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Law Enforcement and Corrections Standards and Testing Program

FULL SCALE ROOM BURN PATTERN STUDY

NIJ Report 601-97

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Full Scale Room Burn Pattern Study

NIJ Report 601-97

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Jeremy Travis
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This report was prepared with the assistance of the Office of Law Enforcement Standards (OLES) of the National Institute of Standards and Technology (NIST) under the direction of Kathleen M. Higgins, Director of OLES. The room fire experiments were conducted in cooperation with the Bureau of Alcohol, Tobacco, and Firearms (BATF) as part of an arson investigation training program. The gas concentration measurements included in this report were conducted and the data analyzed by Mr. Nelson Bryner of NIST. The photographs in the report were provided by Mr. John Goetz of Investigative Resources Global, Inc., and Dr. Robert Levine of NIST. The drawings were produced by Mr. Bill Josler of NIST. This work was sponsored by the National Institute of Justice, David G. Boyd, Director of Science and Technology.

FOREWORD

The Office of Law Enforcement Standards (OLES) of the National Institute of Standards and Technology (NIST) furnishes technical support to the National Institute of Justice (NIJ) to strengthen law enforcement and criminal justice in the United States. OLES's function is to conduct research that will assist law enforcement and criminal justice agencies in the selection and procurement of quality equipment.

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This document covers research conducted by OLES under the sponsorship of the NIJ. Additional reports as well as other documents are being issued under the OLES program in the areas of protective clothing and equipment, communications systems, emergency equipment, investigative aids, security systems, vehicles, weapons, and analytical techniques and standard reference materials used by the forensic community.

Technical comments and suggestions concerning this report are invited from all interested parties. They may be addressed to the Office of Law Enforcement Standards, National Institute of Standards and Technology, Gaithersburg, MD 20899-0001.

David G. Boyd, Director
Office of Science and Technology
National Institute of Justice

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LIST OF ACRONYMS USED IN THIS REPORT

CE	capillary electrophoresis
DBP	dibutylphthalate
DEP	diethylphthalate
DNT	dinitrotoluene
DPA	diphenylamine
EC	ethyl centralite
MC	methyl centralite
MECE	micellar electrokinetic capillary electrophoresis
NC	nitrocellulose
nDPA	nitrodiphenylamine
NG	nitroglycerin
NGU	nitroguanindine
N-nDPA	N-nitrosodiphenylamine
SDS	sodium dodecylsulfate
SEM	scanning electron microscopy
SEM/EDX	scanning electron microscopy/energy dispersive X-ray analysis
OLES	Office of Law Enforcement Standards
NIST	National Institute of Standards and Technology

GLOSSARY

Accelerant liquid A liquid used to ignite or increase the burning rate or spread of a fire.

Clean burn A fire pattern found on surfaces where smoke deposits have been burned away.

Flashover A transitional phase of a compartment fire where a rapid change from localized burning to involvement of all exposed combustible materials occurs.

Heat flux The rate of transfer of heat to a surface. Examples of units of measurement are kW/m^2 or $Btu/(hr\text{-}ft^2)$

Neutral plane The vertical location in a fire compartment opening above which hot fire gases flow out of the opening, and below which cooler gases flow into the opening. The pressure on this horizontal plane is equal to local atmospheric pressure.

Post-flashover The phase of a compartment fire occurring after flashover.

Thermocouple Temperature measurement device, consisting of a junction of two dissimilar metals which produce an electric potential, the magnitude of which is dependent on the temperature of the junction.

V pattern Lines of demarcation formed on surfaces in the shape of a "V" as the result of burning or differences in the deposition of smoke.

View factor radiation A coefficient used in heat transfer calculations that takes into account the geometric relationship that exists between the emitter and the receiver of the radiant heat.

FULL SCALE ROOM BURN PATTERN STUDY

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One method fire investigators use to determine the cause and origin of a fire is the study of patterns or "indicators" left on building components or building contents by the fire. Previous studies have shown that some traditionally used indicators have little or no technically defensible basis. In order to study the patterns or "indicators" produced by fires, full scale experiments were conducted using test rooms furnished as residential bedrooms. Temperatures and heat fluxes at various locations in the rooms were measured. In some cases, the concentrations of oxygen, carbon monoxide and carbon dioxide were measured. This report describes the experimental setup, measurement results, and the post fire inspection of the rooms.

Key words: accelerants; arson; building fires; burn patterns; carbon dioxide; carbon monoxide; char; charring; fire investigations; fire measurements; oxygen concentration; residential buildings; room fires.

1. INTRODUCTION

Fire investigators may determine the cause and origin of a fire from patterns or "indicators" left on building components or building contents by the fire. Previous studies have shown that some traditionally used indicators have little or no technically defensible basis. The National Fire Protection Association (NFPA) 921 committee "Guide for Fire and Explosion Investigators," is working to document legitimate fire investigation methodologies, in order to discourage the use of technically unfounded or indefensible methods. Support for such endeavors, as well as a common interest in the development and verification of fire investigation tools has come from the Bureau of Alcohol, Tobacco and Firearms (BATF), the National Institute of Justice (NIJ), and the United States Fire Administration (USFA).

In order to study the patterns or "indicators" produced by fires, a series of four full scale experiments involving two different fire ignition scenarios were conducted at the University of Maryland, Maryland Fire & Rescue Institute (MFRI) using test rooms furnished as residential bedrooms. The first scenario involves a fire in an upholstered chair, ignited by newspaper. The second scenario includes a gasoline spill fire on the hardwood floor of the room. The fuel loads of all four rooms, with the exception of the flooring material, were very similar. The test rooms were instrumented and the data recorded by the University of Maryland, with the exception of the gas concentration measurements in this report, which were provided by NIST. Reports of test have been provided by the University of Maryland which describe and report data from the experiments.[1,2]

Temperatures and heat fluxes at various locations in the room were measured. Concentrations of oxygen, carbon monoxide and carbon dioxide were measured in two of the experiments. After fire extinguishment, the condition of the rooms and contents were studied. This report describes the experimental setup, measurement results, and the post fire inspection of the rooms.

2. EXPERIMENTS

2.1 Structure

Rooms with features resembling typical residential bedrooms were constructed within the fire tower at MFRI. The rooms in all four experiments were approximately 3.66 m wide, 3.66 m long, and 2.44 m high. Each room had a single

[1] Milke, J. A., and Hill, S. M. "Full-Scale Room Fire Experiments Conducted at the University of Maryland." NIST GCR-96-703, National Institute of Standards and Technology, October 1996.
[2] McGarry, A. J., and Milke, J. A. "Full-Scale Room Fire Experiments Conducted at the University of Maryland." NIST GCR- 97-716, National Institute of Standards and Technology, March 1997.

open doorway, with a door that was completely open during the experiments. The doorways measured approximately 0.91 m wide, with heights of approximately 2.09 m. The rooms were each fitted with one, double-hung window. The overall dimensions of the window frames were approximately 0.91 m wide and 2.09 m high, with the bottoms of the window frames located approximately 0.90 m above the floor. Each pane of glass measured approximately 0.69 m wide by 0.38 m high. The windows in two of the experiments were double pane windows, while the other two experiments utilized single pane windows. The window types for the experiments are identified in Table 1.

TABLE 1. *Window type*

Experiment	*Window Type*
1	double pane
2	double pane
3	single pane
4	single pane

While the layout of each of the rooms was nearly identical, the locations of the rooms inside the burn tower differed. The differences in the locations of the rooms resulted in differing ventilation conditions for the experiments, which will be discussed later. The need for different room locations was a result of the time constraints of the experimental series, which was performed in conjunction with a BATF fire investigation training program.

2.2 Chair Ignition Fires (Experiments 1 and 2)

2.2.1 Fuel Load

The rooms were furnished as typical residential bedrooms. The contents of each room included a bed, dresser, nightstand, wastebasket, two lamps, and an upholstered chair. The rooms had wall-to-wall nylon carpeting on the floor, over a polyurethane carpet pad. Unpainted wooden baseboard molding was provided around the perimeter of the carpeted floors. A list of room furnishings, including descriptions of the items, is provided in Table 2. The individual and total masses of the room furnishings are listed in Tables 3 and 4. Note that the differences in the masses of the room furnishings in these two experiments is due to the types of lamps in the room. While the construction of the lamps is expected to have little, if any, effect on the fire development within the rooms, the types and locations of the lamps are evident in the post fire photographs, and are listed in the tables and diagrams for completeness.

Figure 1 shows the plan view of the furnished room. Experiments 1 and 2 were ignited using four sheets of newspaper on the seat of an upholstered chair. A book of paper matches was ignited, and placed under the newspaper.

2.2.2 Thermocouples

The rooms were instrumented for the measurement of temperature with thermocouple arrays strung vertically between the ceiling and the floor. The locations of the thermocouple arrays are shown in Figure 2. Each array was composed of eight thermocouples, at vertical spacings of approximately 0.31 m. Table 5 indicates the distance of each thermocouple in the array above the floor of the room. A thermocouple array was also installed near the door of the room. This array had different thermocouple spacings than the arrays in other locations. The distances of thermocouples above the floor in the doorway are indicated in Table 6.

TABLE 2. *Room furnishings*

Item	*Description*
Bed	Approximately 1.82 m by 0.91 m by 0.56 m. Mattress and box spring on metal frame. Bed made with sheets, blanket, polyurethane bedspread, and pillow.
Dresser	Approximately 1.32 m by 0.46 m by 0.76 m.
Nightstand	Approximately 0.53 m by 0.22 m by 0.55 m.
Lamp, type 1	Ceramic lamp with bulb. Approximately 0.66 m high, with diameter of base varying from 0.25 m to 0.15 m.
Lamp, type 2	Metal lamp with bulb. Approximately 0.63 m high, with 0.16 m base diameter.
Wastebasket	Constructed of thermal plastic. Approximately 0.38 m high, 0.31 m wide, and 0.18 m deep.
Upholstered chair	Approximately 0.97 m wide by 0.91 m deep. Back approximately 0.61 m high, seat approximately 0.41 m high. Wood frame, fabric over polyurethane padding.

TABLE 3. *Mass of furnishings, Experiment 1*

Item	*Approximate Mass (kg)*
Bed—includes mattress, box spring, and headboard	37.5
Bed frame (metal)	12.5
Bedding materials—includes two sheets, pillow case and pillow, blanket, and bedspread	4.5
Carpet and pad	21.0
Upholstered chair	32.0
Dresser	42.0
Nightstand	15.0
Lamp, type 1	2.5
Lamp, type 1	2.5
Wastebasket, with trash	0.6
Total	170.1

TABLE 4. *Mass of furnishings, Experiment 2*

Item	*Approximate Mass (kg)*
Bed—includes mattress, box spring, and headboard	37.5
Bed frame (metal)	12.5
Bedding materials—includes two sheets, pillow case and pillow, blanket, and bedspread	4.5
Carpet and pad	21.0
Upholstered chair	32.0
Dresser	42.0
Nightstand	15.0
Lamp, type 2	3.0
Lamp, type 2	3.0
Wastebasket, with trash	0.6
Total	171.1

TABLE 5. *Thermocouple locations*

Thermocouple Number	*Distance Above Floor, m (ft)*
8	2.44 (8.00)
7	2.14 (7.00)
6	1.83 (6.00)
5	1.53 (5.00)
4	1.22 (4.00)
3	0.92 (3.00)
2	0.61 (2.00)
1	0.31 (1.00)

TABLE 6. *Thermocouple locations, near door*

Thermocouple Number	*Distance Above Floor, m (ft)*
8	2.44 (8.00)
7	2.08 (6.82)
6	1.78 (5.82)
5	1.47 (4.82)
4	1.17 (3.82)
3	0.86 (2.82)
2	0.55 (1.82)
1	0.00 (0.00)

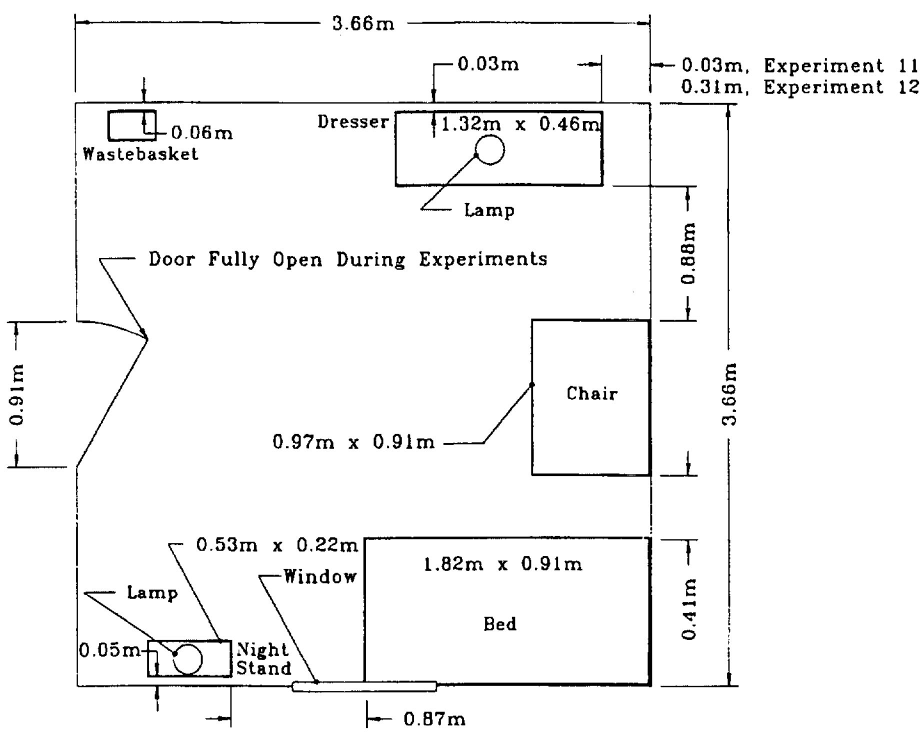

FIGURE 1. *Plan view of furnished rooms. Experiments 1 and 2.*

2.2.3 Heat Flux Transducers

Water cooled heat flux transducers were installed at two locations in the room as shown in Figure 2. The transducers were installed approximately 0.15 m above the floor of the room, facing upwards. One of the heat flux transducers was installed in the center of the room, with a second installed in the doorway. The transducers and their associated wiring and cooling water tubes were protected by a wooden bridge measuring approximately 0.15 m wide by 0.15 m high.

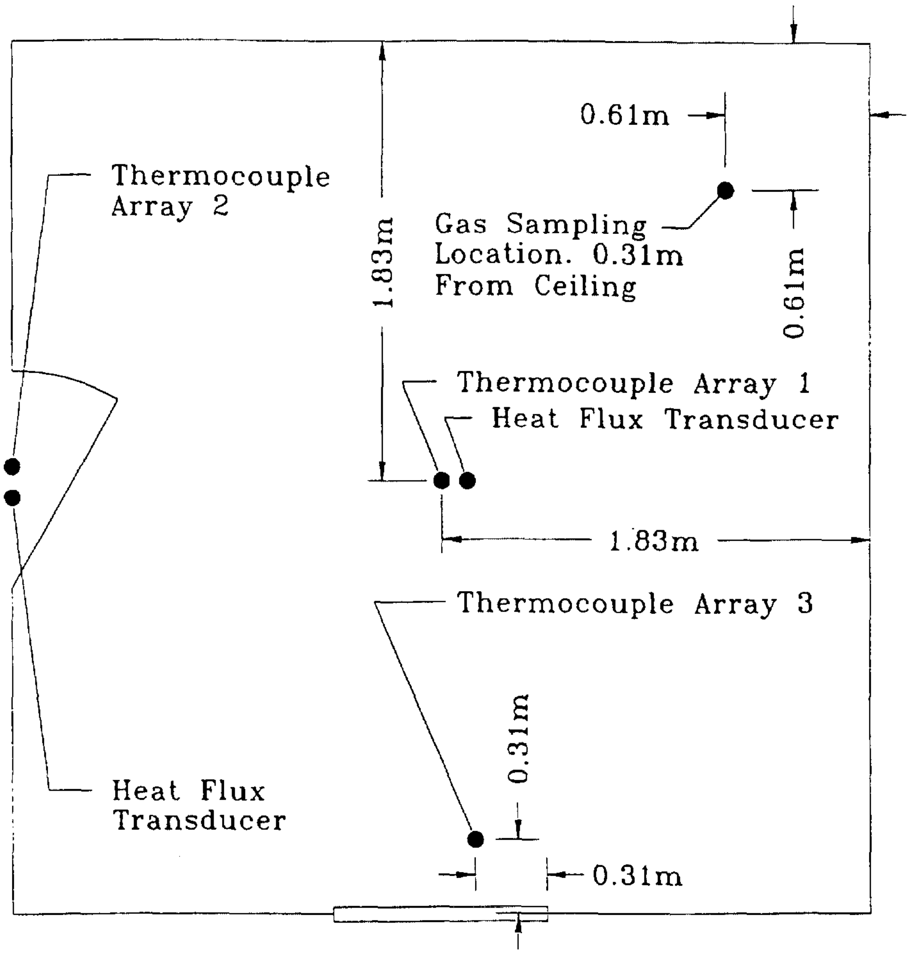

FIGURE 2. *Instrumentation locations in experiments 1 and 2.*

2.2.4 Gas Analysis

Real-time gas analysis was used to measure the concentrations of oxygen, carbon monoxide, and carbon dioxide in the fire rooms during the experiments. Room gases were continuously removed from the room through a gas sampling probe, and piped to gas analyzers outside of the room. The location of the gas sampling probe is indicated in Figure 2.

