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Center for Fire Research
Institute for Applied Technology
National Bureau of Standards
Washington, D. C. 20234

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Interim Report

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This work reported here covers work now in progress at the National Bureau of Standards and will be superseded by a future publication.

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U. S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary
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A variety of upholstered chairs and wood cribs were burned within a ventilated compartment. The experimental measurements of weight loss, smoke concentration, temperature and heat flux levels are summarized. A reproducible fire obtained from burning a standardized wood crib array was found to be capable of representing the essential features of incidental fires of moderate intensity.

Key words: Buildings; combustibility; fire intensity; flames; furnishings; heat release; ignition; smoke; thermal radiation; upholstery; waste receptacle.

## 1. INTRODUCTION

An incidental fire which starts in a wastebasket or on a piece of furniture may cause ignition of adjacent combustibles such as interior finish materials or furnishings and may grow into a fully-developed compartment fire. Information related to the characteristics of the environment created by such minor fires is desirable as a basis for both the development of rational procedures for designing the needed fire resistance of building constructions and for the establishment of design concepts for reduction of fire hazard. An experimental study of the burning behavior of various combustible contents of wastebaskets and individual pieces of upholstered furniture has been reported previously [1].[1]

Combustible wall and ceiling finishes in fire situations are generally recognized as a primary or contributing factor in the spread of a building fire. Most building codes provide specifications to regulate general use of interior finishes and have adopted the ASTM E-84 flame spread tunnel furnace test as a method for hazard evaluation. However, it is not clear to what extent the conditions presented inside the tunnel before and during the test can rationally simulate the environment encountered in an actual fire, since material location, orientation, and the magnitude of the fire exposure have a pronounced effect on fire behavior. To evaluate the thermal responses of different types of interior finish materials exposed to real fire situations it is necessary to acquire information on burning characteristics of the initiating fire such as the range of possible fire intensity, duration and flame

[1]Numbers in brackets correspond with the literature references listed at the end of this paper.

size. Such data can provide a base for developing an effective test method as an evaluation tool for classification of materials according to degree of fire hazard.

The present room fire study program in NBS is designed to quantify the contribution made by interior finish materials to the growth of a fire in a compartment, to determine if a useful correlation exists between standard laboratory and full-scale test methods for evaluating hazard potential of materials, and to suggest improved performance criteria of interior linings for building construction. This paper is a report of work in progress. The objectives of this phase of the compartment fire program are to characterize the fire environment to which the interior finish materials are likely to be exposed and to develop a standardized wood crib to duplicate the conditions produced by typical incidental fires.

This paper presents some experimental results on the burning characteristics of upholstered chairs and cross piles of wood under a well-ventilated condition in a test compartment. The experimental study is mainly concerned with a characterization of the environmental conditions due to typical incidental fires by measurement of the levels and ranges of temperature rise, the incident heat flux, the duration of burning, and the rates of heat release and smoke generation.

## 2. EXPERIMENTAL DETAILS

### 2.1. Test Compartment

Experiments were conducted in a burn room measuring 2.9m by 3.2m by 2.4m high. One door measuring 1.3m wide by 2m high was located in one of the smaller compartment walls and was kept fully open during the test. The entire test compartment was enclosed in a large building to provide wind and draft-free conditions. The test compartment was constructed of reinforced concrete and the interior surfaces which were exposed to the fires were lined with 16mm thick gypsum wallboards sprayed with a vermiculite gypsum plaster.

### 2.2. Instrumentation

Commercial radiometers and heat fluxmeters, placed at selected locations in the test compartment, were used to determine the heat flux due to radiation alone and also due to the combination of convection and radiation.

Direct measurements of the weight loss rate of the burning combustible materials were made with four strain-gage type load cells positioned at the corners of a 0.94 by 1.60m platform. A single layer of painted 16mm thick gypsum wallboard nailed to wood studs extending from floor to ceiling, was located near the fire and served to represent a typical dwelling wall and to provide an estimate of the fire intensity by the surface area burned.

A Gardon-type heat fluxmeter was mounted on the painted gypsum board for continuous monitoring of heat flux incident on the board from the test fire. This heat fluxmeter was placed at a height of 730mm above the floor, and spaced 51mm from the chair back and small sized wood crib, or 102mm from the medium and large wood cribs. This transducer was made from a copper block with an opening of 19mm in diameter and a 50mm blackened platinum foil screwed over the opening on the copper body. With two fine copper wires soldered to the body and the center of the foil, the meter thereby constituted a copper-platinum thermocouple. The transducer output was calibrated against the radiant flux from of a blackbody cavity placed in a muffle furnace and showed linearity of signal output with an accuracy of $\pm$ 5% over the flux range corresponding to the blackbody temperature range of 500 to 910°C.

The temperatures of the plume gas along the flame axis above the chair or wood crib, the surface of the finished gypsum board, and the heated air at various locations within the compartment were determined by barebeaded thermocouples of 0.5mm diameter Chromel-Alumel wire.

Measurement of the smoke produced by the test fire in the compartment was made by the use of the attenuation of light principle. A photometric system which consisted of a voltage controlled light source, appropriate lenses to collimate and focus the beam, and a photodetector tube was used for continuous measurement of the decrease in light transmittance. The concentration of smoke buildup within the compartment was determined at two locations: one at the 1.52m above the floor with a horizontal beam parallel to the gypsum wall board, situated at a spacing of 2.3m from the gypsum board, and covering the whole room width with a path length of 3.17m; the other at a location near the center of the compartment, separated a horizontal distance of 1.4m from the center of the fire with the beam collimated perpendicular to the floor and having a path length of 2.41m.

All output signals from the radiometers, thermocouples and heat fluxmeters were punched on paper tape for data processing as well as being recorded digitally at 1-minute intervals on a high speed digital acquisition system. Two 2-channel potentiometric strip chart recorders were used to monitor the outputs of smoke meters and load cell.

## 2.3. Test Specimens

The chairs, obtained from a local used furniture outlet, had different weights and constructions and had experienced various degrees of use and wear. Several types of upholstery fabrics were used on these chairs, including cotton, nylon, and rayon. The cushion pads were made of cotton batting, latex rubber, or urethane foam.

The standarized wood cribs were designed to duplicate the conditions produced by the test fires with furniture. A large crib was used to simulate the incidental furniture fire of moderate intensity. This crib, measuring 0.56m x 0.56m x 0.55m high and weighing approximately 33kg, was constructed of cross piles of 34 pieces of nominal 51 x 102 x 560mm long hemlock sticks. A medium sized, 0.51m cubic crib weighing about 25kg and constructed by stacking 30 pieces of 0.51m long sticks was used to represent a lower intensity furniture fire. A smaller 0.36 x 0.36 x 0.30m high crib weighing about 6.3kg and constructed by piling 28 pieces nominal 51 x 51 x 360mm long sticks was used to represent an incidental fire of lower flame height and shorter duration. The large and medium sized cribs had 8 and 7 layers, respectively, each containing four sticks with a 64mm stick spacing for the top four layers, and a 25mm spacing for the remaining layers, plus a bottom two-stick layer, with successive layers laid crosswise. The small crib consisted of six 4-stick and two 2-stick layers and the spacing between sticks except for the bottom two layers was 51mm. The moisture content of the wood cribs was found to be approximately 9 percent. Table 1 summarizes the main parameters of the combustibles involved for each test. Fire load density is defined as the weight of combustible materials per unit projected gross area of the specimen on the floor.

## 3. TEST PROCEDURE

For each upholstered chair test, the ignition source was a methenamine "timed burning" tablet placed at the junction of the chair back with the seat cushion.

For the wood crib tests, the fire was initiated by application of an open flame to ignite 150ml of ethyl alcohol in a square steel pan placed beneath the crib. At ignition of the alcohol all recording instruments were turned on simultaneously. The development and burning behavior of each test fire was observed and recorded during the test.

## 4. TEST RESULTS

### 4.1. Temperature and Heat Flux Levels

Summary data on duration of burning, the maximum rate of weight loss, hot gas temperature, rates of heat transfer to surroundings, smoke generation at the peak of the fire, and the maximum distances at which specimen indicators were affected for each test are presented in table 2.

Most of the upholstered chairs examined burned completely in 40 to 86 minutes with an average of 50 minutes. The duration of the chair fire seems to correspond fairly well to the types of padding materials used in the seat cushion, longer durations being associated with cotton felt.

Table 1. Description of Upholstered Chair and Crib Tests

| Test No. | Materials: Upholstery Fabric | Materials: Padding: Body | Materials: Padding: Cushion | Chair or Crib: Weight (Kg) | Chair or Crib: Width (cm) | Fire Load Density ($g/cm^2$) |
|---|---|---|---|---|---|---|
| 47 | Cotton | Cotton | Cotton | 9.64 | 64 | 2.60 |
| 48 | Rayon/Nylon | Cotton | Cotton | 20.87 | 69 | 3.54 |
| 49 | Nylon | Cotton/ Hair | Cotton | 12.81 | 56 | 3.23 |
| 50 | Cotton | Cotton | Cotton | 21.32 | 58 | 4.44 |
| 51 | Rayon | Cotton | Urethane Foam | 22.91 | 80 | 3.70 |
| 52 | Cotton | Cotton | Urethane Foam | 21.41 | 58 | 4.90 |
| 53 | Cotton | Cotton | Urethane Foam | 14.52 | 65 | 3.09 |
| 54 | Rayon | Cotton/ Hair | Urethane Foam | 27.76* | 76 | 4.36 |
| 55 | Rayon | Cotton/ Hair | Urethane Foam | 29.26 | 102 | 2.36 |
| 56 | 56% Rayon/ 40% Cotton/ 4% Metallic | Cotton | Latex Rubber | 34.47* | 97 | 3.86 |
| 57 | 75% Rayon/ 25% Cotton | Cotton/ Hair | Latex Rubber | 24.81 | 79 | 3.16 |
| 58 | 60% Rayon/ 40% Cotton | Cotton/ Sisal | Urethane Foam | 18.05 | 66 | 2.86 |
| 59 | Cotton | Cotton/ Sisal | Latex Rubber | 25.63 | 69 | 4.42 |
| 60 | 50% Cotton/ 49% Rayon/ 1% Metallic | Cotton/ Hair/ Sisal | Latex Rubber | 32.43 | 97 | 4.01 |
| 61 | Rayon | Cotton/ Wood Fiber/ Hair | Urethane Foam | 29.26 | 102 | 2.36 |
| 62 | 85% Rayon/ 15% Cotton, Cotton** | Cotton/ Hair | Latex Rubber | 29.94* | 71 | 4.28 |
| 63 | Wood Crib (Large Size) | | | 32.89 | 56 | 10.53 |
| 64 | Wood Crib (Large Size) | | | 33.34 | 56 | 10.68 |
| 65 | Wood Crib (Medium Size) | | | 25.76 | 51 | 9.98 |
| 66 | Wood Crib (Medium Size) | | | 25.18 | 51 | 9.75 |
| 68 | Wood Crib (Small Size) | | | 6.35 | 36 | 4.90 |

*Including 2.81 Kg of a 94 - by 127 cm acrylic carpet placed underneath the chair.

