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PREDICTION OF FIRE DAMAGE TO INSTALLATIONS AND BUILT-UP AREAS FROM NUCLEAR WEAPONS

FINAL REPORT - PHASE III

EXPERIMENTAL STUDIES-APPENDICES A-G

National Military Command System Support Center
Washington 25, D. C.
Contract No. DCA-8

IIT RESEARCH INSTITUTE

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EXPERIMENTAL STUDIES - APPENDICES A - G

by

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Washington 25, D. C.
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IIT RESEARCH INSTITUTE

FOREWORD

IIT Research Institute is presently engaged in developing a mathematical model for prediction of fire damage to urban areas from nuclear weapons (Contract No. DA-49-146-XZ-021 and DCA-8). The program, for the National Military Command System Support Center, is being conducted under the guidance of Mr. J. Crowley and Mr. T. R. Epperson, Project Monitors.

Although the study, as originally conceived, was to be based on existing information gathered from the literature, it became apparent that some additional knowledge pertaining to free-burning fires was needed. For this reason, an experimental program was initiated with the goal of augmenting existing information and generally to upgrade the "state of the art" in the field of initiation and spread of fires. The following report, on the results of these studies, is presented as a series of appendices to "Prediction of Fire Damage to Installations and Built-up Areas from Nuclear Weapons - Phase III Report", which discusses the development of the mathematical model.

Respectfully submitted,
IIT RESEARCH INSTITUTE

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ABSTRACT

Experiments were performed to provide necessary data for the prediction of fire damage to urban areas exposed to a nuclear burst. The investigations dealt with: flame heights and burning rates of well-ventilated fires, fire spread within structures - model room experiments, fire spread from interior kindling fuels, fire spread from exterior kindling fuels, full-scale building fires and coalescence of convective columns from free burning fires. Detailed description of the employed instrumentation is given. The derived correlations as well as the actual data are included in the report.

ACKNOWLEDGEMENTS

Experimental fires, whether conducted in the laboratory or in the field, require, due to their very nature, the close cooperation of a large number of individuals and organizations. This number grows most rapidly when the burning of a full-scale structure is contemplated. The cost of the experiment itself is dwarfed by the investment represented by fire fighting equipment which must, in the interest of safety, be available during its conduct.

Such cooperation was received throughout the program herein described. IIT Research Institute and its Fire Research personnel wish to thank the following organizations for their aid in providing the necessary structures and/or aid in the experimental fires.

1. The Chicago Fire Department, the Department of Urban Renewal, and the Smoke Abatement Department for the Ellis Parkway Apartment Burn.

2. The Kane County Fireman's Association and the many departments who contributed to the Plato Center School Burn.

3. The Lake Forest, Illinois, Fire Department for the Lake Forest Residence Burn.

4. The Homewood, Illinois, Fire Department for the Homewood Residence Burn, and

5. The Gary, Indiana, Fire Department for the Gary Residence Burn and the large scale coalescence burns.

It should be noted that all of the individuals of these various departments were contributing their time, in part or in total, and in the interest of fire fighters everywhere to increase the understanding of this spectacular and frightening phenomenon.

The authors also wish to thank their many collaborators on the IITRI staff, particularly Mr. I. B. Fieldhouse and Mr. G. Maatman, who bore the brunt of the many necessary contacts and conferences required for preparation of each full scale fire. Messrs. W. J. Murphy and G. Nagumo gave field direction to a major portion of the laboratory studies on the coalescence of wood cribs. Mr. R. B. Varley correlated the data for the coalescence studies and assisted in the preparation of the report. Messrs. R. Bogot, D. Carter, J. Marolda, S. Noreikis, and J. Pavletich constructed and instrumented the many laboratory experiments as well as a large portion of the full-scale burns. Mr. A. Pintar aided the authors in a significant portion of the data reduction and interpretation, as well as in bringing the report into its final form.

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GLOSSARY

Combustion

A rapid oxidation accompanied by the evolution of heat and light.

Compartment

That portion of a structure which allows the uninhibited involvement of fuel and the flow of heat and fire gases, without penetration through a physical barrier (such as a wall, a closed door, a floor or ceiling and roof construction).