2.2.5 Results

Time lines for experiments 1 and 2 are provided in Figures 3 and 4. Included in the time lines are observations made during the experiments.

The temperatures measured by the thermocouple array located in the center of the room are shown in Figures 5 and 6. The temperatures for both experiments are similar, and the rapid increase in temperature at approximately 330 s suggests similar times to flashover. The duration of the post-flashover stage of the fire, the time between flashover and suppression, is approximately 180 s for both experiments. As mentioned previously, the ventilation conditions for the experiments are expected to differ due to the different locations of the rooms within the fire tower. The differences in ventilation are also suggested by the differences in post-flashover temperatures within the rooms, with experiment 2 reaching higher temperatures. A slight delay, of approximately 60 s, in the transition to flashover is indicated in the temperature data for experiment 1 when the hot layer temperature of the room reaches approximately 600 °C.

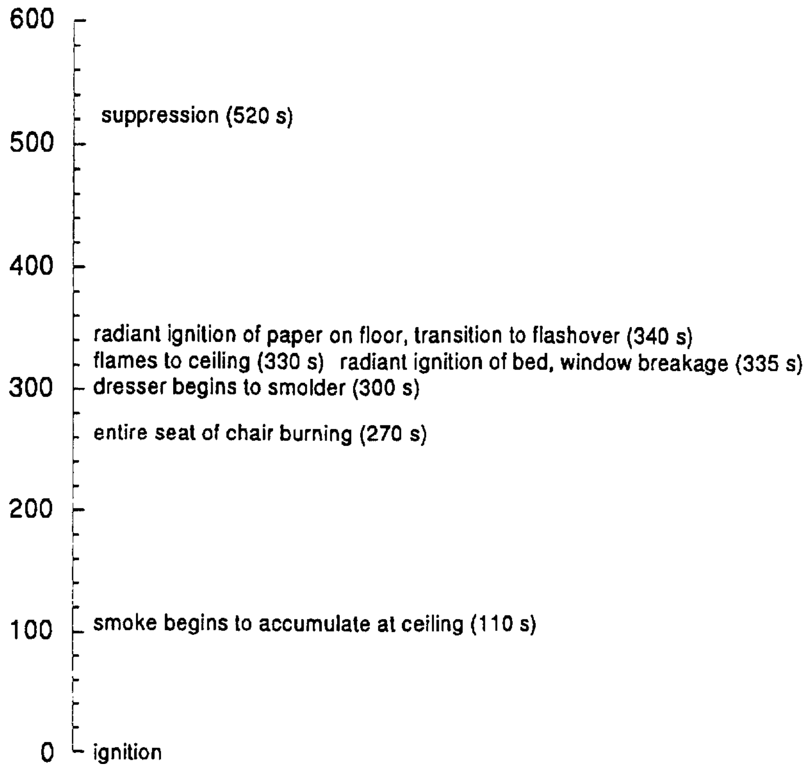

FIGURE 3. *Time line, in seconds, for experiment 1.*

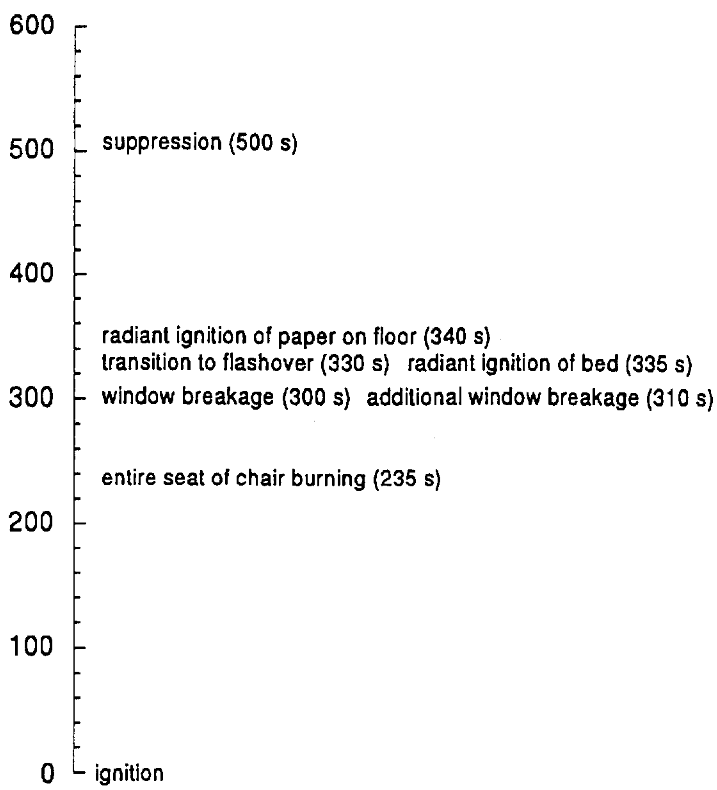

FIGURE 4. *Time line, in seconds, for experiment 2.*

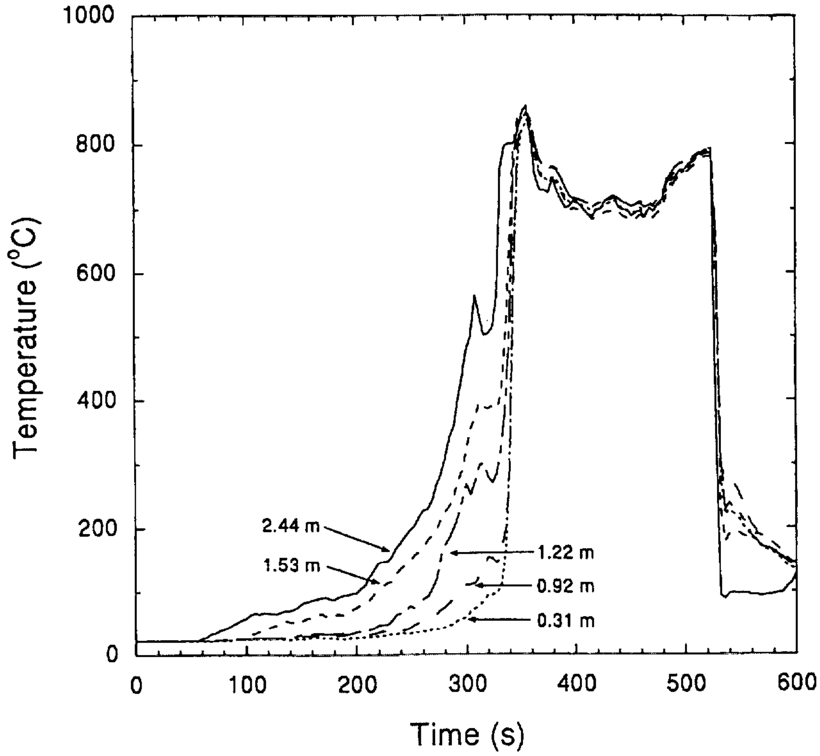

FIGURE 5. *Temperature of thermocouple array 1 at the center of the room. Experiment 1.*

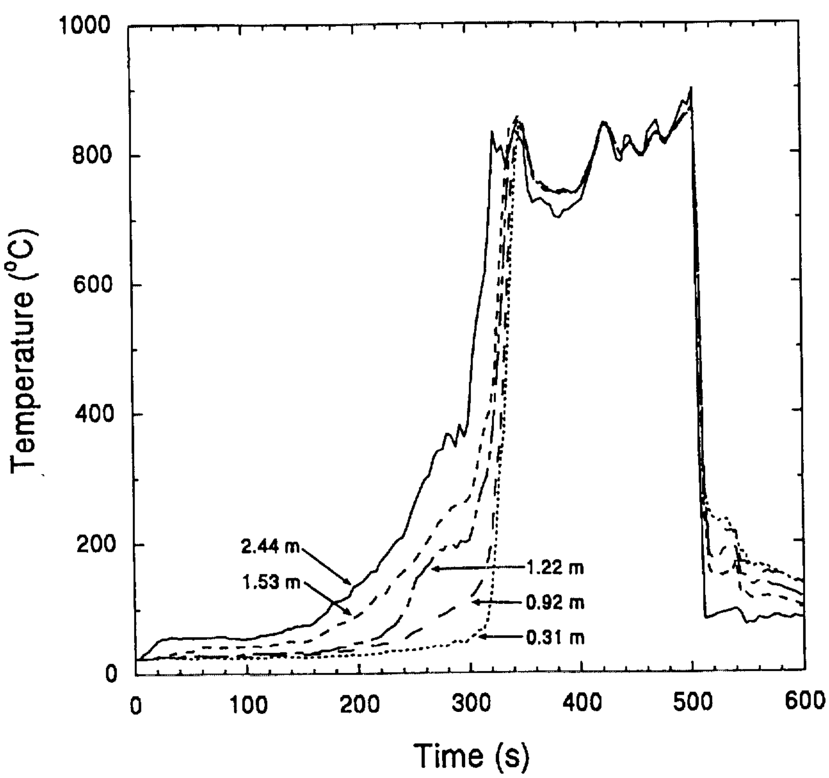

FIGURE 6. *Temperature of thermocouple array 1 at the center of the room. Experiment 2.*

The thermocouple array located near the window of the room serves as an indicator of the flow conditions at the window during the fire experiments. In both experiments, the temperatures at the windows suggest either intact glass or flow out of the room after window breakage. Inward and outward flow at the window would result in a neutral plane level in the window where flow conditions transition from outward to inward flow. No such neutral plane was seen during the experiments, nor is it indicated in the temperature measurements. As in the center of the room temperature measurements, the post-flashover temperatures of the second experiment are greater than those of the first experiment by approximately 100 °C. With the exception of the post-flashover temperatures, the temperature measurement results at the windows of both experiments are in agreement. The temperatures measured near the windows of the rooms are shown in Figures 7 and 8.

Thermocouple measurements in the doorway of the room serve as an indication of flow conditions during the experiments. In experiment 1, the temperatures indicate that the neutral plane is located in the doorway, approximately 1.2 m to 1.5 m from the floor of the room from approximately 150 s to approximately 220 s after ignition. During the transition to flashover, however, the neutral plane appears to fall to the floor of the doorway, indicating that most of the flow is out of the room. Due to the thermocouple spacing and the combustion of floor material near the doorway, however, inward flow close to the floor could not be sensed by the thermocouples. In addition there would also be radiation effects resulting from flame and hot surface radiation absorbed by the thermocouples. The flow in the doorway during the pre-flashover stages of experiment 2 are similar to those in experiment 1, where the neutral plane appears to remain between the levels indicated above until approximately 260 s. However, in contrast to experiment 1, the flow during the post-flashover stage of experiment 2 results in a neutral plane height of between 0.6 m and 0.9 m. Maximum temperatures in the doorways of both experiments are similar. The temperatures measured near the doorways of the rooms are shown in Figures 9 and 10.

The temperatures of the thermocouples located on the windows during experiments 1 and 2 are shown in Figure 11. The temperatures are in agreement with the exception of the post-flashover stage of the fire. During the post-flashover stage, the temperatures on the window in experiment 1 are less than those on the window during experiment 2. This difference is in agreement with the other temperature measurements, which also indicated higher temperatures in experiment 2. The magnitude of the temperatures measured by the thermocouples on the windows are less, however, than those measured by the thermocouple array near the window in both experiments.

Heat flux measurements from the doorway of experiment 1 are consistent with those expected within a post-flashover room. They are also consistent with the indications from the thermocouple measurements in the doorway, suggesting mostly outward flow from the doorway during the post-flashover stage of the fire. Note that since the height of the heat flux transducer is approximately 0.15 m above the floor, flames could be impinging on the transducer while there is still air inflow at the bottom of the door below the thermocouple at the 0.55 m level. The thermocouple at the floor in the doorway could also be affected by combustion of the flooring material near the doorway. In contrast, the heat flux levels in the doorway of the second experiment, approximately 10 kW/m^2 to 20 kW/m^2, are lower than those expected in a post-flashover room for half of the post-flashover burning period. The heat flux levels measured near the doorways are shown in Figure 12.

The heat fluxes measured by the transducers in the middle of the rooms were similar in both experiments. The heat flux levels were consistent with the temperature increases accompanying the transition to flashover conditions, and had the same qualitative behavior as the temperature histories from the thermocouple arrays in the center of the rooms. The heat flux levels measured near the middle of the room are shown in Figure 13.

The gas concentrations measured in the experiments are shown in Figures 14 through 16 for oxygen, carbon dioxide, and carbon monoxide respectively. Note that the gas sample transit time, the time necessary for the gases to be sampled and the concentration measurements to be made, has been taken into account in the plots. The graphs show that the concentrations of the measured gases were in excellent agreement for experiments 1 and 2. Any major differences in the results of the two experiments occurs after suppression, where large variations are expected. Since the concentrations of gases are only measured at one point in each room, results of the measurement can not be extrapolated to the room in general since localized burning would have a large effect on the concentrations of gases in the vicinity. Due to the turbulence associated with the post-flashover stage of the fire, however, the upper layer gases in the room will tend to be well mixed, with the exception of areas near openings, and more homogeneous than prior to flashover. Note that the position of the gas sampling probe, which was approximately 0.31 m from the ceiling, resulted in concentration measurements from the hot layer within the room during most of the experiment.

The concentration of oxygen decreases dramatically upon the onset of full room involvement, as would be expected from a room with a fire that is becoming ventilation controlled. The volume fraction of oxygen in the gases at the sampling point drops to approximately 5 percent during the post-flashover stage of the fire, and remains relatively constant until the fire is suppressed.

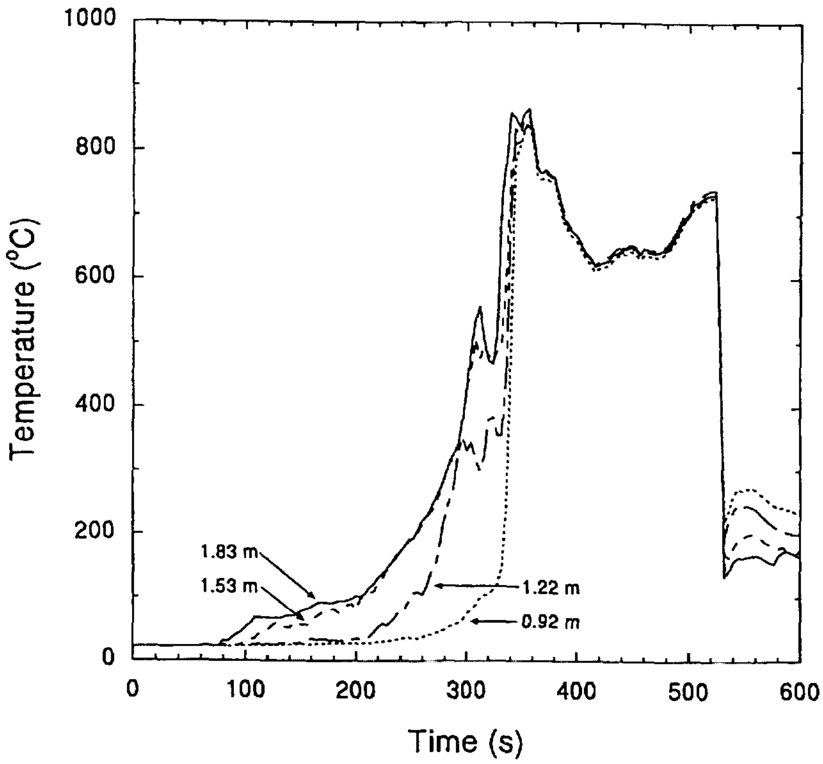

FIGURE 7. *Temperature of thermocouple array 3 at the window of the room. Experiment 1.*

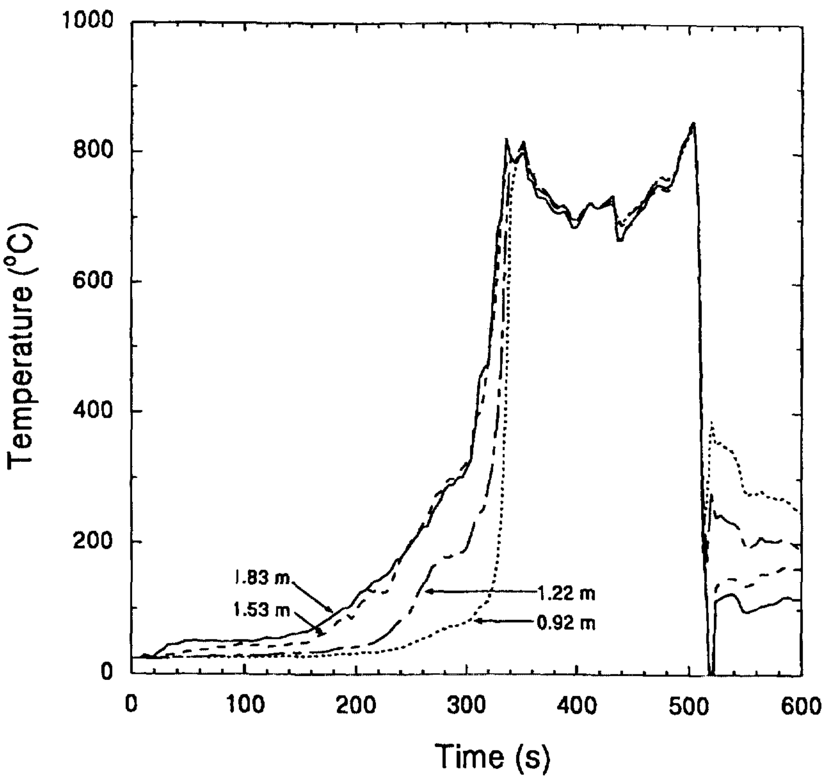

FIGURE 8. *Temperature of thermocouple array 3 at the window of the room. Experiment 2.*