**Fabric used for chair slipcover.

Table 2. Summary of Test Results

| Test No. | Duration (min) | Extent Burned | Maximum Burning Rate (g/min) | Maximum Temperature (°C): Flame Plume | Compt. Ceiling | Inside Compt. (Mean) | On Gypsum Board**: Exposed Surface | On Gypsum Board**: Unexposed Surface | Surface Area Affected on Gypsum Board ($m^2$) | Maximum Heat Flux ($W/cm^2$): On Gypsum Board | Distance from the Chair/Crib Center Line: 46 cm Total | 46 cm Radiant | 61 cm Total | 61 cm Radiant | 76 cm Total | 91 cm Total | Maximum Smoke Concentration: Horizontal Time (min) | Horizontal Conc. (O.D./m) | Vertical Time (min) | Vertical Conc. (O.D./m) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 47 | 83 | Completely Consumed | 424 | 866 | 265 | 46 | 205 | 48 | -- | -- | 0.79 | 0.50 | 0.47 | -- | -- | 0.40 | 13 | 0.10 | 23 | 0.23 |
| 48 | 66 | Consumed Partially | 718 | 863 | 222 | 102 | 600 | 62 | -- | -- | 0.82 | 0.73 | 0.64 | -- | -- | 0.50 | 25 | 0.25 | 29 | 0.32 |
| 49 | 56 | Burned Completely | 225 | 200 | 47 | 36 | 58 | 29 | -- | -- | 0.20 | 0.11 | 0.11 | -- | -- | 0.05 | 49 | 0.15 | 41 | 0.25 |
| 50 | 86 | Completely Consumed | 607 | 868 | 171 | 84 | 341 | 53 | -- | -- | 0.90 | 0.63 | 0.60 | -- | -- | 0.30 | 35 | 0.23 | 30 | 0.35 |
| 51 | 41 | Completely Consumed | 897 | 709 | 202 | 92 | 438 | 64 | -- | -- | 2.08 | 1.66 | 1.17 | -- | -- | 0.58 | 9 | 0.17 | 7 | 0.24 |
| 52 | 47 | Completely Consumed | 815 | 975 | 243 | 200 | 517 | 67 | -- | -- | 4.82 | 4.03 | 1.73 | -- | -- | 1.17 | 6 | 0.32 | 6 | 0.4 |
| 53 | 50 | Completely Consumed | 580 | 930 | 185 | 111 | 304 | 49 | -- | -- | 1.70 | 1.48 | 1.17 | -- | -- | 0.61 | 10 | 0.29 | 10 | 0.3 |
| 54 | 63 | Completely Consumed | 622 | 989 | 356 | 271 | 613 | 84 | -- | -- | 4.03 | 3.54 | 3.44 | -- | -- | 1.97 | 16 | 0.32 | 16 | 0.4 |
| 55 | 61 | Completely Consumed | 953 | 928 | 314 | 195 | 419 | 86 | -- | -- | -- | -- | 2.20 | 1.79 | 1.23 | 1.13 | 19 | 0.29 | 24 | 0.4 |
| 56 | 25* | Partially* Burned | 1,314 | 960 | 519 | 419 | 745 | 110 | -- | -- | -- | -- | 5.52 | 4.03 | 3.08 | 3.0 | 12 | 0.36 | 13 | 0.4 |
| 57 | 54 | Completely Consumed | 638 | 962 | 268 | 169 | 451 | 77 | 0.93 | -- | -- | -- | 3.59 | 3.51 | 2.02 | 1.38 | 13 | 0.36 | -- | -- |
| 58 | 55 | Completely Consumed | 431 | 767 | 233 | 124 | 292 | 71 | 0.55 | 6.12 | -- | -- | 1.30 | 1.05 | 0.99 | 0.51 | 24 | 0.23 | 33 | 0.1 |
| 59 | 66 | Completely Consumed | 677 | 847 | 194 | 101 | 332 | 84 | 0.60 | 3.33 | -- | -- | 1.66 | 1.46 | 0.91 | 0.61 | 13 | 0.36 | 12 | 0.4 |
| 60 | 40 | Completely Consumed | 1,177 | 765 | 329 | 209 | 624 | 96 | 1.58 | 10.9 | -- | -- | 2.93 | 2.71 | 2.10 | 1.34 | 7 | 0.43 | 7 | 0.4 |
| 61 | 43 | Completely Consumed | 1,487 | 913 | 432 | 307 | 737 | 94 | 2.04 | 7.32 | -- | -- | 3.31 | 3.22 | 2.91 | 2.34 | 18 | 0.36 | 19 | 0.4 |
| 62 | 35* | Partially* Consumed | 2,722 | 937 | 363 | 273 | 601 | 91 | 2.15 | 13.9 | -- | -- | 5.41 | 3.78 | 3.20 | 2.40 | 30 | 0.38 | 27 | 0.5 |
| 63 | 50 | Completely Burned | 1,008 | 936 | 392 | 138 | 533 | 81 | 1.18 | 2.21 | -- | -- | 1.30 | 1.25 | -- | 0.63 | 2.6 | 0.14 | 2.6 | 0.0 |
| 64 | 51 | Completely Burned | 1,111 | 968 | 407 | 140 | 511 | 82 | 1.15 | 1.80 | -- | -- | 1.35 | 1.29 | -- | 0.69 | 2.5 | 0.12 | 2.5 | 0.0 |
| 65 | 50 | Completely Burned | 888 | 939 | 349 | 110 | 508 | 62 | 0.90 | 1.19 | -- | -- | 1.02 | 0.99 | -- | 0.56 | 0.5 | 0.06 | 0.8 | 0.0 |
| 66 | 47 | Completely Burned | 837 | 996 | 382 | 144 | 479 | 72 | 0.90 | 1.40 | -- | -- | 1.00 | 0.97 | -- | 0.53 | 0.5 | 0.06 | -- | -- |
| 68 | 13 | Completely Burned | 399 | 895 | 302 | 84 | 556 | -- | 0.50 | 2.99 | -- | -- | -- | -- | -- | 1.05 | 8.7 | 0.21 | 7.1 | 0.17 |

*The test fire was extinguished.
**9.5mm thick board placed either 50.8mm from chair back or 0.38m from crib center line except for test no. 67 where the board was located at 0.23m from crib center line.

The temperature of the gases within the test compartment was calculated by averaging of the room gas temperatures measured at 6 locations: 5 at mid-height and the other one at 25mm below the center of the ceiling. Excluding one chair which only partially burned due to the upholstery fabric, the average temperature of air in the compartment at the peak fire conditions ranged from 45 to 420°C with a mean of 180°C. This temperature level developed during the fire makes human occupancy untenable in a short period. Under the conditions of these tests, the danger due to high temperatures was in general found to precede the hazard due to smoke, except for the burning of upholstered chairs cushioned with latex rubber.

The maximum rate of heat transfer from the fire to a vertically oriented black surface located 0.61m from the flame axis varied from approximately 0.5 to 5.5 $W/cm^2$ with a mean of about 2.2 $W/cm^2$, reflecting the different weights and constructions of chairs tested. This level of incident heat flux resulting from combined radiation and convection heating is capable of causing spontaneous ignition of nearby combustible materials.

## 4.2. Smoke Concentration

The average peak concentrations of smoke generated by the burning of chairs containing latex rubber, urethane foam and cotton felt padded seat cushions in the test compartment were of the order of 0.45, 0.34 and 0.30 Optical Density/m (O.D./m), respectively. The elapsed times to reach these peak levels were found separately to be about 10, 17 and 27 minutes after initiation of the fire.

Figure 1 shows the time history of smoke concentration, expressed in terms of optical density per metre smoke thickness, as measured horizontally at 1.53m above the floor, across the width of the test compartment, for fires with typical upholstered chairs and the standardized wood crib. The rate of smoke production during the test was highly variable as it strongly depended upon the nature of the fuel involved and the size and intensity of the fire. The measurement data as shown in the figure indicate that under well-ventilated conditions, the chairs cushioned with latex foam generated the greatest amount of smoke, whereas an open crib produced the least. The smoke concentration within the compartment 1.5m above the floor averaged over the test period was found to be 0.03, 0.29, 0.15 and 0.09 O.D./m, respectively, for fires involving wood crib and the chairs having latex rubber, urethane foam and cotton cushions. The development of smoke was found to occur at the peak of these fires, and as shown in figure 1 the smoke could give rise to a highly dangerous situation.