Configuration Factor

The ratio of intensity received from a radiating source to that which would be received from a hemispherical source completely filling the field of view of the receiving element.

Conflagration

A mass fire with a moving front. Strong winds or topography cause the fire to spread in a particular direction.

Convective Column

The rising column of hot gases observed over a fire or other heat source.

Critical Ignition Energy

The ignition energy, in calories per square centimeter, of the incident thermal radiation from an atomic weapon burst that will just ignite a kindling fuel.

Exposed Structure

A structure exposed to fire from neighboring structures.

Exposing Structure

A burning structure heating neighboring structures.

Exposure

The hazard of ignition to a structure or its contents from fire in an adjoining building or other exterior source.

Fire Duration

The time from the origin of fire until burnout.

Fire Load

Potential heat energy of fuel per unit area (combustible contents including combustible building components) Btu/sq ft or kcal/sq m; also expressed in weight units of fuel, lb/sq ft or kg/sq m of floor area.

Fire-Resistive Construction

A building with structural members of noncombustible materials of such quality and so protected that they will resist the maximum severity of fire expected within the structure without collapse.

Fire Spread

The travel of fire from point to point within a building or collection of fuel, as well as from one building or collection of fuel to another.

Fire Storm

A mass fire with stationary front. Strong inward winds are caused by rising columns of hot gases, and the spread of fire is largely limited to the initially ignited area. Within the fire perimeter, virtually complete destruction will occur.

Flashover

Instantaneous spread of surface flaming of combustibles, due to heating and ignition of gaseous decomposition products.

Free Burning Fire

Uncontrolled burning of combustible materials.

Ground Zero

The point on the ground directly below the point of burst of an atomic weapon.

Heat of Combustion

The heat released by combustion of a unit quantity of a fuel, referred to some temperature and pressure (Btu/lb-mol., Btu/lb or kcal/kg).

Heat of Reaction

Heat evolved or absorbed due to reaction of unit quantity of substances, referred to some temperature and pressure (Btu/lb-mol., Btu/lb, kcal/kg).

Ignition

Initiation of visible combustion in the form of glow or flame.

Kindling Fuel

Any combustible material that can be ignited by the thermal radiation from an atomic weapon.

KT

Kilotons of TNT, equivalent in energy to the total yield of an atomic weapon.

Laminar Flow

A flow of fluid in which neighboring layers are not mixed.

Masonry Wall and Wood Construction

A building with exterior walls, court walls, and fire walls of masonry, and with roofs, floors, and interior framing wholly or partly of wood. Note: Includes heavy timber and ordinary joist construction.

Mass Fire

A fire which occurs from the merging of several separate fires into a single fire involving a large number of buildings.

Modeling

Representation of a process using physical, chemical, and mathematical similarities.

Noncombustible Construction

A building, constructed of materials which will not contribute a significant amount of fuel to a fire, with structural members either totally unprotected or inadequately protected to meet the requirements for Fire-Resistive Construction.

Peak Fire Duration

The time period of a fire during which maximum flaming occurs, beginning with flashover and continuing until flaming subsides.

Pilot Ignition

The act of starting combustion of heated solids by the application of flame, spark, or hot surface to gaseous decomposition products mixed with air.

Primary Fire

Self-sustained combustion resulting from a primary ignition. (In this report, unless otherwise indicated, primary fire implies a fire of sufficient intensity and duration to cause flashover in the compartment of origin.)

Primary Ignition

Kindling of fuel into flaming or glowing combustion of more than momentary duration by the thermal radiation from an atomic weapon.

Rated Resistance

Time required for fire penetration of barriers subjected to standardized fire exposure.

Slant Range

The distance between the point of detonation of an atomic weapon and the exposed material being considered.

Spontaneous Ignition

Initiation of self-sustained combustion in the absence of a pilot ignition source, due to self-acceleration of exothermic reaction supplementary to an external heat source.

Tract Data

Data for an urban area that consists of small areas (tracts) in which the buildings are relatively homogeneous with respect to occupancy, height, construction type, and density (ratio of building plan area to ground area).