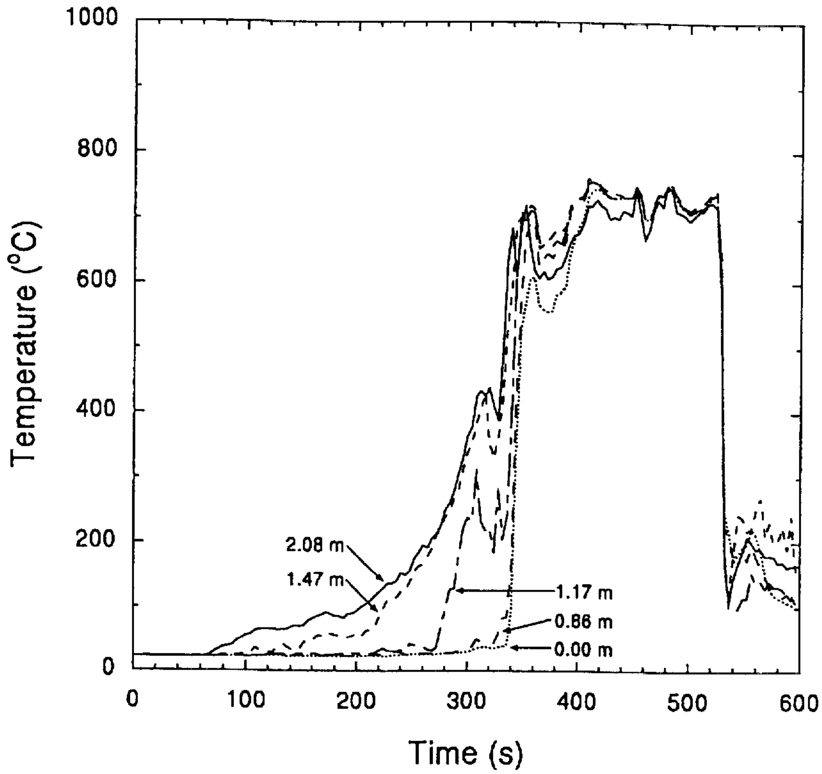

FIGURE 9. *Temperature of thermocouple array 2 at the door of the room. Experiment 1.*

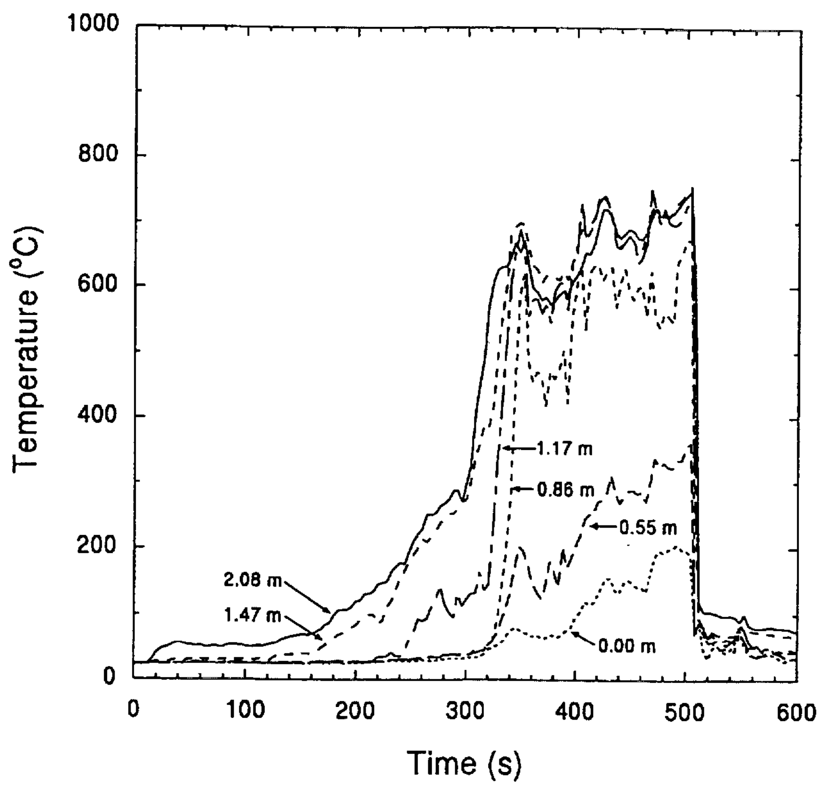

FIGURE 10. *Temperature of thermocouple array 2 at the door of the room. Experiment 2.*

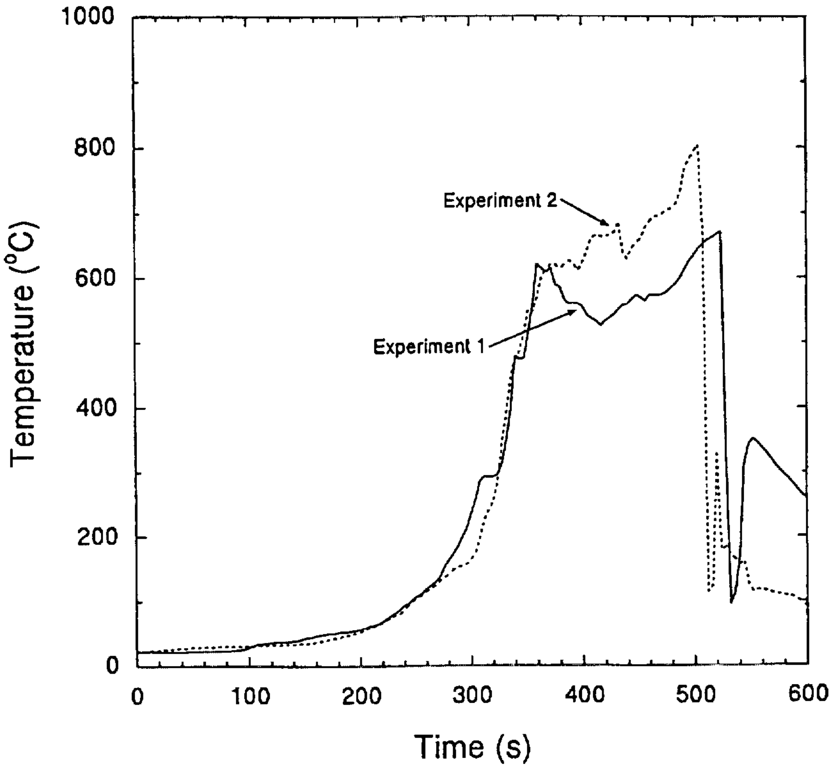

FIGURE 11. *Temperature of the thermocouples on the windows of experiments 1 and 2.*

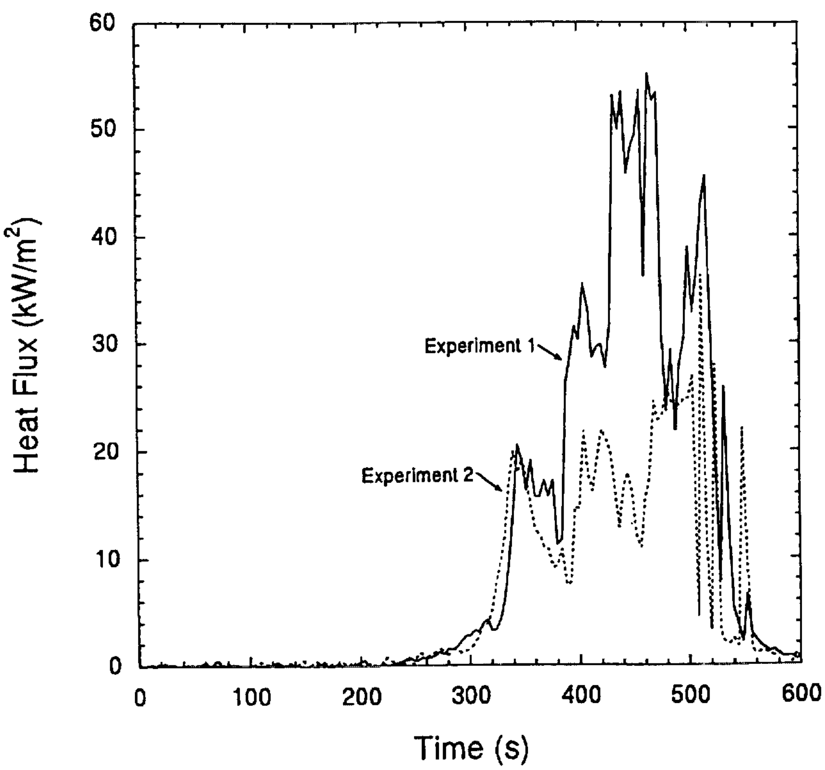

FIGURE 12. *Heat fluxes in the doorways of experiments 1 and 2.*

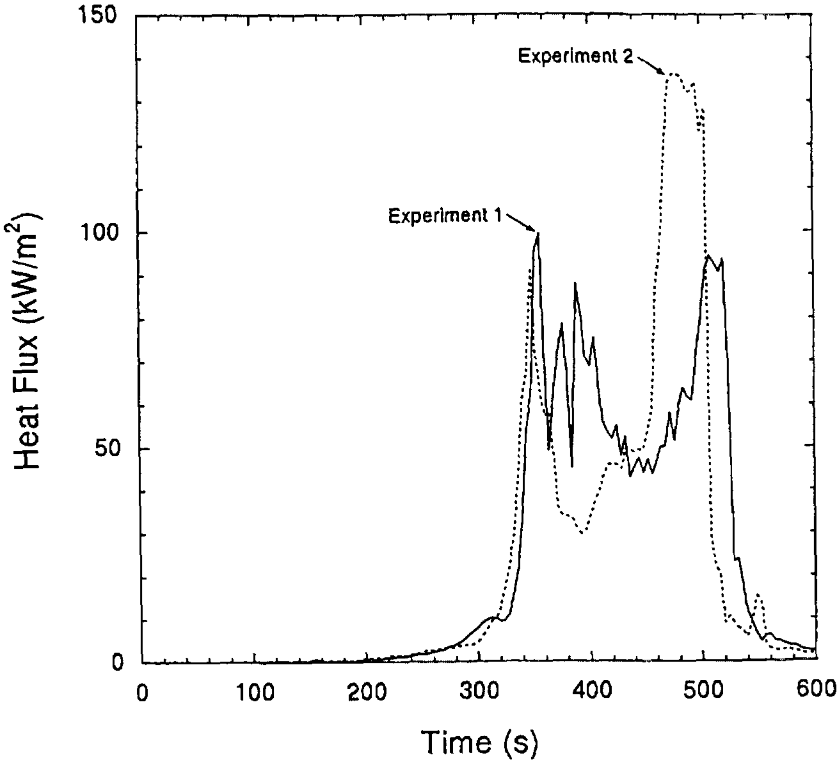

FIGURE 13. *Heat fluxes near the centers of the rooms in experiments 1 and 2.*

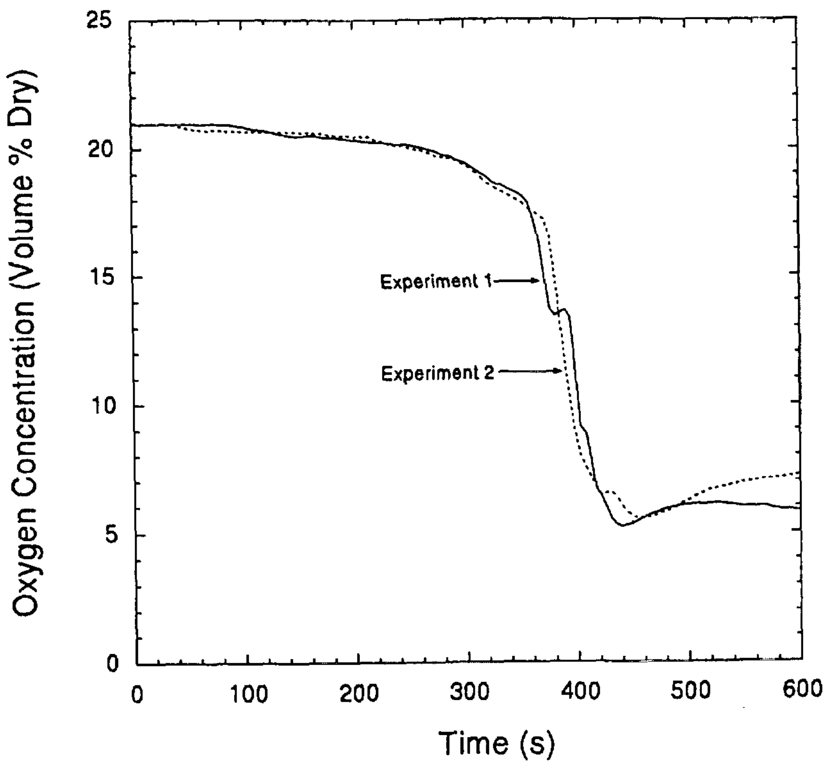

FIGURE 14. *Oxygen concentrations in the rooms during experiments 1 and 2.*

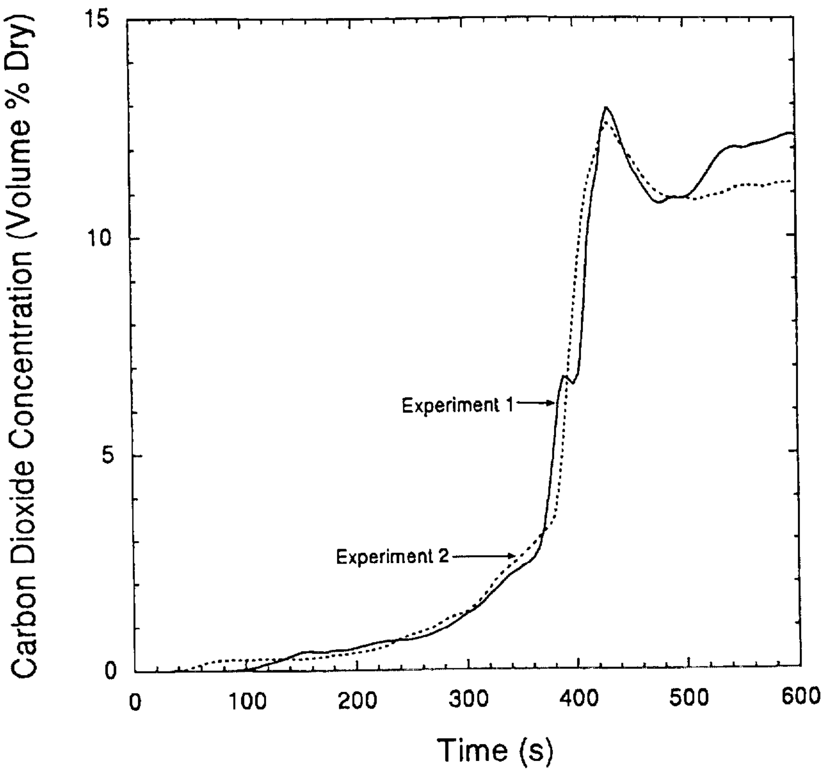

FIGURE 15. *Carbon dioxide concentrations in the rooms during experiments 1 and 2.*

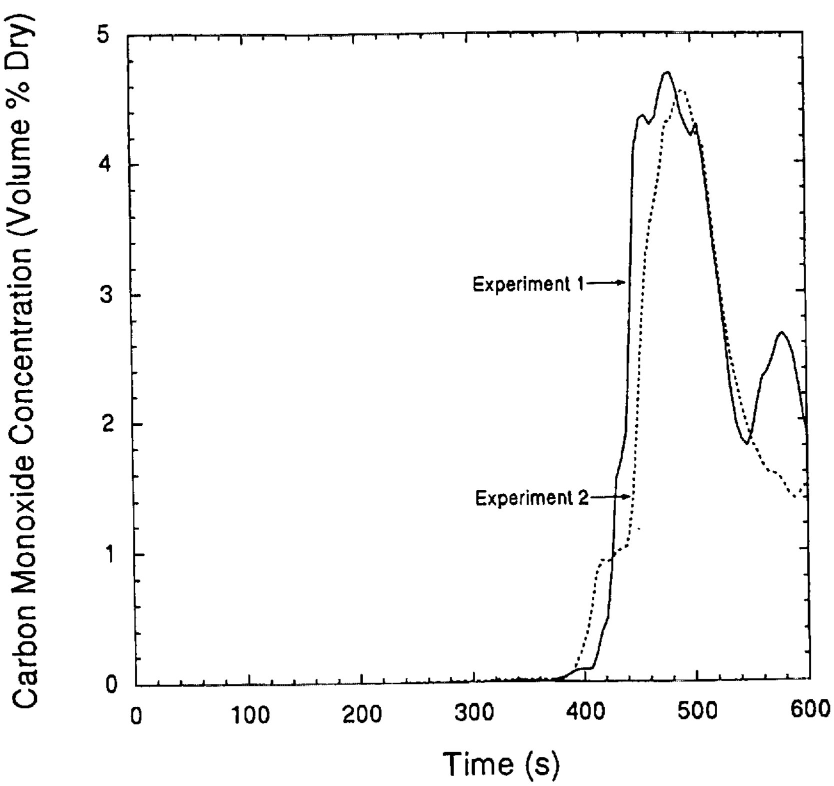

FIGURE 16. *Carbon monoxide concentrations in the rooms during experiments 1 and 2.*

The concentration of carbon dioxide behaves in a similar manner to the oxygen concentration, only it increases as the fire grows. The carbon dioxide volume fraction peaks at approximately 13 percent during the post flashover stage of the fire. The concentration then decreases and levels off shortly before the fire is suppressed. As with the oxygen concentration, the slope of the concentration versus time curve changes drastically shortly after the transition to full room involvement.