## 4.3. Effect of Carpet

A preliminary study was made to determine the effect of a carpet on fire behavior by placing a 0.94 by 1.27m acrylic carpet (random shear

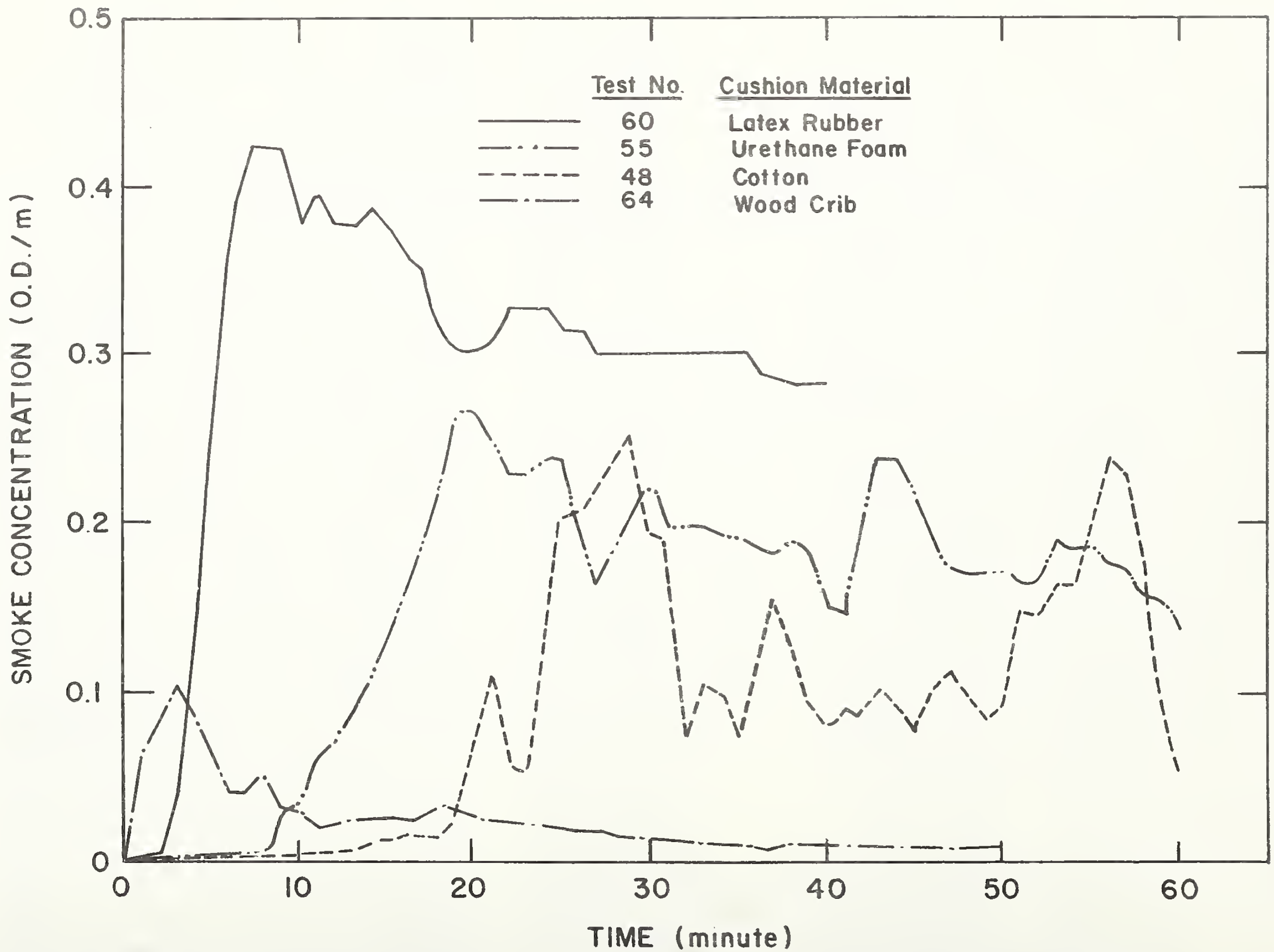


Figure 1. Development of smoke measured at 1.5m above the floor for fires with upholstered chairs and wood crib.

type, polypropylene/jute, pile height 1.6 to 8mm, total weight 2.81kg) underneath the chair. In two of the three tests conducted, it was observed that the entire chair and carpet were enveloped in flames at approximately 30 minutes after ignition and the chair burned more rapidly than those without carpets. This flameover phenomena appeared to result from the ignition of the carpet through direct flame contact with burning chair fragments, however, it was undoubtedly associated with an accumulation of combustible gases generated by the carpet exposed to intense radiation.

## 4.4. Wood Cribs

The behavior of the wood cribs was similar to the upholstered chairs in terms of a relatively low rate of weight loss at the early stage followed by active burning and decay periods. It was found from replicate tests that the weight loss rate, the heat transfer rate to surroundings, and the burning time of these crib fires were fairly repeatable. As illustrated in table 2, at peak fire conditions the average temperature of air inside the test compartment generally increased 80 to 140°C, the air temperature near the ceiling above the crib varied from 300 to 410°C. The total surface area of the painted gypsum board burned was measured after each test and found to be comparable to that of a chair fire.

## 4.5. Waste Receptacle Experiment

In the waste receptacle fire experiment involving the burning of 2.82kg of plasticized paper milk cartons in a nominal 120 liter steel waste receptacle the original weight diminished relatively rapidly during the initial stage of the fire and then at a slower rate. This was due to the change of burning conditions from unlimited air supply to partially restricted air flow as the fire propagated lower into the waste receptacle. In general, waste receptacle fires containing combustibles commonly found in a dwelling or an office had a shorter buildup period than chair or crib fires.

## 4.6. Comparison Data

Typical curves of weight loss versus time for some chair, waste receptacle and crib fires are shown in figure 2. It can be noted from the figure that the upholstered chairs, after being ignited, required between less than 10 to more than 20 minutes to develop into fully involved fires. The maximum weight loss rate for chair fires was quite variable because of diverse weights and constructions of upholstered chairs used for each test.

Figure 3 shows a comparison plot of air temperature measured directly above the fire and measured at 2.5 cm below the ceiling versus

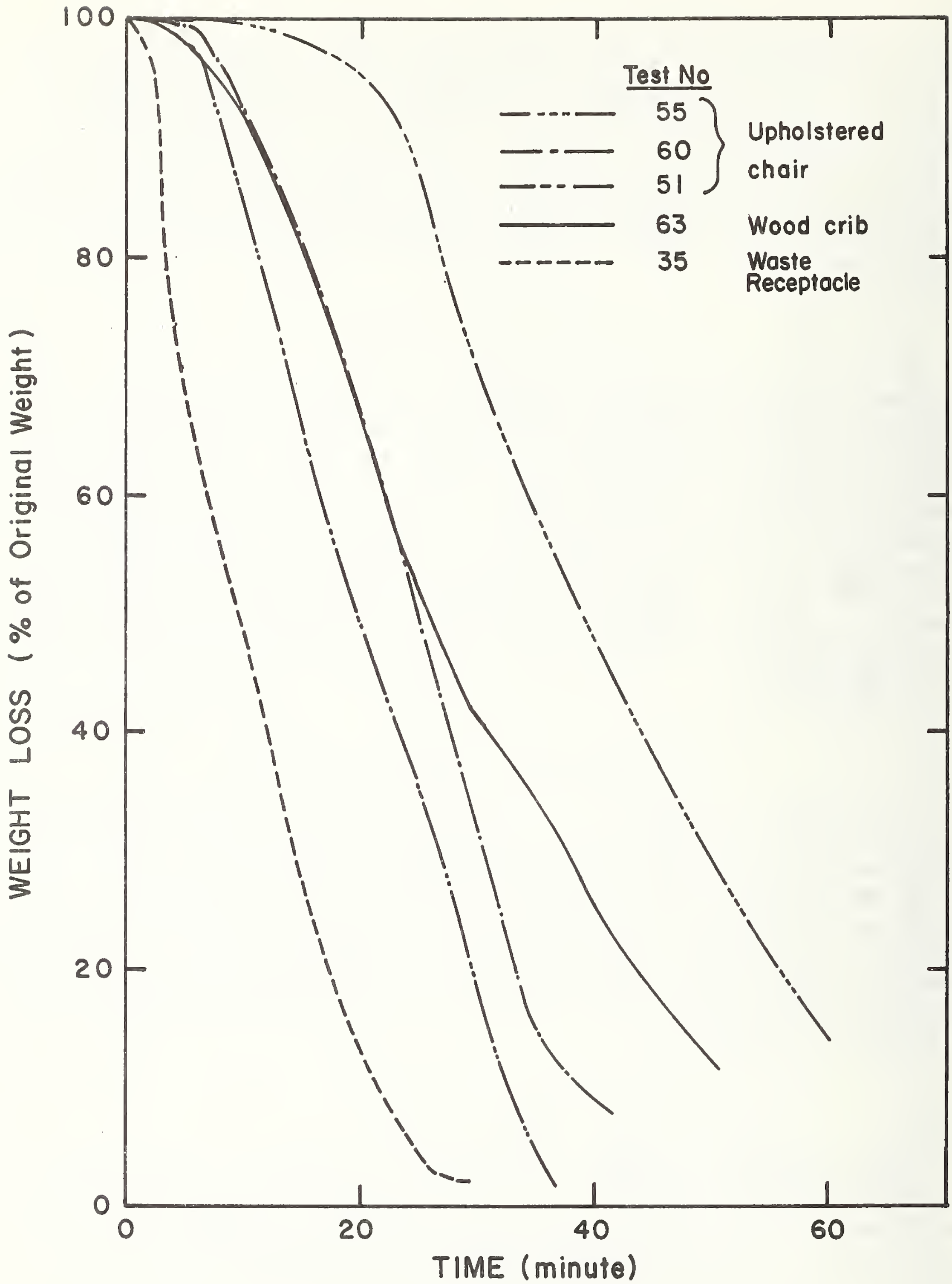


Figure 2. Weight loss versus time curves for fires involving upholstered chairs, wood crib and plasticized milk cartons in a waste receptacle.