Transmission Factor

The fraction of the radiant exposure received at a given distance after passage through any medium, relative to that which would have been received at the same distance if no medium were present.

Turbulent Flow

A haphazard motion of fluid due to eddies.

Wood Frame Construction

A building with exterior walls, partitions, floors, roof constructions, and supports of wood or other combustible material.

NOMENCLATURE

Symbol	Quantity	Units
A	Area	ft^2
C	Proportionality Constant	
D	Size of Fire or Width of Crib Array	ft
d	Enclosure Depth, Crib Depth, or Crib Separation	ft
g	Acceleration due to Gravity	ft/sec^2
H	Enclosure Opening above the Crib, $H = h - \ell$	ft
h	Window Height or Enclosure Height, or Heat Transfer Coefficient	ft BTU/ft^2-hr R
I	Radiant Intensity, or Electrical Current	cal/cm^2-sec amps
k	Proportionality Constant in Scaling	
L	Flame Height	ft
ℓ	Crib Height	ft
m	Time Constant in Flashover Correlation	min
N_{Re}	Reynolds Number, $Vw\rho / \mu$	
n	Number of Cribs in Coelescence Studies	
R	Burning Rate, or Electrical Resistance	lb/min ohms
T	Absolute Temperature	^oR
TC	Thermocouple	
t	Temperature	^oF
V	Velocity of Gases Leaving the Top of the Crib, or Volume Involved in Flashover	ft/sec ft^3
W	Furniture Weight	lb
w	Enclosure Width, Crib Width, or Window Width	ft

Symbol	Quantity	Units
ε	Emissivity	
μ	Viscosity	gm/cm-sec
ρ	Density of Burning Gases or Density of Air	gm/cm^3;lb/ft^3
σ	Stefan - Boltzman Constant	cal/cm^2-sec K^4
τ	Time	sec;min
ϕ	Configuration Factor	

SUBSCRIPTS

Symbol	Quantity
A	Ambient
C	Chopper
E	Epply Cell
f	Full Scale, or After First Flashover
fr	To Receiver from Flames above Window
i	Impinging Radiation
L	Lamps
o	Ambient, or At First Flashover
R	Radiometer
r	Receiving Element
S	Shutter, or Source
s	Surface Controlled
v	Ventilation Controlled
w	Window
wr	To Receiver from Flames in Window
τ	At time τ

I. INTRODUCTION

A. GENERAL

The development of an accurate model for predicting fire damage to an urban area as a result of a nuclear burst depends primarily on a thorough understanding of the processes governing the initiation and spread of fires and the reliability of the data employed to describe these processes. During IIT Research Institute's work concerned with the construction of such a model, considerable effort has been expended to satisfy these two requirements. In some cases, however, the required information was inadequate, if not lacking entirely, to permit representation of the phenomena. Hence, it was necessary to use extensive extrapolation of a few pieces of information, and even to hypothesize without actual scientific verification. Of course, such methods can considerably reduce the accuracy of the fire damage model. To rectify this situation, IIT Research Institute undertook a series of experiments to provide the needed data. The experiments were not designed to exhaustively treat any one area of research on fire, but rather only to upgrade the "art" to a usable level. The information sought and the methods employed in obtaining it are discussed below. First, however, to indicate more specifically the need and the application of the data obtained, the salient features of the fire damage model are described.

B. COMPUTER PROGRAM FOR THE PREDICTION OF FIRE DAMAGE

In an urban area subjected to a nuclear burst, the development of fire can be identified by three main stages. These are: ignition, fire spread within and between structures, and development of mass fire.

The part of the computer program which deals with the initiation of fire by the thermal pulse is referred to as the "ignition model". In constructing the ignition model, an assumption is made that only kindling fuels, such as fabrics, newspaper, etc., can be ignited by the thermal pulse. This fact, as reported in the literature, has been verified by numerous full scale and laboratory experiments. Since even sound wood was found not to sustain burning when ignited by the pulse, the initial fires from a nuclear burst can result only from kindling fuels located within or outside structures. In this connection, experiments which are described later on have shown that the ignition of exterior structural members requires large quantities of exterior kindling fuels, not usually found in urban areas. Hence, the ignition model assumes that fires from a thermal pulse will result primarily within structures.