The carbon monoxide volume fraction at the sample point increases drastically from trace levels to almost 5 percent approximately 60 s after the transition to full room involvement.

2.3 Gasoline Spill Fire Experiments (Experiments 3 and 4)

2.3.1 Fuel Load

Experiments 3 and 4 had hardwood floors, installed over a layer of plywood and a concrete floor slab. The urethane finished parquet floor tiles, measuring approximately 0.305 m by 0.305 m by 8 mm thick, were glued to the plywood. Note that the tiles did not completely cover the floor from wall to wall, and left an uncovered gap of up to approximately 0.45 m from two of the four walls in each experiment. This gap can be seen in the photographs of the rooms discussed later in this report.

A list of room furnishings, along with descriptions of the items, are in Table 2. The individual and total masses of the room furnishings are listed in Tables 7 and 8. Note that the furnishings in the gasoline ignited fires are the same as those in the upholstered chair fires with the exception of floor materials.

TABLE 7. *Mass of furnishings, Experiment 3*

Item	*Approximate Mass (kg)*
Bed—includes mattress, box spring, and headboard	37.5
Bed frame (metal)	12.5
Bedding materials—includes two sheets, pillow case and pillow, blanket, and bedspread	4.5
Hardwood flooring	453.6
Upholstered chair	32.0
Dresser	42.0
Nightstand	15.0
Lamp, type 1	2.5
Lamp, type 1	2.5
Wastebasket, with trash	0.6
Total	602.7

TABLE 8. *Mass of furnishings, Experiment 4*

Item	*Approximate Mass (kg)*
Bed—includes mattress, box spring, and headboard	37.5
Bed frame (metal)	12.5
Bedding materials—includes two sheets, pillow case and pillow, blanket, and bedspread	4.5
Hardwood flooring	453.6
Upholstered chair	32.0
Dresser	42.0
Nightstand	15.0
Lamp, type 2	3.0
Lamp, type 2	3.0
Wastebasket, with trash	0.6
Total	603.7

In experiments 3 and 4, a spill of gasoline on the floor of the room was the first fuel item ignited. Approximately 0.95 L (1.0 qt) of gasoline was poured on the floor of the room, centered around thermocouple F10, located approximately 6 mm above the floor. A book of paper matches near the spill was ignited electrically, thereby igniting the gasoline. Figure 17 shows the plan view of the furnished room.

2.3.2 Thermocouples

The rooms were instrumented for the measurement of temperature with thermocouple arrays strung between the ceiling and the floor. Each array was composed of eight thermocouples, at vertical spacings of approximately 0.31 m. Table 9 indicates the distance of each thermocouple of the array above the floor of the room. The locations of the thermocouple arrays are shown in Figure 18.

TABLE 9. *Thermocouple locations*

Thermocouple Number	*Distance Above Floor, m (ft)*
8	2.44 (8.00)
7	2.14 (7.00)
6	1.83 (6.00)
5	1.53 (5.00)
4	1.22 (4.00)
3	0.92 (3.00)
2	0.61 (2.00)
1	0.31 (1.00)

Thermocouples were also installed beneath the hardwood floor in experiments 3 and 4 to measure the effects of the gasoline spill fire. The thermocouples were located approximately 4 mm below the top surface of the floor. One thermocouple bead, F10, was located approximately 6 mm above the surface of the floor, and above the area of the gasoline spill. A floor plan illustrating the approximate locations of the floor thermocouples is in Figure 18.

2.3.3 Heat Flux Transducers

Water cooled heat flux transducers were installed at two locations in the room. The transducers were installed through the walls of the room, with their faces parallel to the walls. The locations of the transducers are shown in Figure 18.

2.3.4 Results

Time lines for experiments 3 and 4 are provided in Figures 19 and 20. Included in the time lines are observations made during the experiments.

The temperatures measured by the thermocouple array located in the center of the room are shown in Figures 21 and 22. Unfortunately, due to a power failure during experiment 4, measurement results are only available for times from ignition to approximately 150 s after ignition. Note that the temperatures indicated at time zero in the graphs are elevated above ambient temperature. This is due to an error in the start time of the experiment as compared to the zero time in the figures. This error is on the order of 5 s, since the data system took measurements at 4 s intervals. The error is evident in Figures 21 and 22 due to the rapid combustion of the gasoline vapors within the room during experiments 3 and 4.

The temperatures of the thermocouples in the center of the room in both experiments 3 and 4 peaked at approximately 300 °C to 400 °C shortly after ignition of the fire as a result of the burning liquid fuel vapors. Temperatures then decreased to approximately the 200 °C to 300 °C range, before increasing again, with the transition to flashover occurring at approximately 70 s. The post-flashover duration of experiment 3 can be derived from the center thermocouple array temperatures, with a time period of approximately 180 s from the flashover transition to the start of suppression. This time agrees with observations during the experiment. Due to the limited data available for experiment 4, the temperatures during the 3 min post-flashover duration for experiments 3 and 4 can not be compared.

The temperatures of the thermocouples in the array located near the window of each room are shown in Figures 23 and 24. The temperatures measured near the windows are in agreement with the temperatures measured near the center of the room. As in experiments 1 and 2, the thermocouple array near the window can be used as an indicator of the flow conditions through the window after the window breaks. Inspection of the post-flashover temperatures of the thermocouples at the windows suggests the absence of a neutral plane at the window, which implies either outward flow of upper layer gases through the entire window or intact glass.

Temperatures of thermocouples located above and in the floor of the room were recorded and are shown in Figures 25 and 26. The temperatures of all of the thermocouples in the floors of the rooms are similar for both experiments 3 and 4, although the available data for experiment 4 limits the comparison. The temperatures of the thermocouple above the floor, F10, around which the liquid fuel was poured, however, varied by approximately 200 °C between the two experiments, with experiment 3 registering the higher temperature. Due to the low conductivity of the floor, and the locations of the thermocouples under the surface of the floor, the thermocouple measurements do not provide a means for determining the location of the fuel spill during the experiment.

The heat fluxes measured at the walls of the rooms above the nightstand are shown in Figures 27 and 28. The heat flux approximately 0.88 m above the nightstand is shown in Figure 27 for experiment 3 only. A malfunction during experiment 4 resulted in poor data, which was discarded. The magnitude of the heat flux is in agreement with the temperature measurements and observations during the experiment. The heat flux increases greatly as flashover approaches, and reaches levels that are expected during the post-flashover stage of the fire.

The heat flux measured approximately 0.58 m above the floor of the room, which is immediately above the top surface of the night table, is shown in Figure 28. For the time that data is available, the results from experiments 3 and 4 are in agreement. The results of both experiments are also in agreement with the temperature measurements, with a steep increase in flux as flashover approaches. The post-flashover heat fluxes are on the low side, however, especially when compared to the flux measured at 0.88 m above the floor.

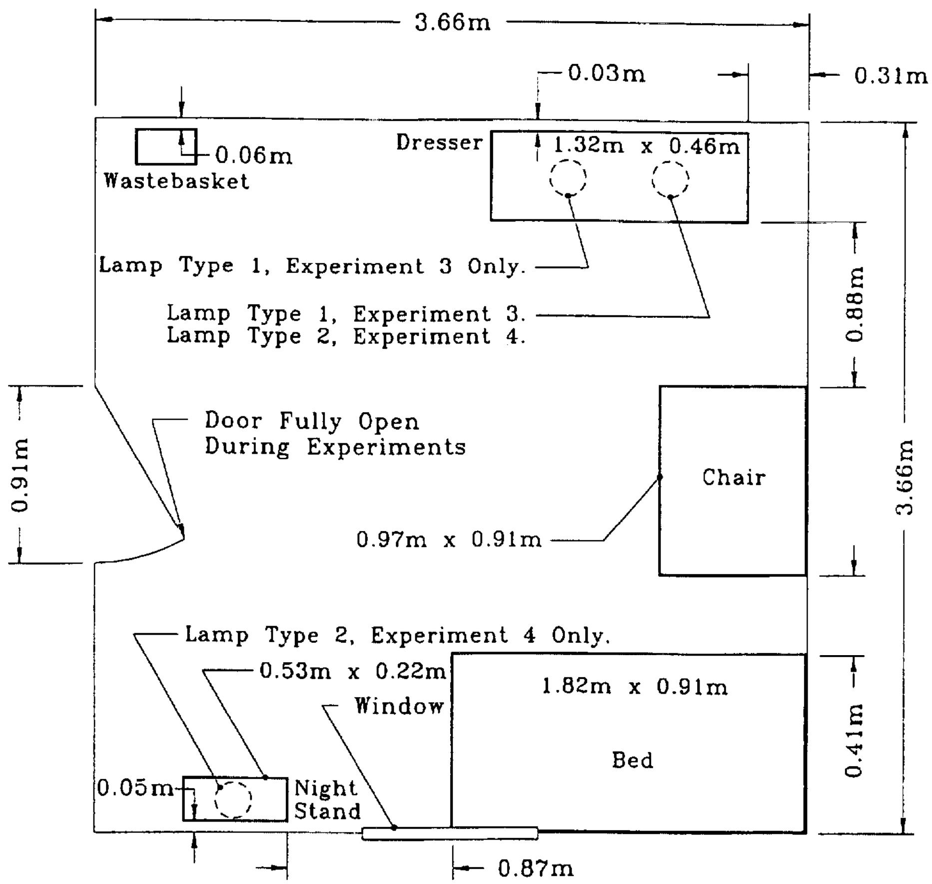

FIGURE 17. *Plan view of furnished rooms. Experiments 3 and 4.*

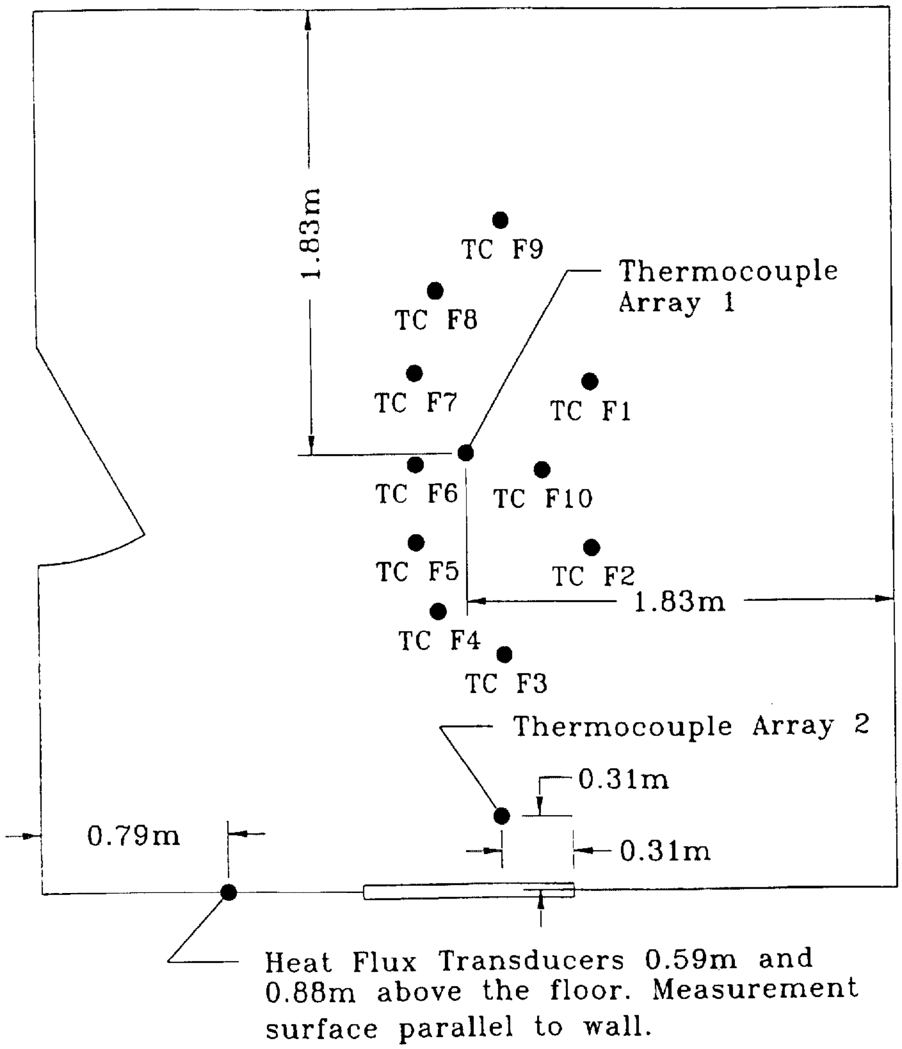

FIGURE 18. *Instrument locations in experiments 3 and 4.*

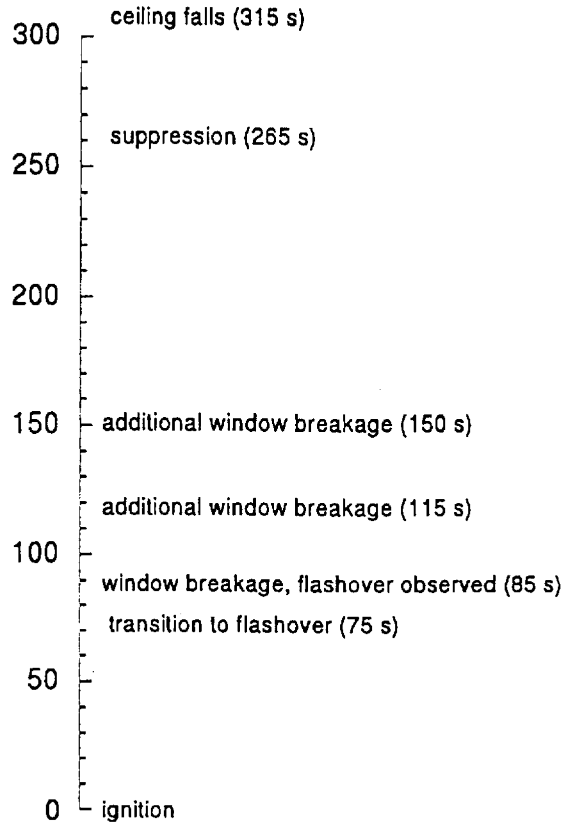

FIGURE 19. *Time line, in seconds, for experiment 3.*

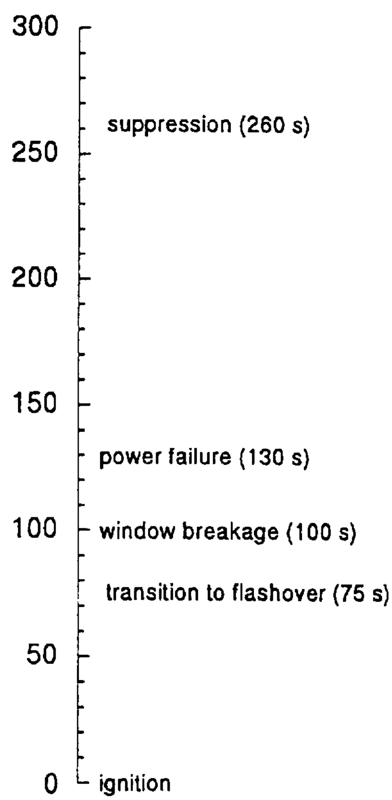

FIGURE 20. *Time line, in seconds, for experiment 4.*

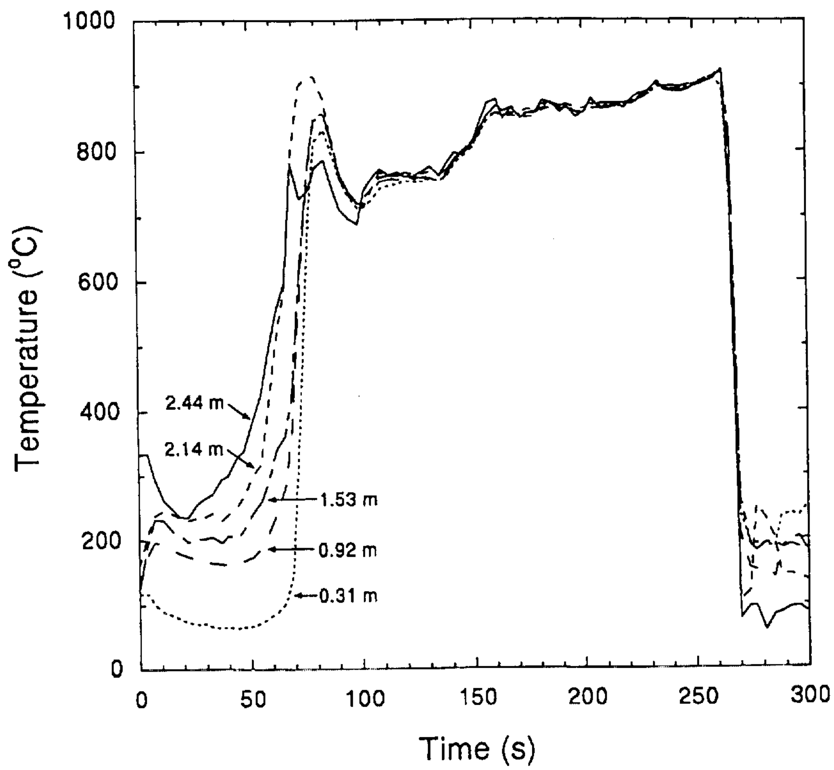

FIGURE 21. *Temperature of thermocouple array 1 at the center of the room. Experiment 3.*