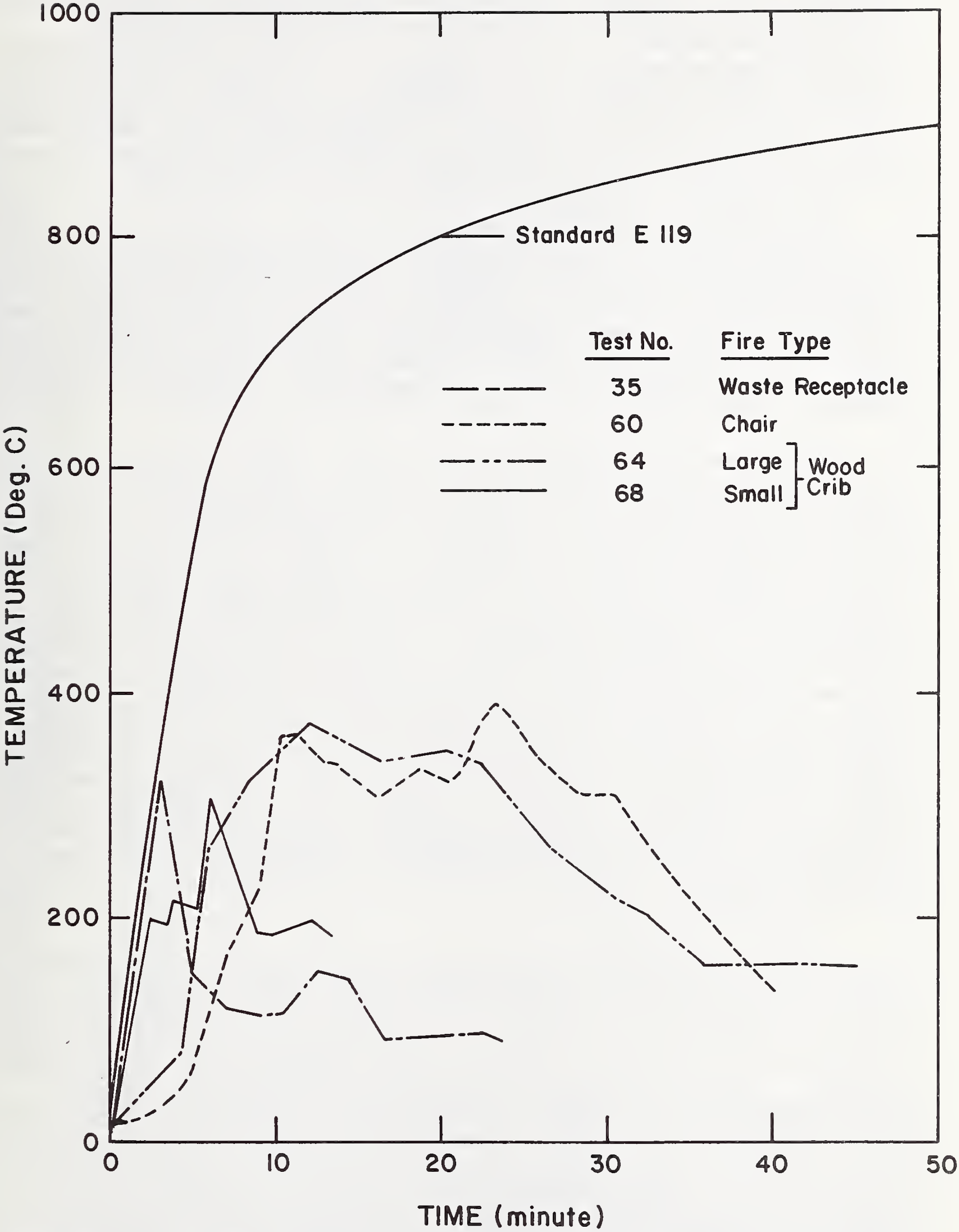


Figure 3. Comparison of air temperature above the fire and near the ceiling for upholstered chair, waste receptacle and wood crib fires.

time for fires involving an upholstered chair, plasticized milk cartons in a waste receptacle and a wood crib. The ASTM E-119 standard temperature-time curve was also plotted in the same figure for comparison. It can be seen that the temperature of hot gases above a waste receptacle fire increases more rapidly than either chair or crib fires during the early stage of burning. The upholstered chair, waste receptacle, and crib fires had a relatively short duration of peak temperature whereas the standard ASTM E-119 curve increased continuously.

The combined radiative and convective heat flux level at various locations was obtained from commercial heat fluxmeters, which were mounted vertically 0.73m above the floor facing the burning object. The measured values of total and radiative fluxes at peak fire conditions for each test are listed in table 2. The experimental data show that radiation was the primary mode of energy transport comprising approximately 75 to 85 percent of the total energy at a distance of 0.46 to 0.61m from the vertical center line of the burning item.

The temporal distributions of the level of heat flux incident on a vertical surface located at a height of 730mm above the floor in the proximity of the test fires and the derived heat flux-time curve for a fully-developed room fire are presented in figure 4. The latter curve has been calculated from the ASTM E-119 standard temperature-time curve with the assumptions that the fire filling a 2.4m high room may be considered as a black-body emitter of infinite width compared to the dimension of a receiver located at a spacing of 0.61m and an elevation of 0.73m measured above the floor. As shown in the figure, the waste receptacle fire had a fairly rapid start and shorter duration in comparison with the fires with furniture or wood arrays. The relatively steep peaks noted in the chair fires are attributed to the high heat release resulting from active burning of the latex rubber and urethane padded seat cushions. The heat flux level for a fully-developed room fire based on the ASTM E-119 test procedure, increases rapidly and continuously with time whereas the typical furniture and crib fires reached peak levels which were considerably lower and occurred within a 30 minute period.

A plot of combined convective and radiative heat flux incident on a vertical plane at 0.61m spacing to the center of the fuel source, is given in figure 5 as a function of heat release rate. The heat release rate was calculated from the rate of weight loss, the projected area of fuel source on the floor, and the calorific values of the combustibles involved. From visual observations, it was found that most chairs burned fairly slowly during the early stage. Then the fire propagated progressively over the highly flammable seat cushion and the back and arms, producing a maximum heat output and large quantities of smoke. Flaming reduced considerably when the upholstered materials were consumed and slower burning wood frames were involved. As illustrated in figure 5, the rate of heat transfer from a freely burning fire was roughly linearly related to the heat release rate. Its magnitude at 0.73m above the floor and 0.61m from the flame axis was estimated to be about 2 percent of the available heat generated, based on unit area occupied by

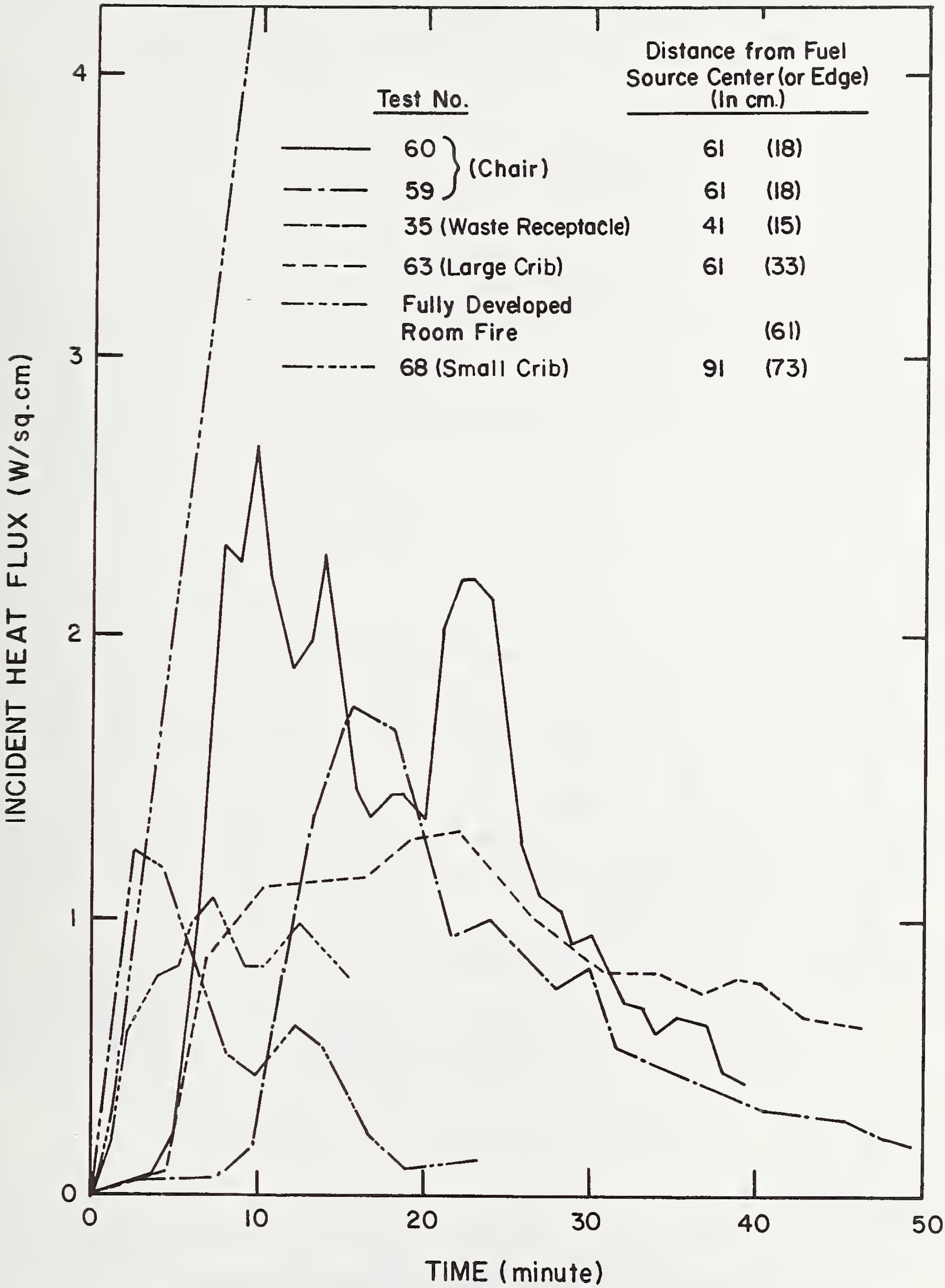


Figure 4. The combined radiative and convective heat flux measured at the selected location versus time for upholstered chair, waste receptacle and wood crib fires.