Two conditions must be met for kindling materials situated within some enclosure to be ignited by a thermal pulse. First, the material must be exposed to the pulse, and second, the radiation intensity must be at least equal to the critical ignition energy of the exposed material. The locations of kindling materials such as upholstered furniture, couches, beds, etc., can be quite arbitrary within each room. Hence, to determine whether kindling materials will be ignited by the thermal pulse, an approach based on probability of ignition must be used. This can be accomplished by assuming that the probability of a kindling item being ignited is equal to the ratio of the room area irradiated with critical ignition energy to the room area within which the material can be located. The computer program dealing with the ignition model calculates the probability of exposure and then assigns it as the probability of ignition of the kindling item.

If fires would not spread from their places of origin, the ignition probabilities would be indicative of the damage to the urban area. But fires do spread, first involving the whole room where the ignition took place and then the floor or the whole building if it is not of fire resistive construction. Depending on the distances and on the heat released by burning structures, fires can spread to adjacent structures not initially ignited by the pulse. The computer program treats this by examing the fire spread within structures and their effects on adjacent structures. The corresponding parts of the program are referred to as "fire history model" and the "fire spread model".

Briefly, the fire history model determines spread of fire within the structure using fire resistance ratings of the structural components. It also provides, as a function of time, information on duration of the fire within various parts of the structure and on the flame area visible from the outside. The latter information is used by the fire spread model to determine the heating and possible ignitions of exposed structures.

The three models, ignition, fire history, and fire spread, are subprograms of the main computer program. The program is designed to treat each structure separately. However, the large number of parameters involved, limits the application of the program to small areas such as blocks or tracts. By studying the fire behavior of these smaller areas, it is possible to predict the damage to the entire urban area.

In the discussion above, the various stages of fire development were enumerated. As it has been pointed out, the description of fire behavior in each stage required additional experimental data. These experiments and their specific objectives are now described. They pertain to the burning rates of the structural contents, fire spread within structures, fire spread from interior and exterior kindling fuels, and coalescence of flames.

C. EXPERIMENTAL STUDIES

1. Flame Heights and Burning Rates of Well-Ventilated Fires

The duration of fire and the flame areas of burning structures determine to a great extent whether an exposed structure will ignite. The flame area is used in the fire spread model to calculate the amount of heat impinging on the exposed structure. By this method, the fire spread between structures is predicted. Since the burning rates of structures determine the number of simultaneous fires, they also effect the heating of exposed structures and, consequently, the spread of fire. Hence, the accurate knowledge of the above parameters is of considerable importance.

It is well-recognized that the burning rate of the fuel depends greatly on the fuel surface area and the amount of the oxygen supplied. Also, depending on the relationship between the two, the fire may be ventilation-controlled (if the amount of available oxygen is less than required for a given amount of fuel), or it may be fuel-controlled (i.e., a well-ventilated fire with an excess supply of oxygen). There may also be some transition region where a fire may be partially ventilation and partially fuel-controlled.

The burning rates of a ventilation-controlled fire have been considered by numerous investigators; and knowledge of them, within the accuracy of the fire damage model, can be assumed as satisfactory. This is not the case for fuel-controlled fires. Only a few preliminary investigations were previously conducted which, in fact, resulted in contradictory opinions. This is unfortunate, because each fire, after penetration or collapse of the roof, becomes well-ventilated. A similar case exists in structures with large window areas.

As indicated above, the flame area from a burning structure is one of the most important parameters governing the spread of fire. It was also the least understood parameter. In consequence, this information, required for the prediction of fire spread, had to be based on pictorial eveidence supplemented by meager data. This approach was, of course, not satisfactory and urgently required improvement by experimental means.

For the reasons discussed, experiments were designed to provide the burning rates of well-ventilated fires and their flame heights. The experiments involved crib fires situated on scales for continuous monitoring of burning rates. The correlation obtained for flame heights and burning rates of fuel controlled building fires improved considerably the accuracy of predicting the fire spread between structures.