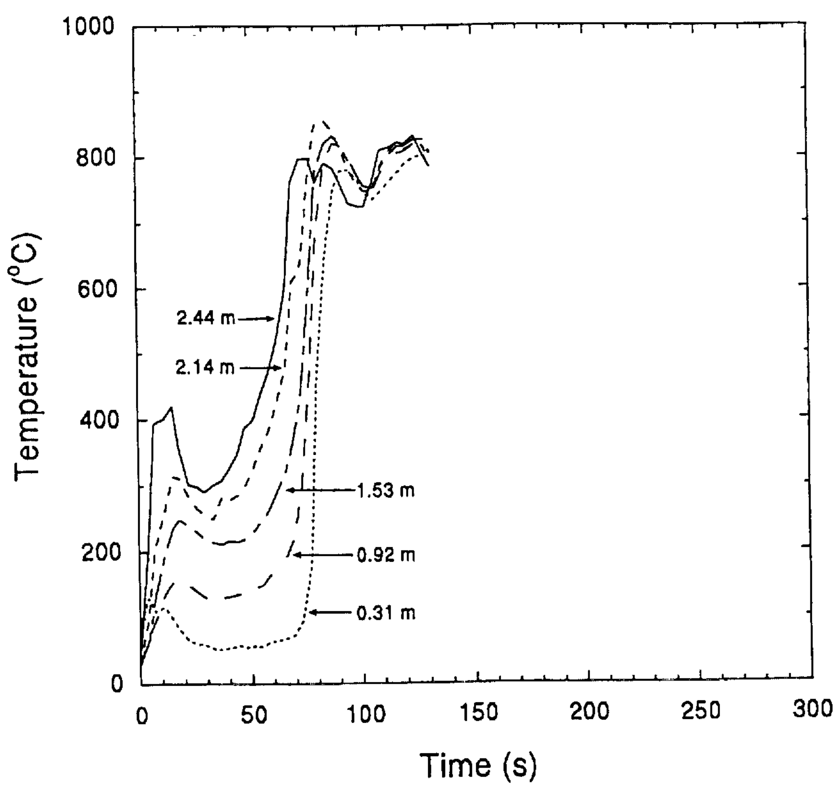

FIGURE 22. *Temperature of thermocouple array 1 at the center of the room. Experiment 4.*

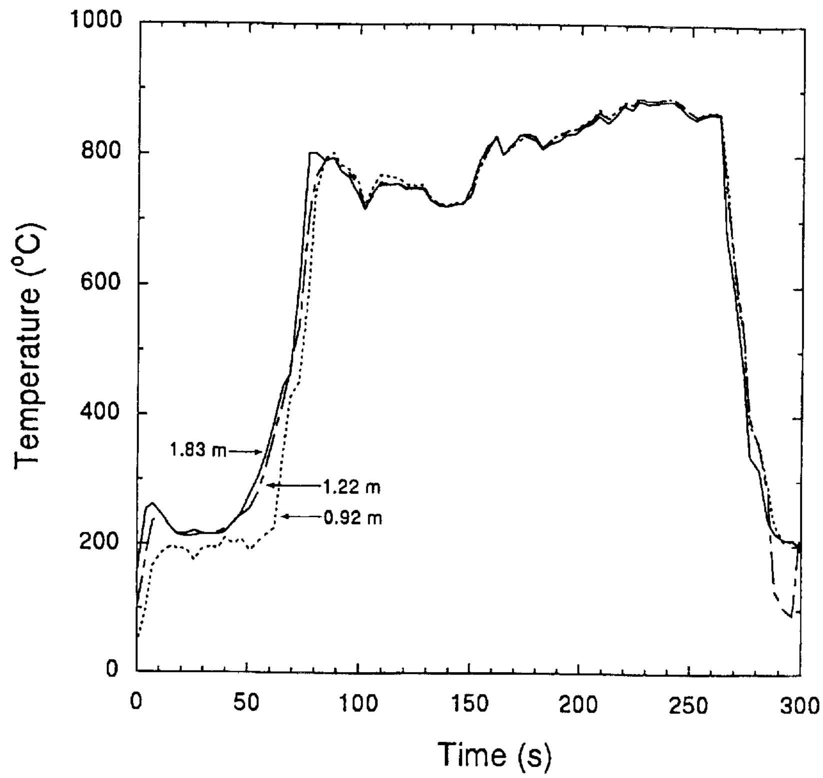

FIGURE 23. Temperature of thermocouple array 2 at the window of the room. Experiment 3.

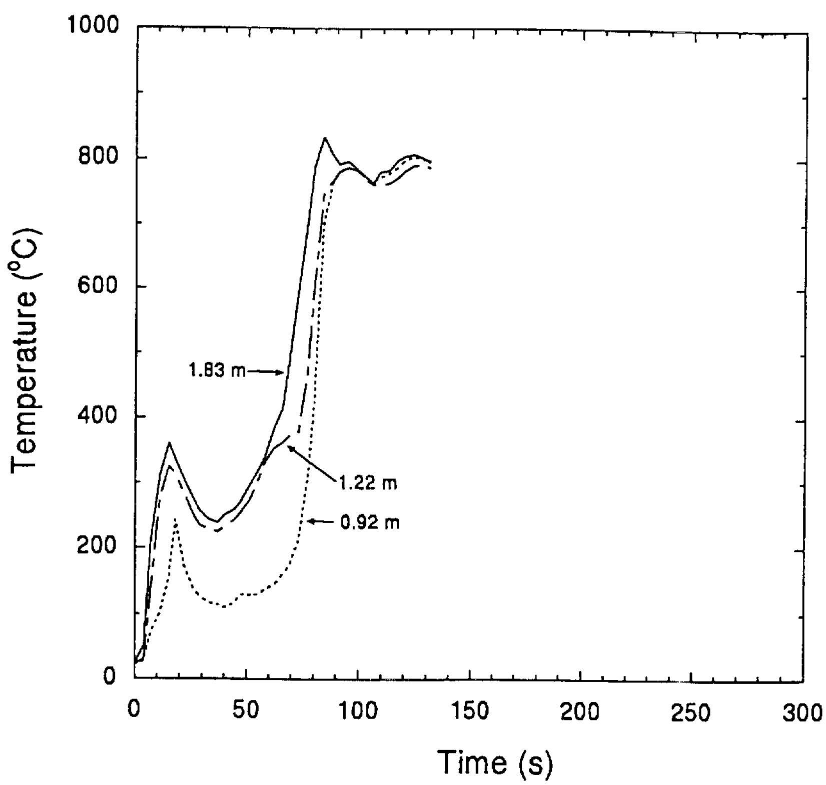

FIGURE 24. Temperature of thermocouple array 2 at the window of the room. Experiment 4.

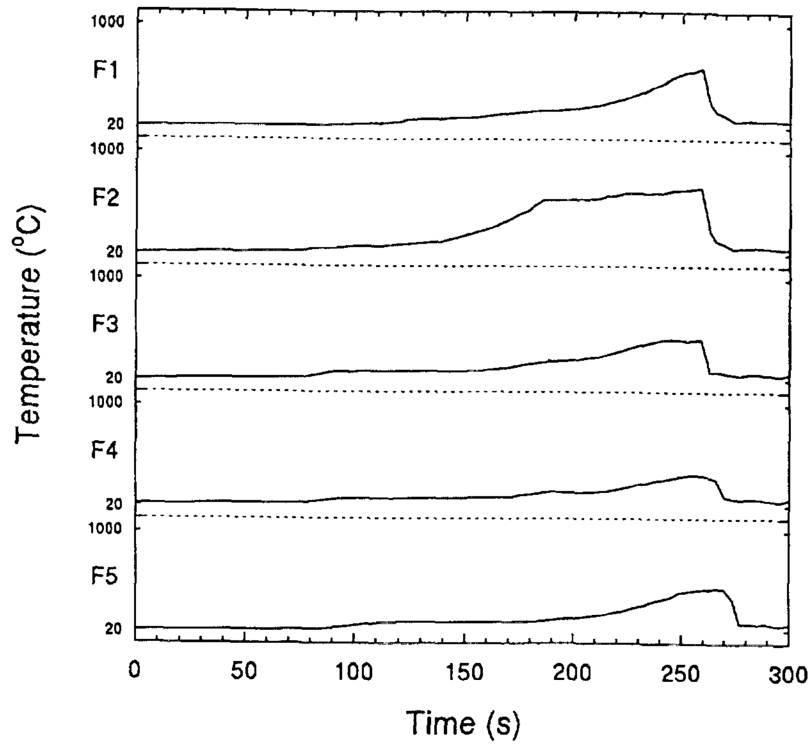

FIGURE 25a. *Temperatures of floor thermocouples F1 through F5. Experiment 3.*

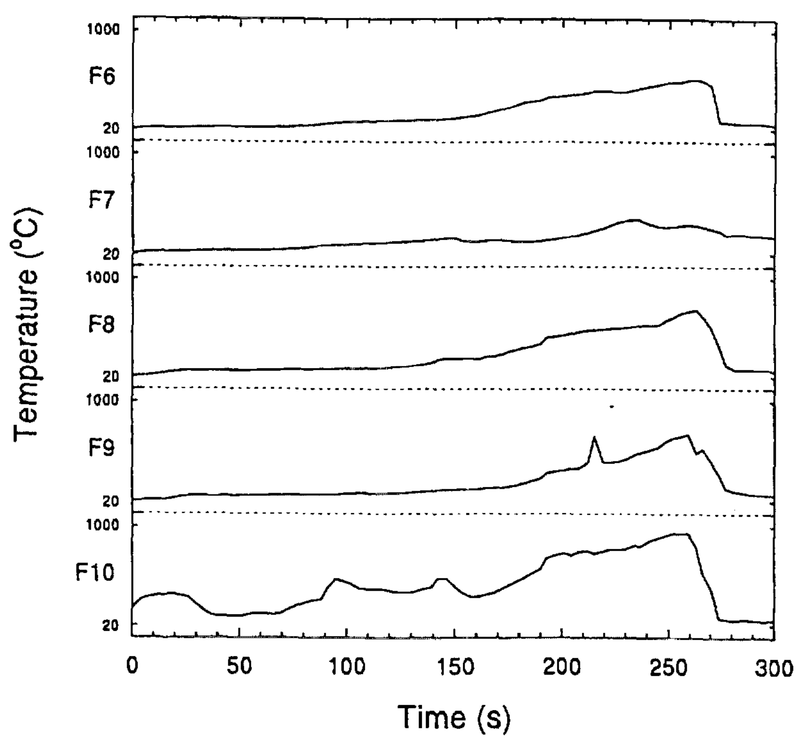

FIGURE 25b. *Temperatures of floor thermocouples F6 through F10. Experiment 3.*

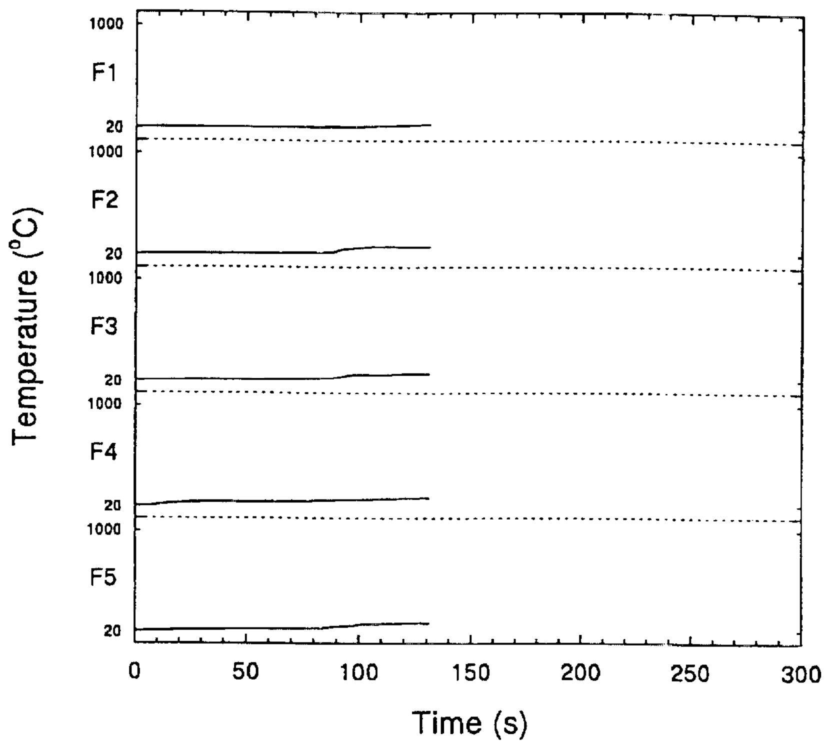

FIGURE 26a. *Temperatures of floor thermocouples F1 through F5. Experiment 4.*

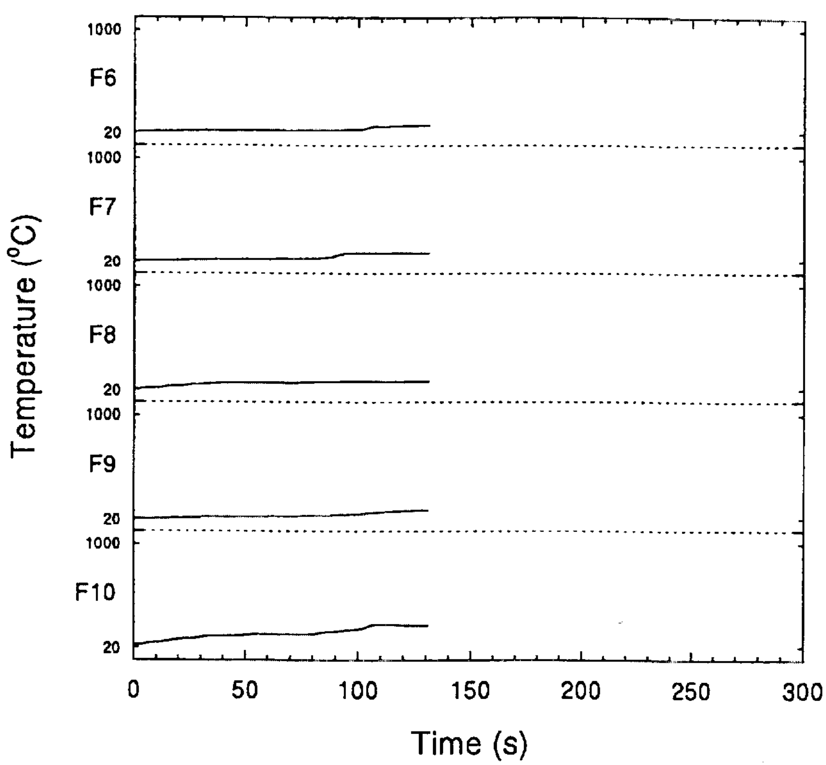

FIGURE 26b. *Temperatures of floor thermocouples F6 through F10. Experiment 4.*

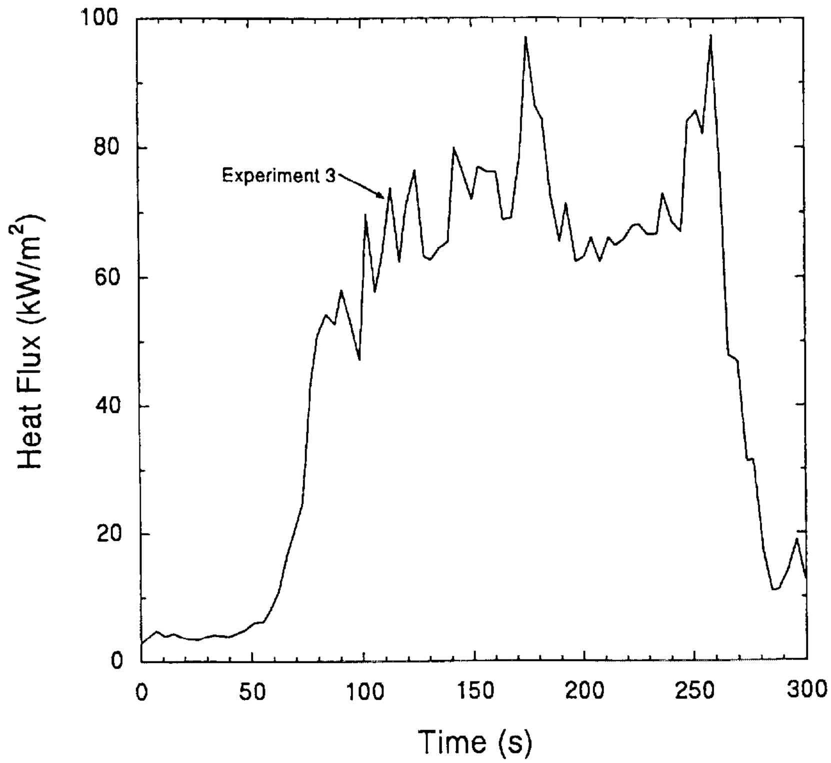

FIGURE 27. *Heat flux above the nightstand. Upper transducer located approximately 0.88 m above floor.*