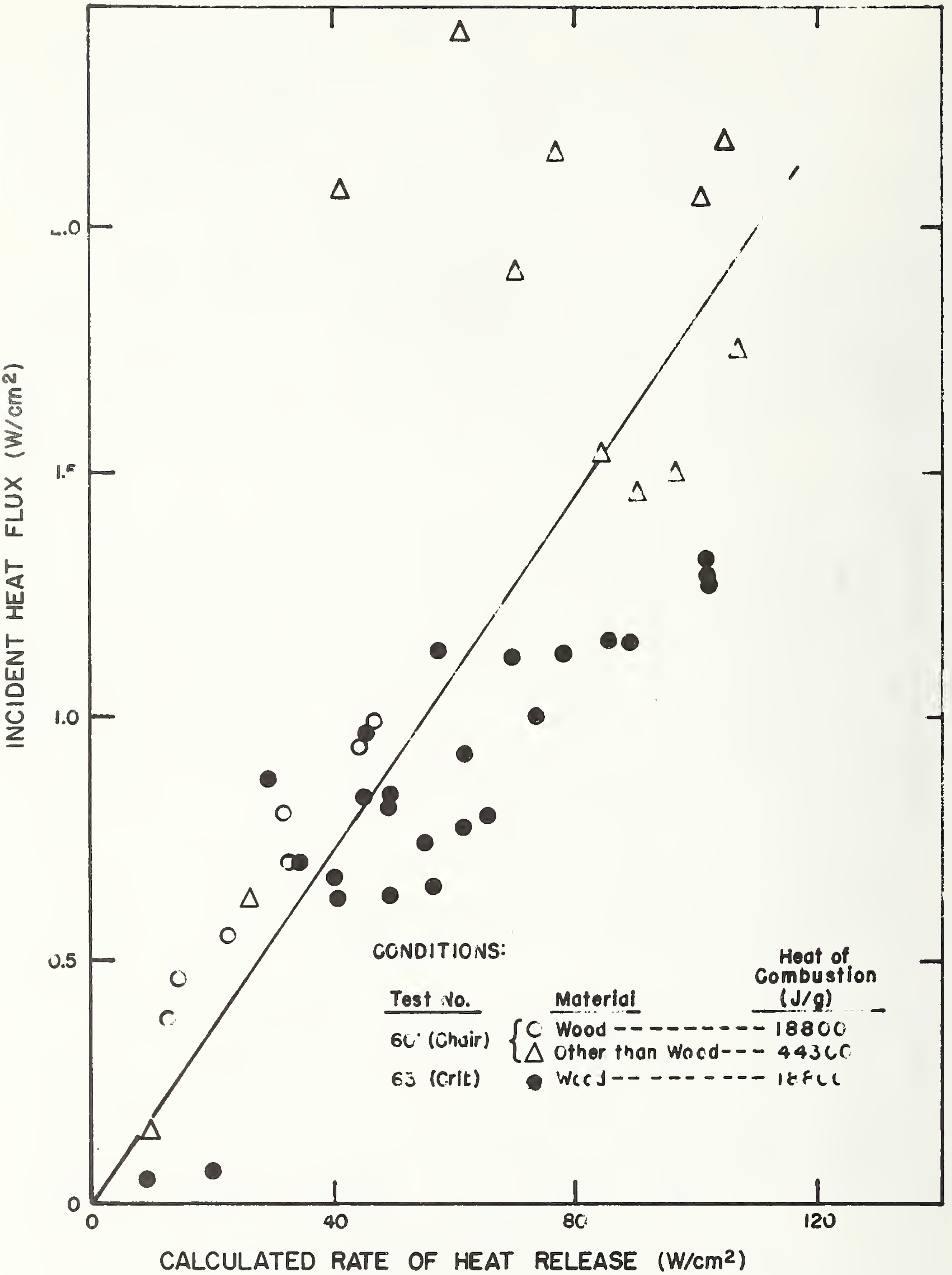


Figure 5. Relationship of combined radiative and convective heat flux incident at 0.61m location and rate of heat release for chair and crib fires.

the fire load. This relationship is expected, since for a given burning source an increase in the burning rate would produce an increase in the flame size, thereby yielding a higher rate of radiative and convective heat transfer.

### 4.7. Spread of Fire

In order to obtain some information concerning the minimum separation distances at which incidental fires would not spread to nearby combustible items, three types of cellulosic materials commonly found in dwellings and offices were studied. These indicator specimens were 0.19mm thick white cotton cloth, 0.08mm thick white paper, and 6.4mm thick cedar wood. All of the specimens were 100mm x 150mm in dimension and were mounted on stands; specimens were mounted on stands at heights of 0.43 and 0.71m above the floor and at fixed distances of 15, 30, 45 and 60 cm from the chair or wood crib. The maximum distance at which the specimen was ignited, charred or scorched by the test fire is given in table 3. There are obvious variations in the distance at which the test fires caused spontaneous ignition. Some fires were unable to ignite white paper as close as 15 cm. These differences are primarily due to the wide variations in fire intensity and periods of exposure to the fluctuating flame. As illustrated in the table, the ignitability of the cotton cloth and white paper used were not much different from that of the wood specimens, and all three seem to provide equal sensitivity as indicators. This is primarily due to low absorptivity of the irradiated surfaces and reduction of the temperature gradients within these thin specimens.

The maximum distance at which the various effects were produced in the specimens of wood, cloth and paper is shown in figure 6 as a function of the maximum fire intensity expressed in terms of the maximum incident heat flux. This heat flux was measured at a horizontal distance of 0.61m from the center of the chair and at a height of 0.73m above the floor. The ignition distances found ranged from 0.15m for light weight upholstered chairs to 0.60m for moderate sized chairs with a carpet beneath. Most chair fires caused ignition of wood at a separation distance of 0.15m, char at 0.30m and scorch at a distance of 0.60m within 30 minutes after ignition of the furniture item.

## 5. CALCULATIONS OF HEAT FLUX

Since radiation is found to be the dominant mode of energy transport, the magnitude of radiant heat flux impinging on a neighboring object from a fire depends upon temperature, total emissivity of the flame, and the view factor between the flame emitter and the receiver.

Calculations of the radiant flux distribution around a radiating flame generally involve complex integration procedures and numerical techniques [2,3]. A mathematical model of free-burning fires [4] has

Table 3. Distances at Which the Indicator Specimens Were Affected for Upholstered Chair and Wood Crib Fires

| Test No. | Maximum Distance (cm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Paper Sheet | | | Cotton Cloth | | | Wood Plate | | |
| | Ignited | Charred | Scorched | Ignited | Charred | Scorched | Ignited | Charred | Scorched |
| 50 | -- | 15 | -- | -- | 15 | -- | -- | 15 | -- |
| 51 | 15 | -- | 45 | 15 | -- | 45 | -- | 15 | 45 |
| 52 | 15 | 30 | 45 | 15 | 30 | 60 | 15 | 30 | 45 |
| 53 | -- | 15 | 30 | -- | 15 | 30 | -- | 15 | 30 |
| 54 | 30 | 60 | -- | 30 | 60 | -- | 30 | 60 | -- |
| 55 | -- | 15 | 30 | -- | 15 | 30 | -- | 15 | 30 |
| 56 | 60 | -- | -- | 60 | -- | -- | 45 | 60 | -- |
| 57 | 15 | 45 | 45 | 15 | 45 | 45 | 15 | 30 | 45 |
| 58 | -- | 15 | 30 | -- | 15 | 30 | -- | 15 | 30 |
| 59 | 15 | -- | 30 | 15 | -- | 30 | 15 | -- | 30 |
| 60 | 15 | 30 | 60 | 15 | 30 | 60 | 15 | 30 | 60 |
| 61 | 15 | 60 | -- | 15 | 60 | -- | 15 | 45 | 60 |
| 62 | 30 | 60 | -- | 30 | 60 | -- | 30 | 60 | -- |
| 63 | 15 | 30 | 60 | 15 | 30 | 60 | 15 | 30 | 60 |
| 64 | 15 | 30 | 60 | 15 | 30 | 45 | 15 | 30 | 45 |
| 65 | 15 | -- | 36 | 15 | -- | 36 | 15 | -- | 36 |
| 66 | 15 | -- | 36 | 15 | -- | 36 | 15 | -- | -- |

