which is carried out at normal laboratory conditions. The present use of the time–heat flux curve, as shown in Figure 2, is to determine the time at which incipient second degree burn can be assumed to occur. However, there appear to be several additional, easily obtainable TPP test results that would make the test even more relevant to predicting the effectiveness of heat protective garments, and that would be useful in research and development work. These are:

- *Rate of increase in radiant energy.* A steep slope of the time–heat flux curve at its intersection with the injury curve (Figure 2) indicates that heat is delivered to the wearer of the garment at a high rate, which is likely to cause the burn injury to progress rapidly into the skin.
- *Effect of heat stored in protective garments.* The typical TPP curve shown in Figure 2 indicates that heat delivery to the sensor continues after a TPP of 35 is reached. Since we cannot assume that the fire fighter can doff the turnout garments immediately after escape, the rate at which the stored heat is delivered to the skin and the total amount of heat delivered are other

factors worth considering in a full characterization of protective garments. This could be assessed by measuring the total heat with the TPP sensor over several minutes.

- *Effect on insulation value of moisture in the turnout garments.* The effect of moisture present in the shell (i.e., outside the moisture barrier where it could have a cooling effect and/or lower the insulation value), or of moisture in the inner liner, where it would lower insulation value and could convert to steam, should be investigated for various materials. Some data in this area have been obtained for glove materials[14] using the TPP apparatus, but more work is indicated.

One way to evaluate TPP results more realistically, especially as they pertain to escape time, would be to expose assemblies varying in TPP in room flashover situations. It would then be possible to relate incident heat flux to heat flux behind the assemblies and by extrapolation to potential burn injury. A more sophisticated estimate of available escape time could be among the results of such experiments. Such experiments are in the planning state at the time of this writing.

The above results apply only to small rooms with typical but by no means maximum fire loads. Situations in larger fires, e.g., warehouse fires, would be very different and possibly much more severe. On the other hand, a fire fighter would probably easily knock down fires in rooms as small as the test rooms with a short squirt from a water hose. Fortunately, fire fighter exposures to the heat fluxes described above are rare: however, this study again shows that such exposure should, if at all possible, be avoided even when state-of-the-art turnout garments are used.

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