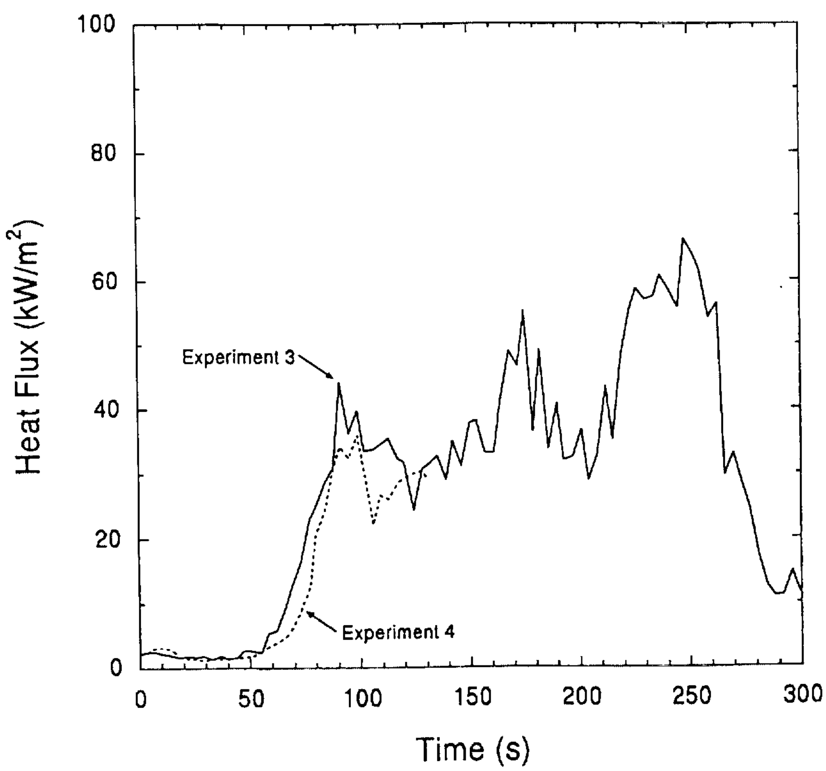

FIGURE 28. *Heat flux above the nightstand. Lower transducer located approximately 0.59 m above floor.*

3. POST FIRE INSPECTION

Following each of the fire experiments, the conditions of the room contents and the building components were examined. Photographs were taken to document the conditions of the room and contents. This section of the report compares the conditions seen in each set of like experiments. In each of the experiments, several different classic fire indicators were present. Due to variability, however, the indicators present in the rooms after burning were not always consistent. The chair ignition fires are not compared to the spill fire ignition fires due to the number of variables between the two types of experiments, i.e., flooring type, ignition method, and ventilation.

3.1 Chair Ignition Fires

In both of the chair ignition fires, the chair was located against one of the walls. The areas around the chairs are shown in Figures 29 and 30, which correspond to experiments 1 and 2 respectively. These photographs were taken from the doorways of the rooms. In Figure 29, the wall directly above the chair is burned white, along with areas to either side of the chair. While the picture quality is poor, Figure 30, in contrast, shows less white area directly above the chair, with the white areas to the left of the chair at a significantly higher elevation than that shown in Figure 29. Also notice the height of the charring on the wood molding of the door to the room in Figure 30. Recall that the thermocouple array suggested that the neutral plane in the doorway was located between 0.6 m and 0.9 m during the post- flashover stage of the fire in experiment 2. The white area to the left of the chair in experiment 2 is further illustrated in Figure 31.

The upper portions of the walls and the ceiling above the chairs are shown in Figures 32 and 33. Note that the white patches in experiment 1 continue up the wall and onto the ceiling above the chair, while the upper portion of the wall behind the chair is not white in experiment 2. In addition, the white patches on the ceiling of experiment 2 cover a larger area, and are not as limited to the area above the chair, as in experiment 1.

The walls behind the chairs in experiments 1 and 2 are shown in Figures 34 and 35, respectively. Notice that the outlines of the chairs are visible, and that the baseboard and portions of the floor have been protected by the chair in both experiments. Notice, however, that the baseboard in Figure 34 is also undamaged to the right of the chair location, in contrast to Figure 35. In addition to the baseboard, the chair in experiment 2 has protected the wall in two areas. Corresponding areas of the chair fabric were also protected, as shown in Figure 36. The chair from experiment 1 is shown in Figure 37, and illustrates the burning of the back surface of the chair. A portion of the fabric on the left side of the back of the chair near the bottom is not heavily charred, however, and corresponds to a difference in the darkness of the pattern from the chair in Figure 34.

Other room surfaces were protected by the furniture in the room. The carpet under the beds in both experiments, for example, was protected from the radiation emitted by the hot upper layer by the beds. The protected carpet is shown in Figures 38 and 39. The wooden baseboard molding on the walls behind the beds was also protected.

The aforementioned figures also illustrate the condition of the bed mattresses after the experiment. The springs from the mattress in experiment 1 have retained most of their original shape, while the springs in experiment 2 have relaxed and lost their shape. In both cases, the combustible portions of the mattresses were almost completely consumed. Recall that both experiments were of similar duration, burned in the post-flashover stage for the same period of time, and both mattresses were subjected to similar loads (their own weight). The thermocouple arrays in experiment 2, however, sustained higher temperatures than experiment 1, and the fire was possibly better ventilated, suggesting that higher temperatures within the room and/or greater radiative heat transfer from the hot gases in the room contributed to the relaxation of the mattress springs. This conclusion assumes, of course, that the properties of the steel in the mattresses, which were of the same model, were identical.

The window of the room in experiment 1 is shown in Figures 40 and 41. The figures illustrate that the window retained the second, outer panes of glass through the experiment. The window in experiment 2, however, as shown in Figure 42, broke out totally during the experiment, providing additional ventilation for the room during the post-flashover stage of the fire. The window conditions shown are consistent with observations made during the experiments.

The conditions of the light bulbs in the lamps are shown in Figure 43 for experiment 1 and Figure 44 for experiment 2. The light bulb in the nightstand lamp of experiment 1 has deformed in the direction toward the upper middle of the room. The deformity in this direction suggests that radiation from the hot layer within the room affected the deformation of the bulb to a greater extent than individual fuel packages. The bulb in the nightstand lamp of experiment 2 was also deformed, but it has broken free of the bulb base, and the direction of the deformation is not clear.

The walls to one side of the doorway in experiments 1 and 2 are shown in Figures 45 and 46. The doorway of the room can be seen in the far left side of the figures. Note that the amount of damage is greater in experiment 1, as suggested by the condition of the wallboard, the charring of the baseboard molding, the floor covering, and the electrical outlets. The remains of the wastebasket can be seen in the right side of Figure 46, near the baseboard.

3.2 Gasoline Spill Fire Experiments

The upholstered chairs from experiments 3 and 4 are shown in Figures 47 and 48. Due to poor photo quality the conditions of the chairs cannot be closely compared. The patterns on the walls behind the chairs of the experiments are quite different. The white area ("burned clean") in Figure 47 covers much of the area of the wall above the chair. Figure 48, however, has the white area limited to a much smaller region located above the chair. Note that the ceiling in experiment 3, Figure 47, has fallen. The lack of heat damage and charring on the ceiling joists, as shown in Figure 49, suggests that the ceiling fell due to the weight of suppression water, or was knocked down during overhaul. Audio from the fire videotape confirms the falling of the ceiling and provides the time of the event.

The condition of the flooring material is illustrated in Figures 50 and 51. The charring of the flooring materials was more severe toward the center of the room in both experiments. While the liquid accelerant was poured in the center of the rooms, the area that was actually covered by the accelerant is not known. In addition, the area of the floor near the center of the room would be expected to receive the most damage due to the radiative heat transfer view factor between the room floor and the layer of hot gases within the room, regardless of the presence of an accelerant. In order to compare to the areas of heaviest damage, the location of the accelerant after pouring should be compared to the damage patterns. In future experiments, the location of the accelerant after the pour should be monitored, perhaps with additional surface thermocouples or with infrared imaging, to facilitate the damage comparisons. The data available from these experiments are not complete enough to be able to draw conclusions as to the effect of the flammable liquid pour on the severity of the burn patterns on the floor.

The bed mattresses from the experiments are shown in Figures 52 and 53. As discussed in the previous section, the condition of the mattress springs can provide an indication of the relative temperatures or durations of heating. The springs from mattresses in both experiments have relaxed and lost their shape in most areas except perhaps the edges along the walls of the room. The photos shown in Figures 54 and 55 illustrate that the bed frames have also deformed during the experiments. In addition, the combustible portions of the mattresses were almost completely consumed. Recall that both experiments were of similar duration, burned in the post-flashover stage for the same period of time, and both mattresses were subjected to similar loads (their own weight). This would suggest similar fire exposures in both experiments. This conclusion assumes, of course, that the properties of the steel in the mattresses, which were of the same model, were identical.

The dressers used in the rooms are shown in Figures 56 and 57 after the experiments. The side of the dresser in experiment 3 is more heavily damaged than from experiment 4. The side of the dresser in Figure 56 has burned through in several places, and the drawers inside of the dresser can be seen. The side of the dresser from experiment 4 is still intact, although heavily damaged. The nightstands in both experiments, as shown in Figures 58 and 59, are both heavily damaged on the side facing the bed. In both cases, the side of the nightstand is burned away, and the drawers inside can be seen.

The areas behind the doors to the rooms in experiments 3 and 4 are shown in Figures 60 and 61. Although the doors have burned away, a line of demarcation can be seen on the wall where it was located in experiment 3. The location of the door is not clear from Figure 61, however.

4. DISCUSSION AND CONCLUSIONS

The results of the measurements during the experiments showed good agreement between experiments with the same method of ignition. In addition, the times to events such as window breakage and transition to flashover were also similar. A limited number of point measurements, however, cannot be expected to accurately portray localized conditions throughout the burn room. This is especially true for the measurement of gas concentrations, where it would be useful to know the concentrations of oxygen, and fire gases in the lower layer of the room, near the fuel packages. Differences in the measurements between experiments of the same type included maximum temperature and the neutral plane height in doorways. These differences could be attributed to ventilation effects. The ability to compare measurements from the gasoline ignited experiments, however, was limited due to the power failure during experiment 4.

Comparisons of the conditions of the rooms and furnishings after the experiments resulted in the determination of several similarities, as well as many differences, between experiments with the same method of ignition. Examples of similarities include sagging of bed springs (gasoline ignition) and bed frames, protection of room surfaces by furniture, the presence of deformed light bulbs, more severe burning of floor surfaces near the center of rooms as compared to near the edges of rooms, and the presence of areas burned clean of soot. Areas with differing levels of soot deposition, and areas burned clean of soot formed patterns corresponding to indicators defined in NFPA 921 such as clean burns and "V" patterns. Similarities are summarized in Table 10, where the presence of a condition in an experiment is indicated by "Y" for yes, the condition was present; or "N" for no, the condition was not present. Dashes in the table indicate that the experiment could not be compared to the other experiments in a comprehensive manner due to the limitations of the data or photographs.

TABLE 10. *Experiment similarities*

	Experiment			
Condition	*1*	*2*	*3*	*4*
Doorway char indicator	N	Y	–	–
Clean burn on the wall above and behind chair	Y	Y	Y	Y
Furniture outline	Y	Y	–	–
Protection behind and/or below furnishings	Y	Y	–	–
Mattress spring sag	N	Y	Y	Y
Bed frame sag	N	N	Y	Y
Pulled bulbs	Y	Y	–	–
Heavy charring in center of floor	–	–	Y	Y
Pattern behind door	–	–	Y	N
Clean burns	Y	Y	Y	Y
"V" patterns	Y	Y	Y	Y
Window breakage	N	Y	Y	Y

One similarity of interest found in the gasoline experiments was the heavier burning found near the center of the rooms. While this is the same area where the gasoline was poured, the cause of the heavier burning in these experiments was not conclusively demonstrated. Other possible explanations are ventilation effects from the door, and radiant heat transfer view factors between the floor and the hot gases in the upper layer. The formation of flammable liquid burn patterns is a potential topic for further study.

Significant differences in the condition and appearance of the burn rooms and furnishings were present between experiments with the same method of ignition. The differences consisted of the severity of burning, the locations of patterns, and the types of patterns present. Overall, there was a lack of pattern consistency. As mentioned previously, ventilation effects are the likely cause of the pattern inconsistencies, and should be tightly controlled in future experiments. Characterization of the ventilation conditions present would be aided by the instrumentation of openings for the measurement of flow velocity. Only if ventilation effects are minimized will it be possible to fully gauge the effects of ignition scenarios on pattern formation.

While they are not discussed in detail in this report, there are consistent differences between the results of the chair ignition and the gasoline ignition fires. An example is present in the aforementioned Table 10, where the bed frame was deformed during the gasoline ignited fires (experiments 3 and 4), but were not deformed during the chair ignition fires (experiments 1 and 2). Due to the small number of experiments conducted, as well as the other variables in the experiments such as ventilation conditions, the results are not conclusive. Further experimental study, with the goal of understanding the conditions present in the fire rooms, are necessary before conclusions can be drawn as to the impact of the fire ignition method on indicator formation.

FIGURE 29. *Photograph of the chair as viewed through doorway. Experiment 1.*

FIGURE 30. *Photograph of the chair as viewed through the doorway. Experiment 2.*

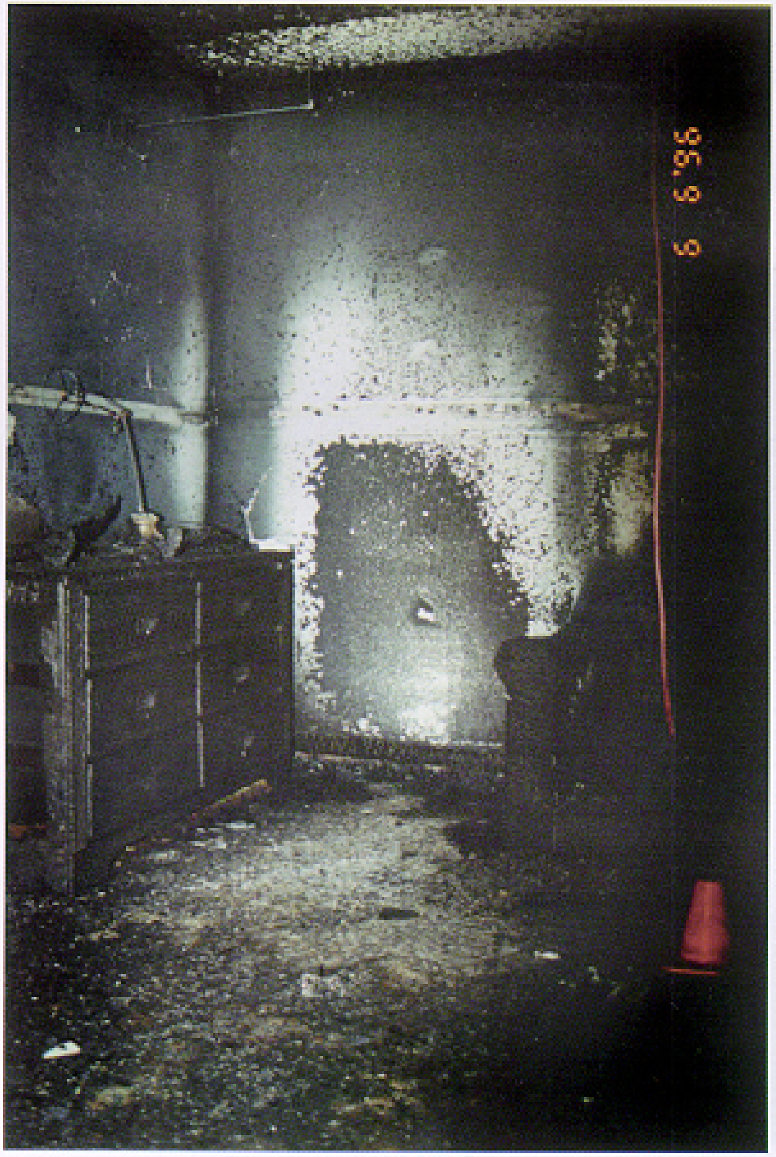

FIGURE 31. *Photograph of the clean burn on the wall between the chair and the dresser. Experiment 2.*