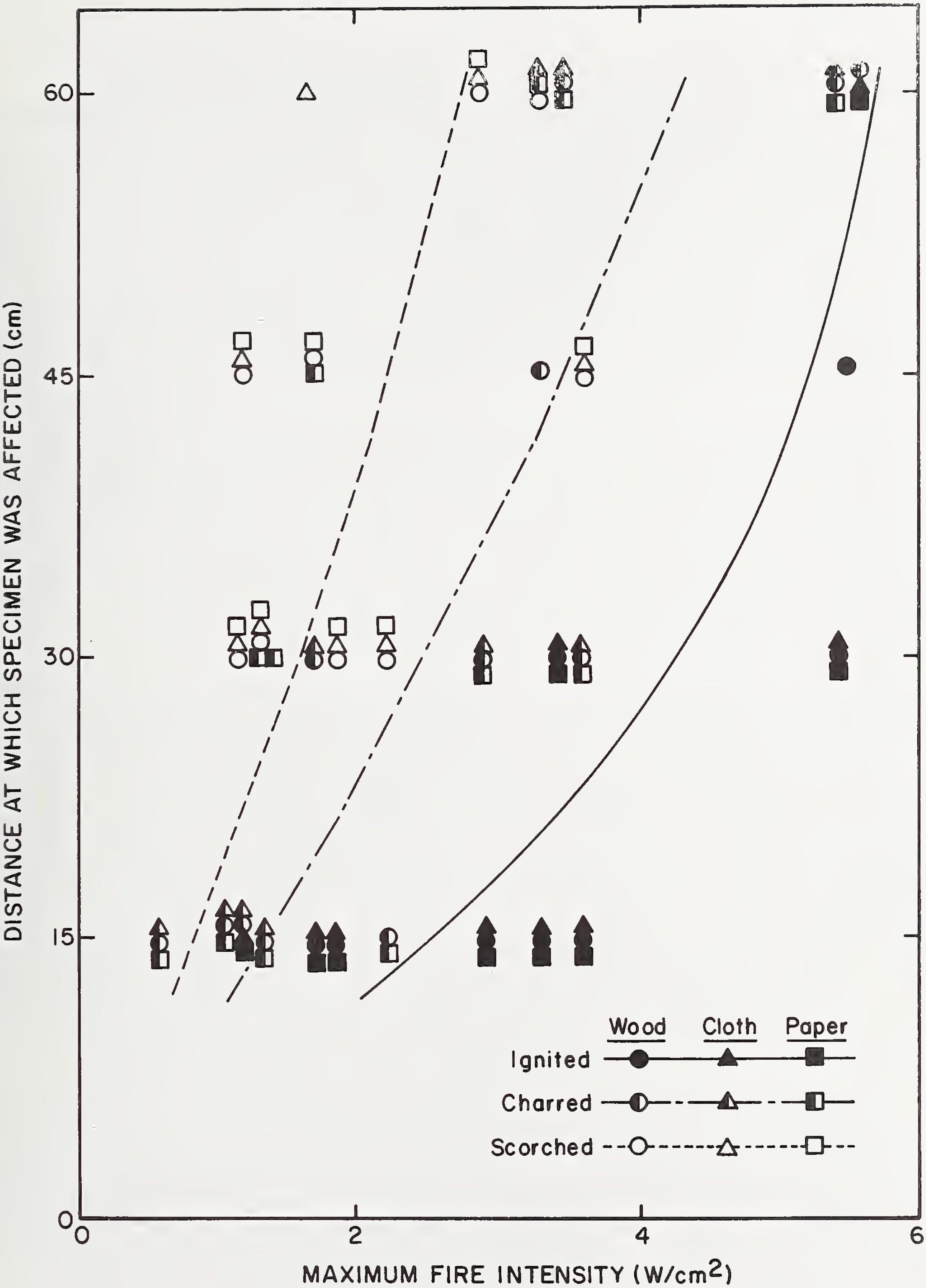


Figure 6. Fire intensity and distances at which specimens were affected.

been recently developed to relate the burning rate and fuel properties to the flame physical and geometrical properties, which are essential information required in radiative analysis. In order to estimate heat flux levels at various locations, the freely burning fire is assumed to be a finite cylinder having a diameter equal to the fuel source width, a height identical to the visible flame height, a constant emittance, and a constant temperature. Figure 7 presents calculated curves of view factor for radiant exchange between a differential plane receiver and a right circular cylinder, as a function of the dimensionless separation distance for two typical dimensionless flame heights, and two heights of the receiver measured above the flame base. An analytical expression of the view factor for the configuration illustrated in the figure is given in appendix A.

Experimental data on heat flux measured at different locations are plotted and presented in figure 8, where the incident heat flux at peak fire conditions is plotted against the geometric view factor calculated on the basis of the relative location of the heat fluxmeter, the width of the combustible item and the measured flame height. It can be seen that all the data in each test fall adjacent to a regression line, and the resultant heat flux conditions produced by the fires from the developed simple wood arrays lie within those created by incidental fires.

Figure 9 compares the curves showing the time history of rate of heat release, based on the projected area of the combustible item on the floor, for fires with upholstered chair, wood crib and plasticized milk cartons in a waste receptacle. As noted before, the rates of heat output from the burning chairs are widely varied and significantly dependent upon the types of padding materials, design and construction of the furniture item involved. The simplified fuel arrays can be utilized to synthesize fire buildup conditions for furniture since the heat output pattern of standardized crib fires approximately simulate that of certain furniture fires as shown in the figure. The maximum rate of heat output and the total amount of heat energy released per unit projected area by test fires were estimated to be of the order of 120 kW and $2.7 \times 10^4$ J/cm$^2$, respectively, for waste receptacle fires, 320 kW and $15 \times 10^4$ J/cm$^2$ for large crib fires and 130 kW and $5.8 \times 10^4$ J/cm$^2$ for fires involving a small wood crib, and 870 kW and $16 \times 10^4$ J/cm$^2$ for furniture fires of moderate intensity.

Figure 10 shows a plot of the combined radiative and convective heat flux at the flame edge versus the computed rate of heat release at peak fire condition. The former was estimated from figure 8 by extrapolating the regression line to intercept with the ordinate corresponding to a view factor equal to unity. The peak heat flux level in the proximity of the test fire varied widely: ranging from approximately 0.9 W/cm$^2$ for chairs padded with cotton felt to 8.5 W/cm$^2$ for those with plastic foam. As shown in the figure, there was a trend of linear relationship existing between the heat flux from the flame envelope and the computed heat release rate. The heat flux level was estimated to correspond to approximately 4 percent of the available heat released based on unit area projected by the combustible item on the floor.

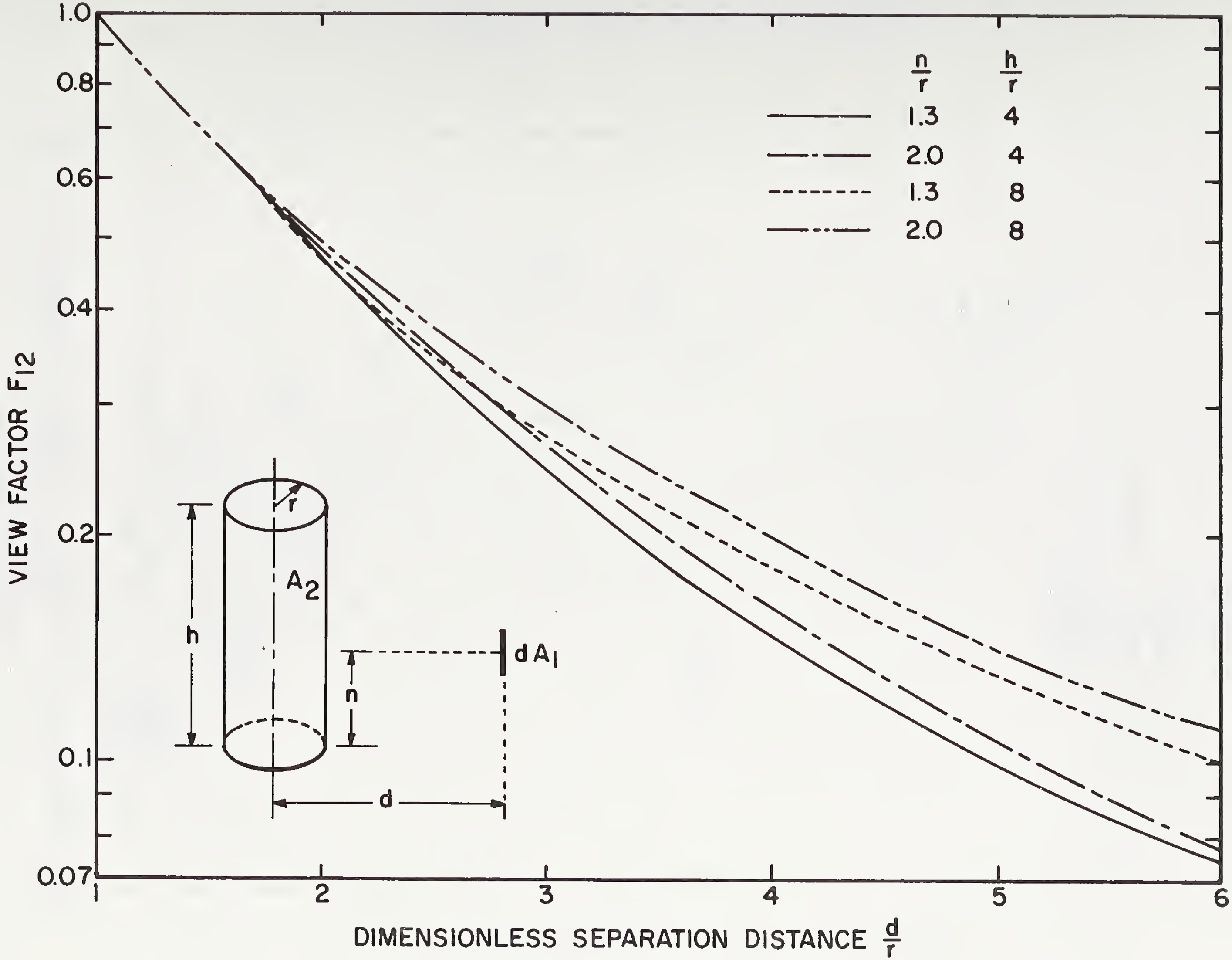


Figure 7. View factor curves for radiant interchange between a differential plane receiver and a right circular cylinder.