2. Fire Spread Within Structures

a. Laboratory Experiments

The progress of fire within structures has a direct effect on the fire spread between structures as it determines the flame area and the duration of fire. Therefore, any error committed in describing the fire histories of structures has a direct bearing on the accuracy of the overall fire damage model.

The existing information pertaining to this problem dealt primarily with the fire histories of single rooms. As a result, in the development of the model it was necessary to use standard fire-test data for describing fire development within structures. For situations where the mode of the fire resembles, at least approzimately, the method employed in standard fire tests, this approach is reasonably good, although the time lag from ignition to flashover in subsequent compartments still needed to be evaluated. However, in numerous cases, the path of fire can create conditions entirely different from those existing during standard fire tests. In such cases, as in the fire spread through stairwells, through corridors, downward through floors, etc., only crude estimates could have been made.

For these reasons, the progress of fire within structures was studied, using 1/2-scale rooms and full-size structures. Particular attention was paid to the relationship between the flame area and the fire spread within the structures.

b. Field Studies

Because the bahavior of free burning fires depends on their size, great care must be exercised to insure that scaling laws based on model studies apply to full-scale cases. For this reason, in designing the laboratory experiments, an attempt was made to use the largest model sizes possible. Nevertheless, to gain confidence in the results obtained, they had to be verifired by some full-scale fires. These experiments were conducted with fires in a number of actual buildings with contents typical of several selected occupancies. Since these experiments were to verify the results obtained with half-scale structures, the information sought was similar in both cases, i.e., the relationship between the flame area and the fire spread within the structure.

3. Fire Spread from Internal and External Kindling Fuels

Because thermal pulse can only ignite kindling materials, the fire spread from these fuels has a profound effect on fire damage from nuclear explosions. Considerable effort was expended in the past to determine the levels of thermal pulse, i.e., critical energy, necessary for igniting kindling materials. Little or no attention was paid to the subsequent behavior of kindling fuel fires. The latter are, however, of primary concern since a kindling fuel fire not capable of spreading fire to other fuels is of little consequence. Experiments were performed to determine what is required for a kindling material fire to ignite other fuel.

For interior kindling fuels, experiments were performed in a full size room (12 x 12 x 8 ft.) using various items of upholstered furniture for ignition points. The amount of kindling fuel needed to flashover the room and the time between ignition and room flashover were investigated. For exterior kindling fuels, various wooden structures (siding, railings, etc.) were exposed to fires of kindling materials.

4. Coalescence of Convective Columns from Free-Burning Fires

In their final stages of development, fires initiated in an urban area by a nuclear burst can coalesce and form a mass fire. Since the coalescence can considerably increase the damage, it must be considered by the fire damage model. Unfortunately, the mechanism governing the formation and the subsequent behavior of mass fires is not known. To gain some understanding of those phenomena, experiments were conducted with liquid fuel and wooden crib fires. The objective was to study the flame coalescence and to develop criteria for the formation of mass fires.

As far as the fire damage model is concerned, such information is sufficient for the case of a fire storm since within its periphery a total destruction takes place. However, for a conflagration the criteria of flame coalescence is only the first step in the analysis of the fire damage because subsequent spread of the conflagration must also be known.

II. SUMMARY AND CONCLUSIONS

The main objective of the performed experiments was to make possible the prediction of fire damage to an urban area subjected to a nuclear burst. As indicated in the introduction, no attempt was made to investigate extensively any particular aspect of free burning fires, but rather to provide minimum data necessary for the development of the fire damage model. Hence, to understand fully the behavior of free burning fires, much work still remains to be done. A step in this direction is made here and the results of this effort are summarized below.