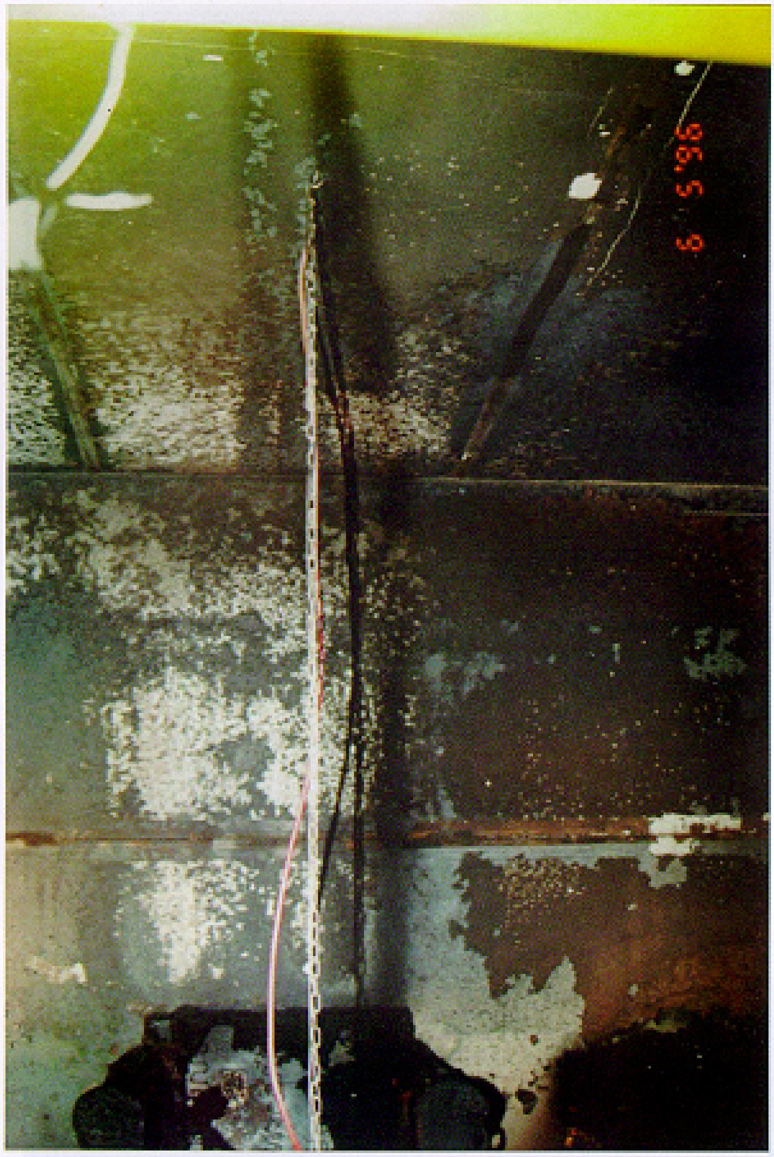

FIGURE 32. *Photograph of the ceiling and wall above the chair. Experiment 1.*

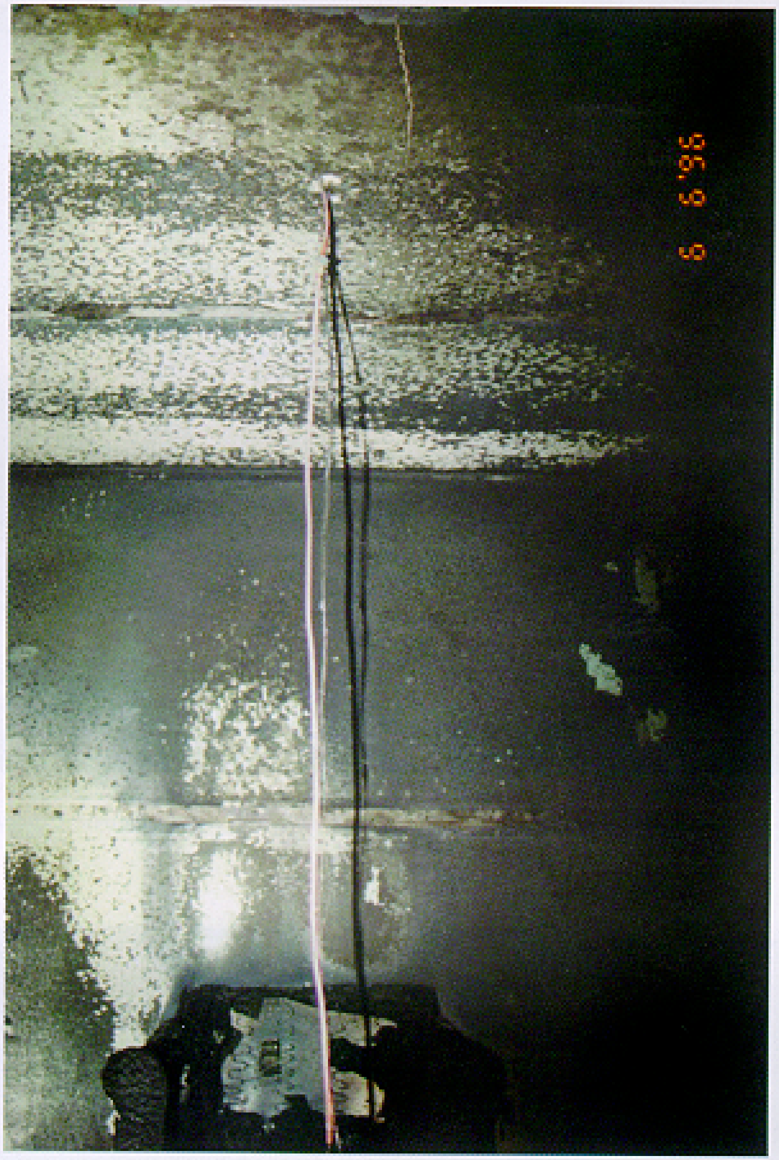

FIGURE 33. *Photograph of the ceiling and wall above the chair. Experiment 2.*

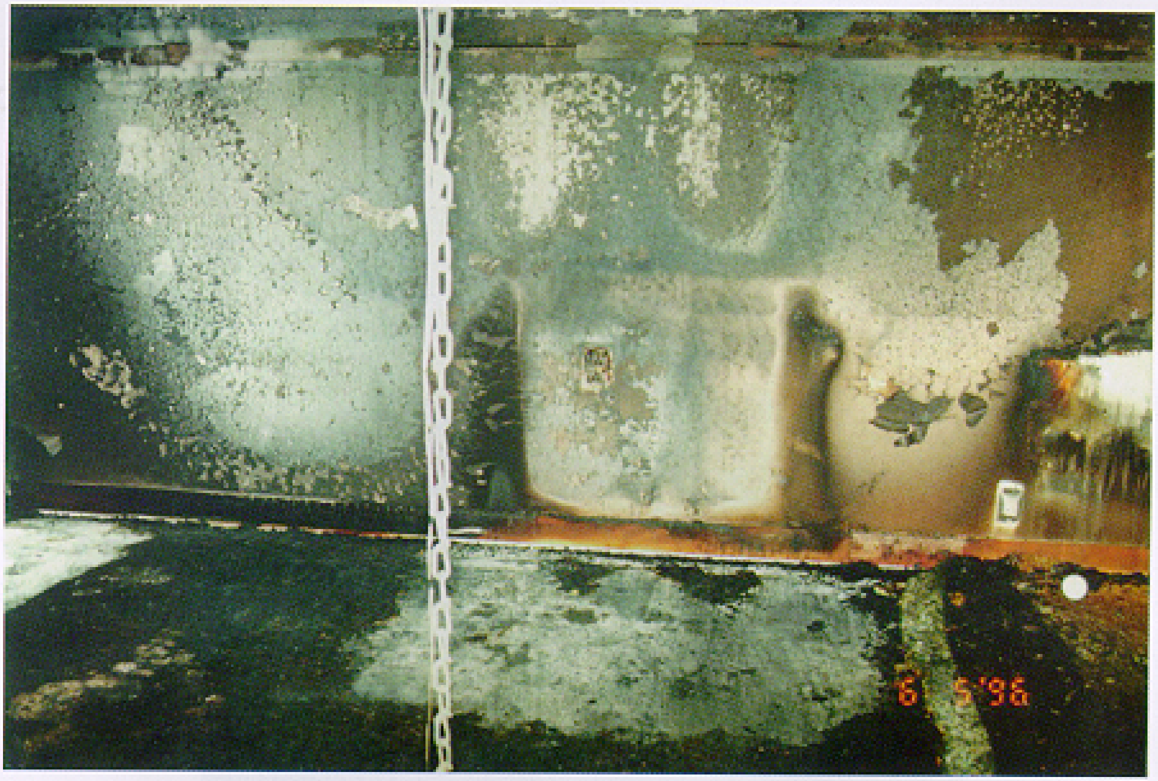

FIGURE 34. *Photograph of the wall behind the chair with furnishings removed. Experiment 1.*

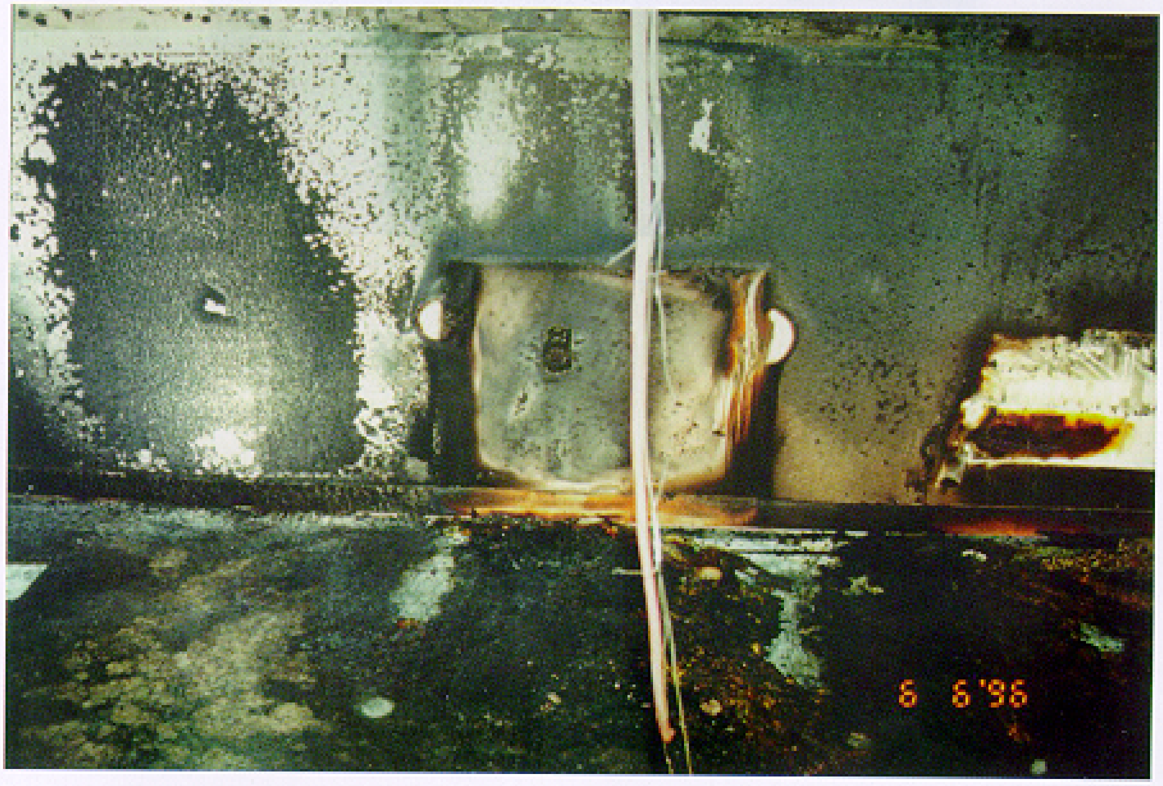

FIGURE 35. *Photograph of the wall behind the chair with furnishings removed. Experiment 2.*

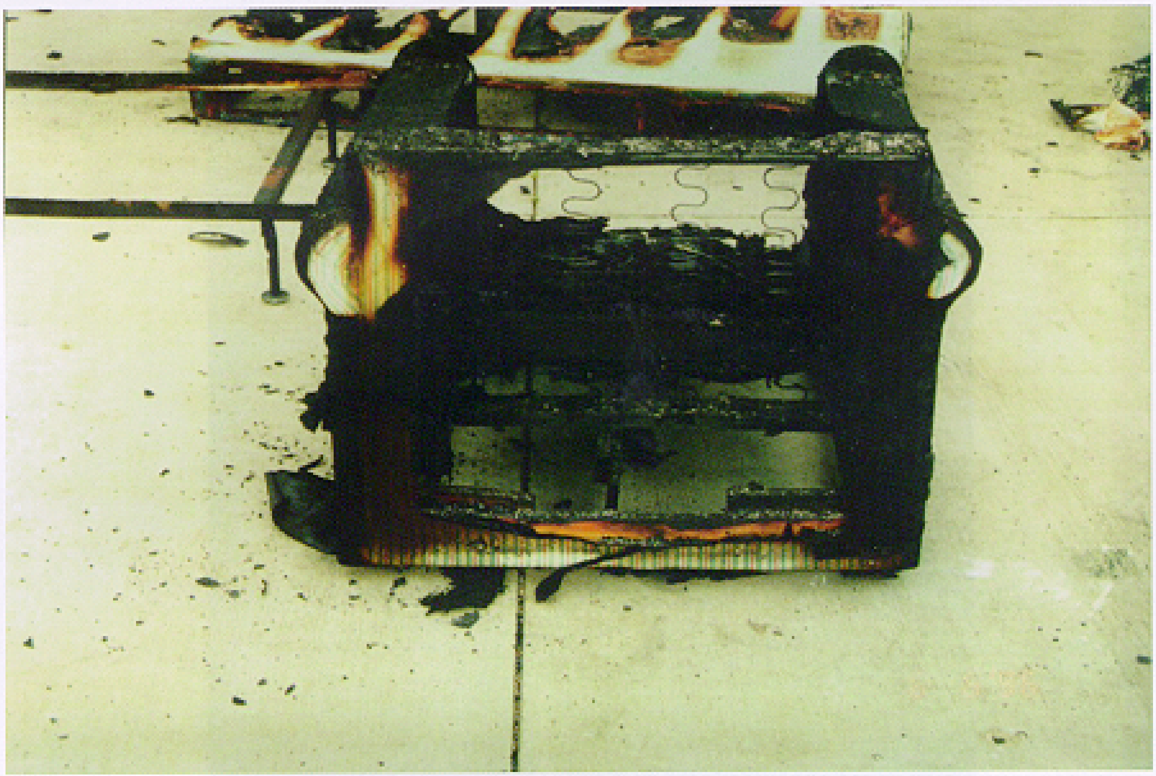

FIGURE 36. *Photograph of the rear surface of the chair, located against the wall. Experiment 2.*

FIGURE 37. *Photograph of the rear surface of the chair, located against the wall. Experiment 1.*

FIGURE 38. *Photograph of the condition of the bed and the protected floor area below. Experiment 1.*

FIGURE 39. *Photograph of the condition of the bed and the protected floor area below. Experiment 2.*

FIGURE 40. *Photograph of the window and surrounding wall. Experiment 1.*

FIGURE 41. *Photograph of the window and surrounding wall. Experiment 1.*

FIGURE 42. *Photograph of the window and surrounding wall. Experiment 2.*

FIGURE 43. *Photograph of a deformed light bulb located in the lamp on the nightstand. Experiment 1.*

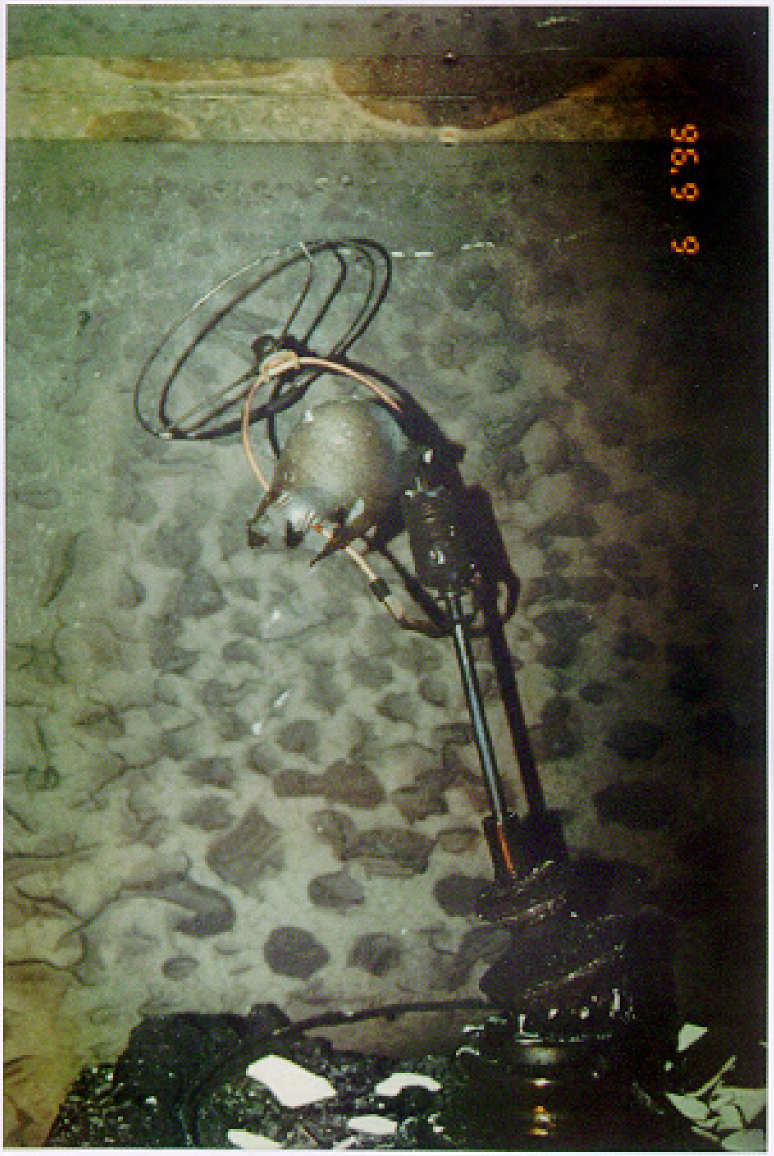

FIGURE 44. *Photograph of a deformed light bulb located in the lamp on the nightstand. Experiment 2.*