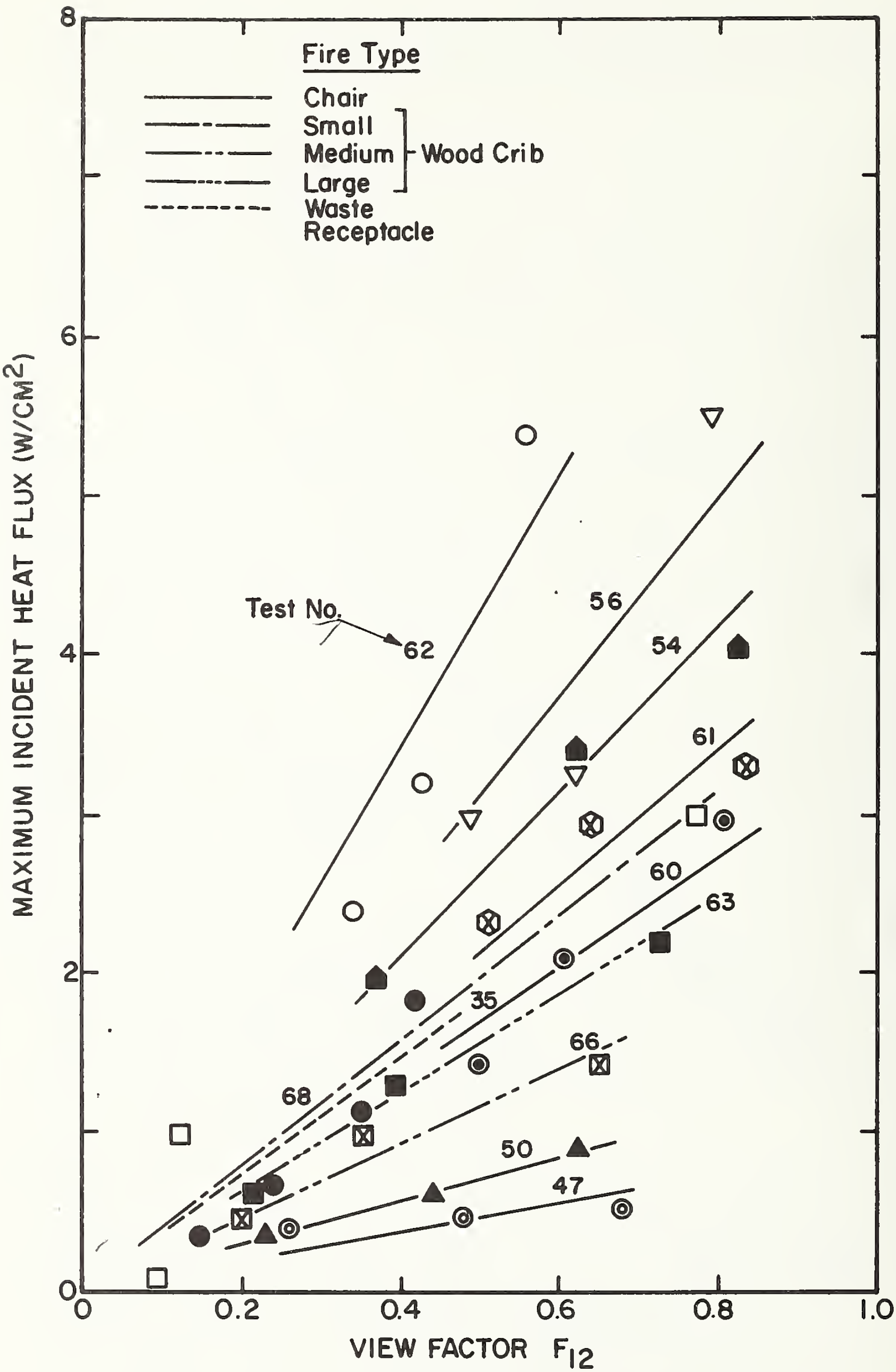


Figure 8. Relationship between the measured incident heat flux and the view factor from the receiver to the fire.

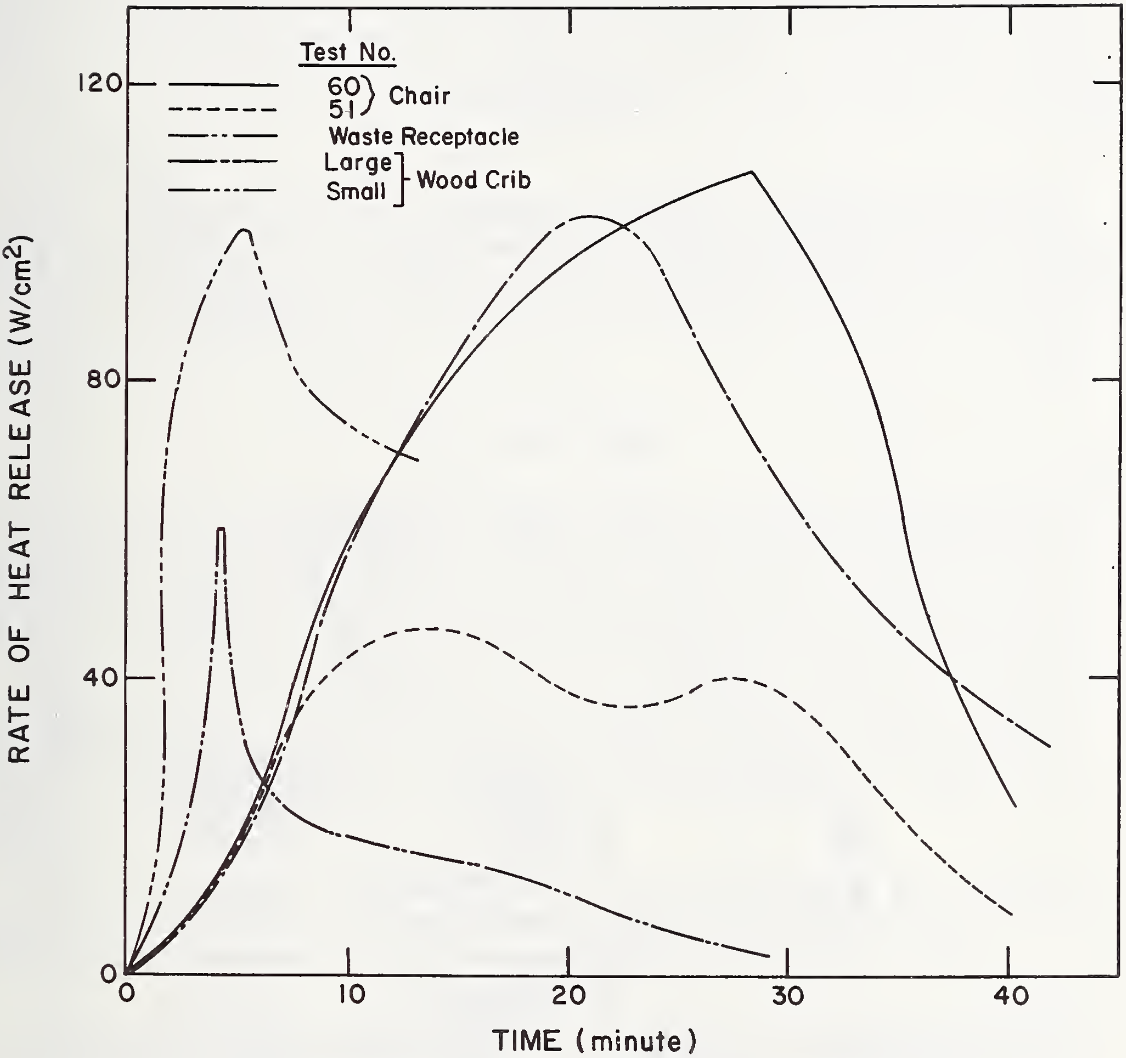


Figure 9. Comparison of rate of heat release for furniture, wood crib and waste receptacle fires.

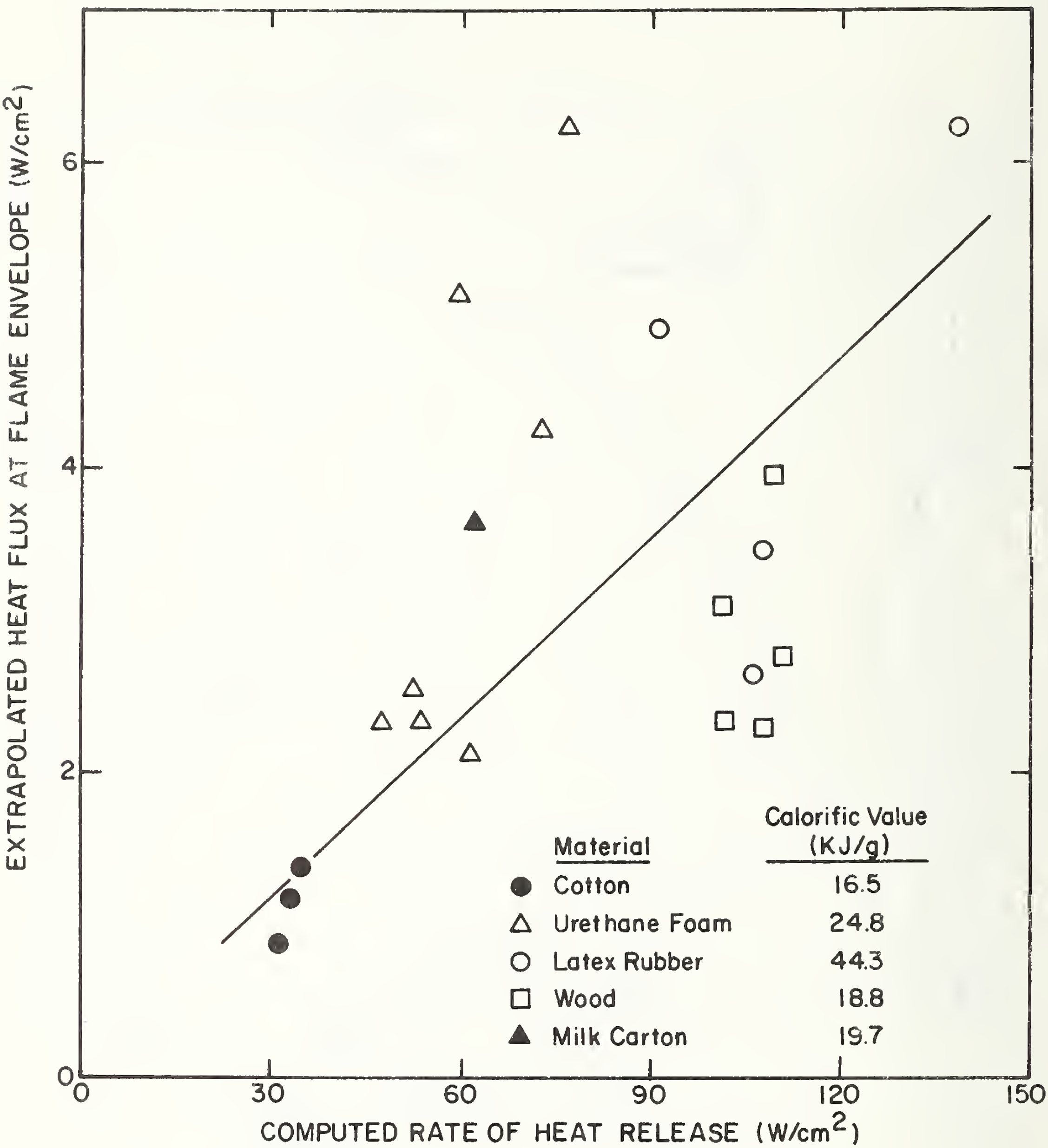


Figure 10. Relationship between the computed rate of heat release and the extrapolated heat flux at flame envelope.

A relationship showing flame emissivity and half-width of the fuel source is presented in figure 11. The emissivity of the flame for each test was calculated by using the extrapolated value of the heat flux at the flame envelope and the flame temperature measured with the unshielded thermocouples located along the flame axis. The flame emissivity data from chair fires was found to be considerably dispersed. This may be attributed to wide variations in the concentration and composition of the radiating gases and the presence of varying amounts of soot and smoke particles from the burning of different types of upholstered chairs. The attenuation coefficient k, is defined by the equation:

$$k = \frac{-\ln (1-\varepsilon)}{r} \qquad (1)$$

This coefficient can be estimated from flame thickness, which is approximately equal to the source width 2r, and calculated flame emissivity $\varepsilon$. The equation of a best fit line drawn in figure 11 was obtained by regression analysis and the average attenuation coefficient for these test fires was found to be $1.13 m^{-1}$.

## 6. CONCLUSIONS

Incidental fires generally produce high fire plume temperatures and intense heat flux in local areas and may approach the fire severity as represented by the ASTM Standard E-119 test method for fully involved room fires. However, these levels of air temperature and heat flux to adjacent surfaces at peak fire conditions exist for only short periods.

The rate of heat transfer from a freely burning fire was found to be roughly linearly related to the heat release rate or fuel burning rate, and its magnitude at the flame boundary accounted for approximately 4 percent of the heat generation rate based on unit area of the combustible item projected on the floor.

The fire with a standardized wood crib can duplicate the essential characteristics, such as burning time, temperature and heat flux levels and the size and shape of the flame, of typical incidental fires.

Data on heat flux levels measured at various locations were, for a given item, correlated fairly well by a simplified derived expression based on an assumption of considering the fire to be cylindrical in shape and a gray-body emitter with constant temperature.

The upholstered chairs furnished with latex foam cushion produced higher levels of smoke concentration than those with cotton felts or urethane foam.

The distances at which spontaneous ignition of wood would occur varied from 0.15m for light-weight burning chairs to 0.45m for moderate sized ones above a carpet.

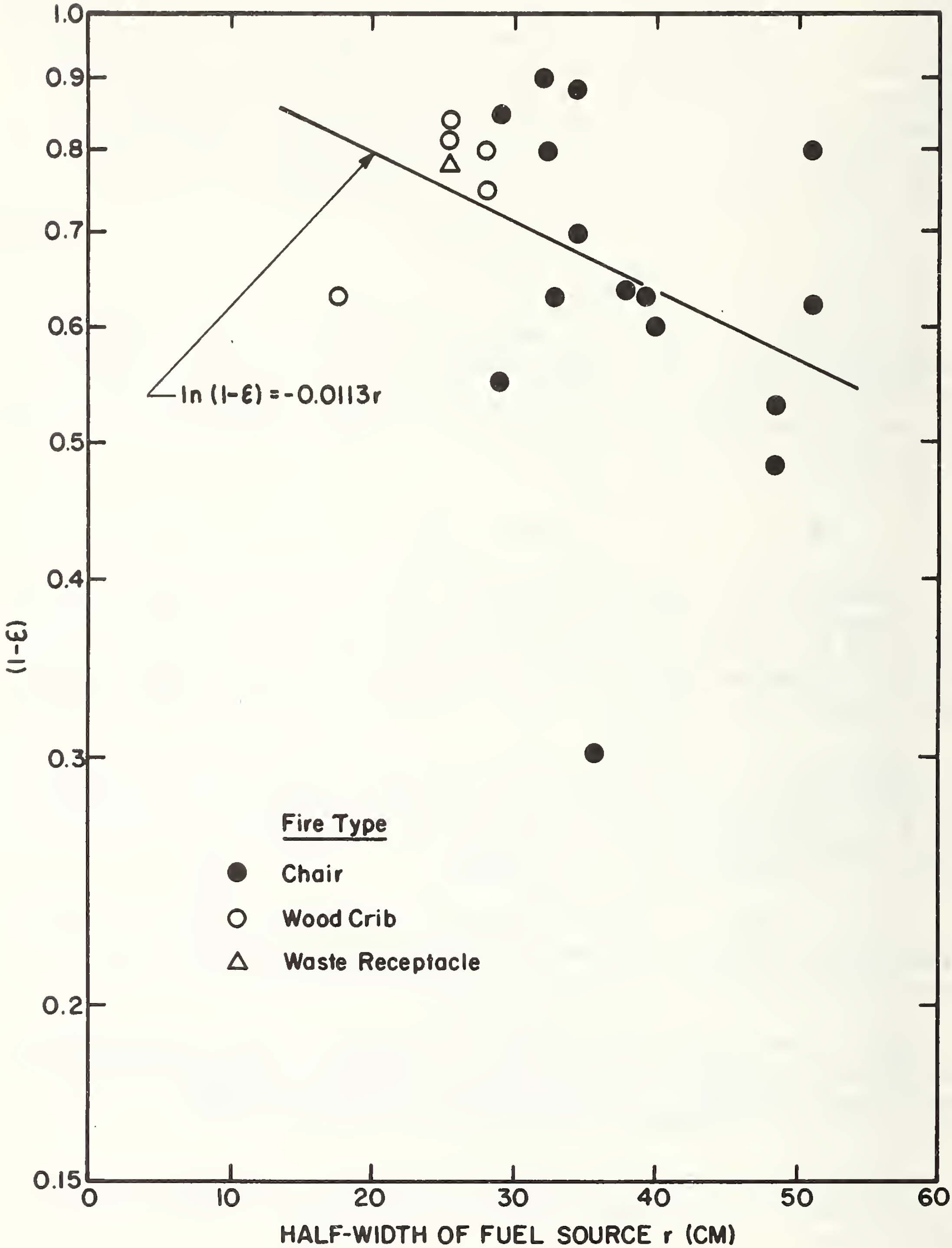


Figure 11. Flame emissivity versus half-width of the fuel source for furniture, wood crib and waste receptacle fires.

## 7. ACKNOWLEDGEMENTS

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## APPENDIX - VIEW FACTOR

The view factor for radiant interchange between a right circular cylinder $A_2$ of radius r and height h, and a differential area element dA, with its normal perpendicular to the axis of the cylinder, as shown in the sketch of figure 7, can be expressed by the following equation [5]:

$$F_{12} = \frac{1}{\pi L}\left\{\tan^{-1}\left[\frac{N}{\sqrt{L^2 - 1}}\right] + \tan^{-1}\left[\frac{(H-N)}{\sqrt{L^2-1}}\right] + \frac{(H-N)\ (P_1-2L)}{\sqrt{P_1 \quad Q_1}} \tan^{-1}\sqrt{\frac{P_1(L-1)}{Q_1(L+1)}} \right.$$

$$\left. + \frac{N(P_2-2L)}{\sqrt{P_2 Q_2}} \tan^{-1}\sqrt{\frac{P_2(L-1)}{Q_2(L+1)}} - H \tan^{-1}\sqrt{\frac{L-1}{L+1}}\right\} \qquad (2)$$

where $L = \frac{d}{r}$, $N = \frac{n}{r}$, $H = \frac{h}{r}$

$$P_1 = (L + 1)^2 + (H - N)^2, \quad P_2 = (L + 1)^2 + N^2$$

$$Q_1 = (L - 1)^2 + (H - N)^2, \quad Q_2 = (L - 1)^2 + N^2$$

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15. SUPPLEMENTARY NOTES

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

A variety of upholstered chairs and wood cribs were burned within a ventilated compartment. The experimental measurements of weight loss, smoke concentration, temperature and heat flux levels are summarized. A reproducible fire obtained from burning a standardized wood crib array was found to be capable of representing the essential features of incidental fires of moderate intensity.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)* Buildings; combustibility; fire intensity; flames; furnishings; heat release; ignition; smoke; thermal radiation; upholstery; waste receptacle.

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