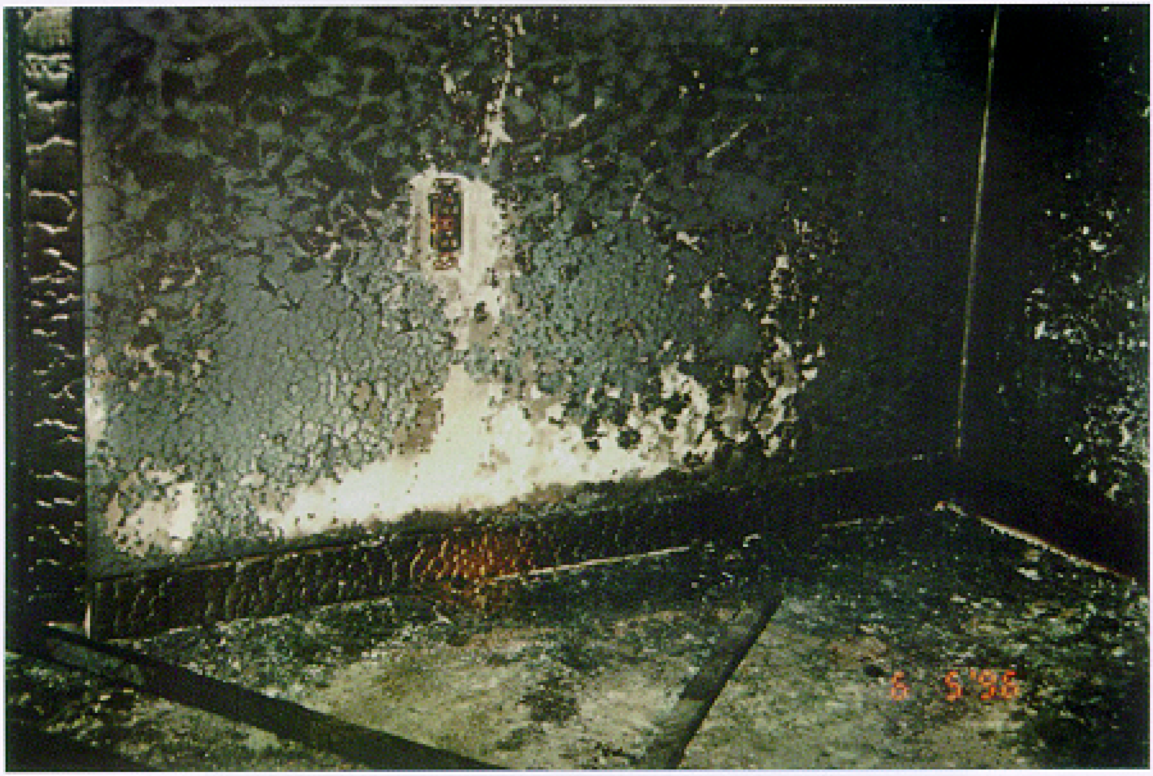

FIGURE 45. *Photograph of the wall to the right of the doorway, viewed from inside the room. Experiment 1.*

FIGURE 46. *Photograph of the wall to the right of the doorway, viewed from inside the room. Experiment 2.*

FIGURE 47. *Photograph of the ceiling and wall above the chair as viewed through the doorway. Experiment 3.*

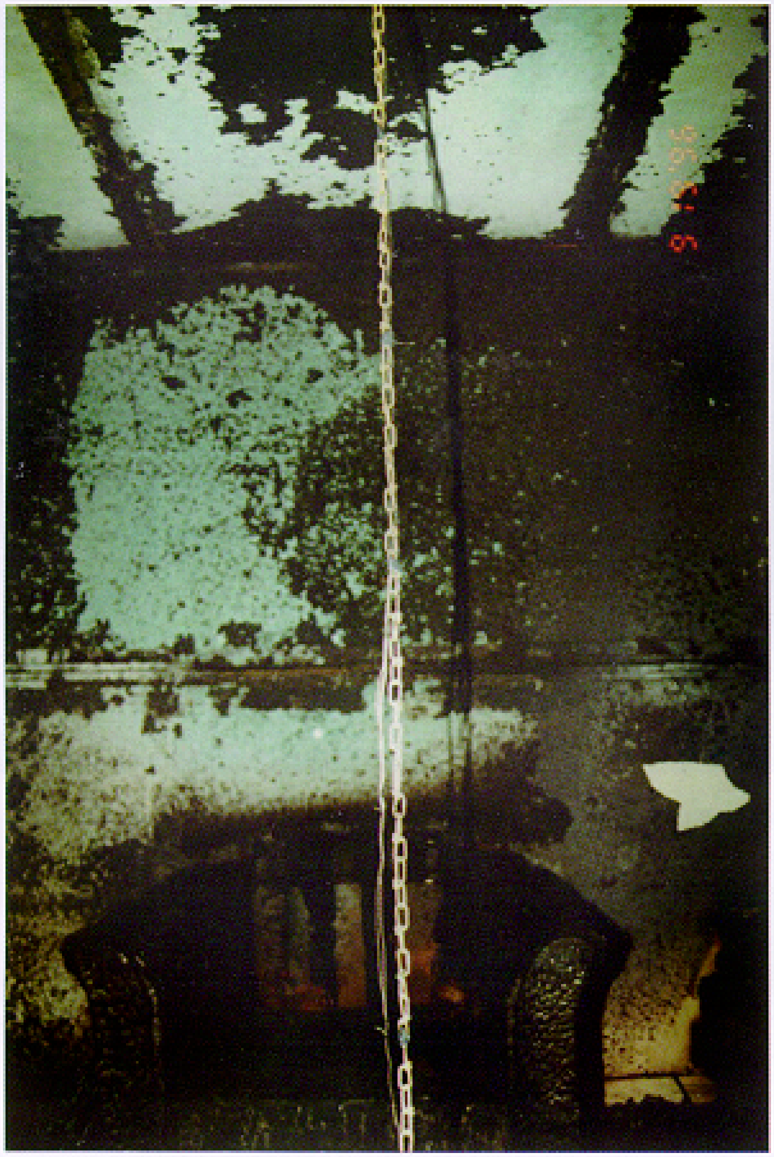

FIGURE 48. *Photograph of the ceiling and wall above the chair as viewed through the doorway. Experiment 4.*

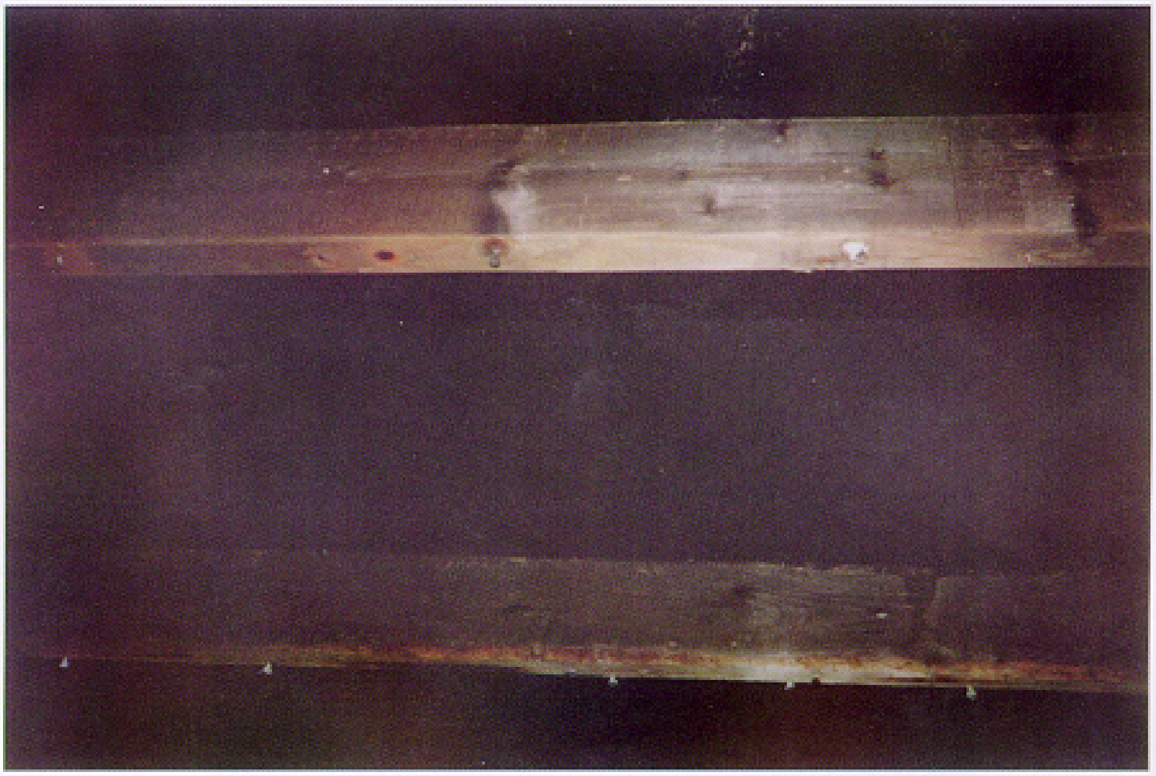

Figure 49. *Photograph of the ceiling joists after extinguishment. Experiment 3.*

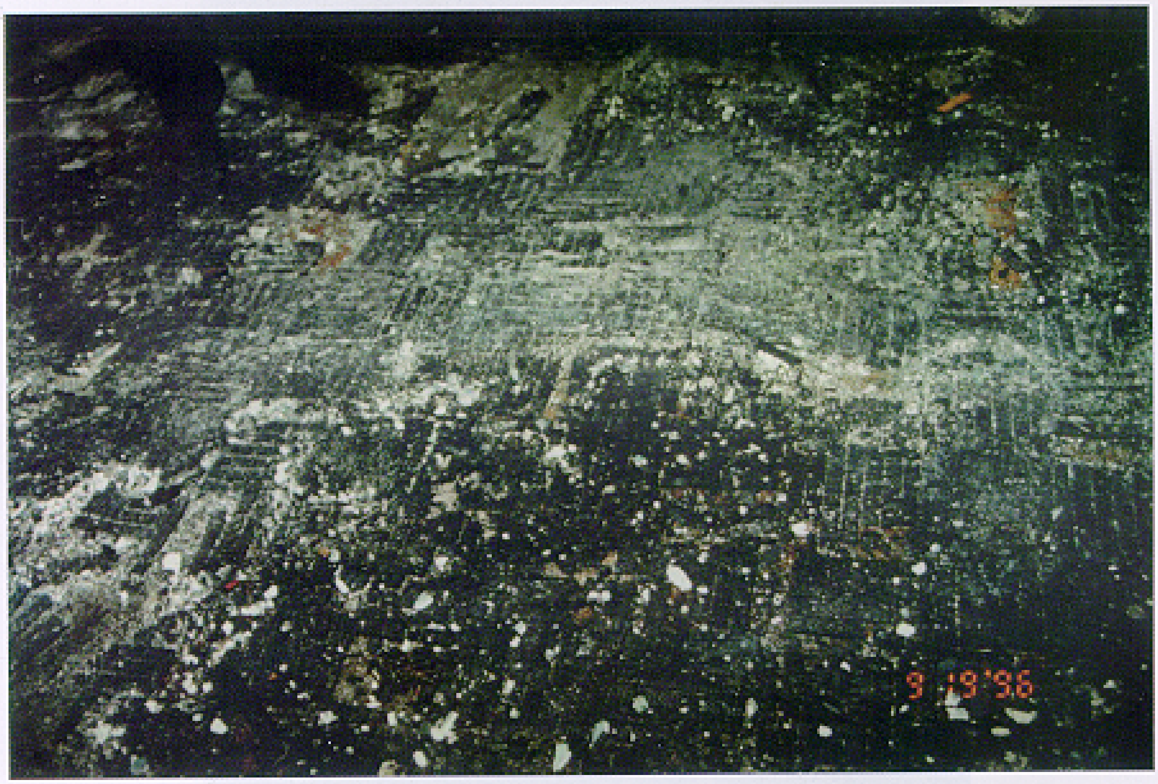

FIGURE 50. *Photograph of the floor. Experiment 3.*

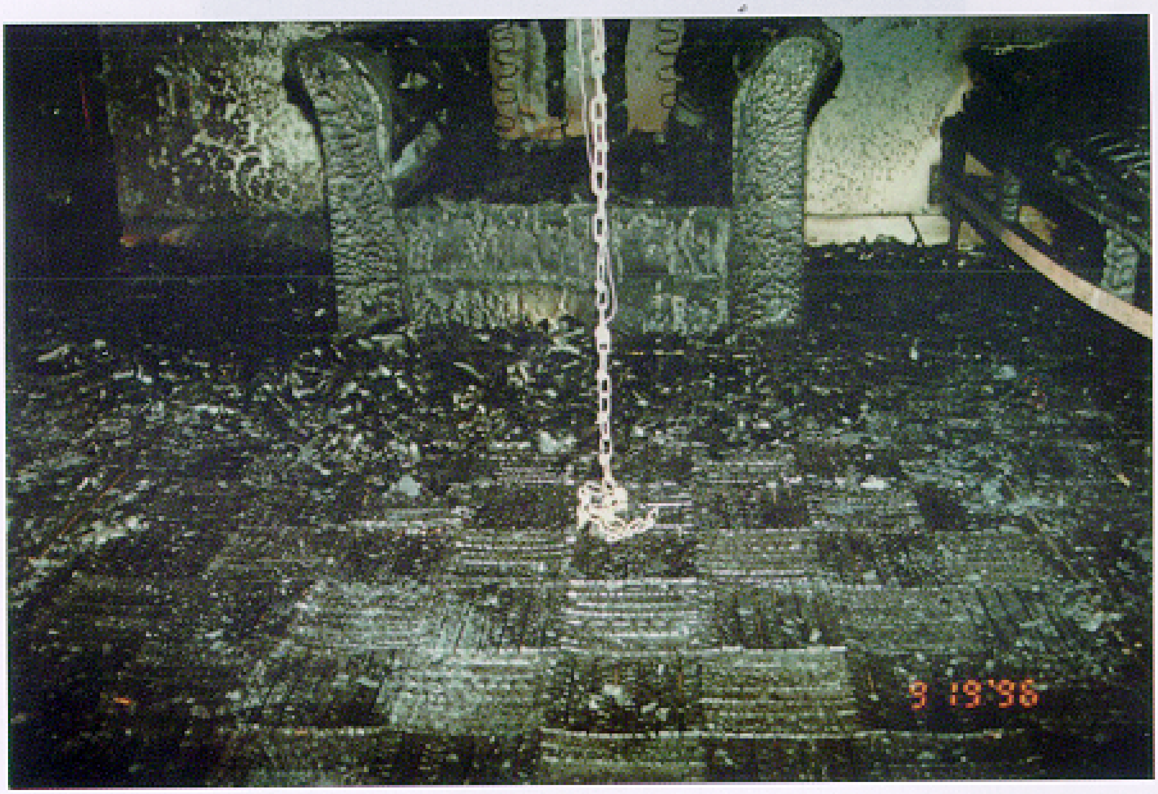

FIGURE 51. *Photograph of the floor. Experiment 4.*

FIGURE 52. *Photograph of the condition of the bed mattress and frame. Experiment 3.*

FIGURE 53. *Photograph of the condition of the bed mattress and frame. Experiment 4.*

FIGURE 54. *Photograph of the bed showing bed frame deformation. Experiment 3.*

FIGURE 55. *Photograph of the bed showing bed frame deformation. Experiment 4.*

FIGURE 56. *Photograph showing damage to the side of the dresser. Experiment 3.*

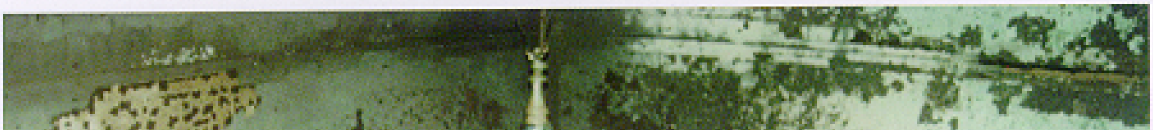

FIGURE 57. *Photograph showing damage to the side of the dresser. Experiment 4.*

FIGURE 58. *Photograph showing damage to the side of the nightstand. Experiment 3.*

FIGURE 59. *Photograph showing damage to the side of the nightstand. Experiment 4.*

FIGURE 60. *Photograph of the wall behind the door of the room, which was consumed by fire. Experiment 3.*

FIGURE 61. *Photograph of the wall behind the door of the room, which was consumed by fire. Experiment 4.*

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