A. FLAME HEIGHTS AND BURNING RATES OF WELL VENTILATED FIRES

Fire spread from burning structures is primarily due to radiative heat transfer. This mode of heating is a function of flame area, which in turn depends on the burning rate. Crib-fire experiments were performed to investigate the relationship between flame area and burning rate for well-ventilated fires. The cribs were burned in a free condition as well as in enclosures. All cribs were constructed of Idaho white fir. The sticks were either 1 x 2 inches or 2 x 4 inches nominal, with spacing between them of 3 or 6 inches. The respective height, width and depth of crib enclosures with one side open were 3 x 3 x 3 ft., 6 x 6 x 6 ft., 9 x 9 x 9 ft., 6 x 3 x 3 ft. and 3 x 6 x 6 ft. In some cases the air flow into the burning crib was restricted by plates placed vertically or horizontally over 50 percent of the open side of the enclosure. Some experiments were conducted with 3 x 3 x 3 ft. enclosures either with a 4 x 6 ft. high wall placed above the opening or with both one side and the top open.

For crib fires burning in the open, the data show somewhat smaller flame height than that reported by other investigators. This difference can be attributed to the variation in wood spacing, which is not included in dimensionless correlations. For cribs burning in enclosures, the analysis of data indicated that when the fire is ventilation controlled, the flame height, L, and the opening (window) height, H, are proportional, i.e., $L \sim H$. However, when the fire is mostly fuel controlled, $L \sim H(\ell/H)^{2/3}$ where ℓ is the crib height.

The addition of a 4 x 6 ft. wall above the opening in a 3 x 3 x 3 ft. enclosure did not affect the burning rate or the flame height. Similarly, the burning rate was about the same when only one side of the enclosure was open or when no enclosure was used. Apparently, the three-foot dimension does not offer significant restriction to the air flow at the stick spacing used.

The burning rate, R, for fuel controlled fire has been confirmed to be $R = 0.09\ A_s$ (lb/min) where A_s is the fuel surface. A graphical relationship has been established for the radiation intensity from crib fires as a function of the burning rate. A datum point obtained for a well-ventilated building fire was in good agreement with this relationship.

The experimental work and the results on flame heights and burning rates for well-ventilated fires are discussed in greater detail in Appendix A.

B. FIRE SPREAD WITHIN STRUCTURES - MODEL ROOM EXPERIMENT

The experiments, considered more fully in Appendix B, consisted of burning model rooms in various combinations under controlled laboratory conditions. The model rooms were scaled from a room 12 ft. square with an 8 ft. ceiling and with a single window, 4 ft. high by 5 ft. wide, on one side. The height and width of the furniture items comprising the contents of the model rooms were scaled directly with the thickness held to the full scale equivalent. In this manner the total surface area was properly reduced while the burning time, under well-ventilated conditions, was held equal to that of full scale items. Experiments included studies of fire spread between adjacent rooms, upward and downward between vertically positioned rooms, and through corridors and stairwells. Instrumentation consisted of thermocouples, radiometers, weighing devices, and photographic equipment.

Preliminary experiments indicated that 1/3 and 1/4 scale models do not properly represent fire behavior in full size rooms. Satisfactory results were obtained with 1/2 scale models, which were subsequently used in the experimental series.

The results show that a description of the insulating qualities, as well as the combustibility of the wall covering materials of a room, are required to adequately describe the fire build-up in a room. Penetration times were obtained for various structural components and compared with their standard fire resistance rating. For the assemblies employed, the penetration times were about 40 minutes for roofs, 25 minutes for finished ceilings, and 5 minutes for plywood doors. Wind has been found to increase the burning rate. The experiments have also shown that the constant, 0.678, appearing in the burning rate equation for ventilation controlled room fires needs modification. The equation obtained is:

$$R = 1.5 A \sqrt{h}$$

where R (lb/min.), A (ft^2) and H (ft.) are the burning rate, window area, and window height, respectively.

For a single room, the radiant energy is given by an approximate equation

$$I_r \approx 1.5 \sigma \emptyset_{wr} T^4$$

where the flame temperature is taken as 1500^oF and $\emptyset_{wr}$ is the configuration factor of the radiating window opening. For two story structures, the recommended equation is:

$$I_r \approx 4 \sigma \emptyset_{wr} T^4$$

where the flame temperature for these conditions is taken as 1600^oF. The flame thickness for the one story structure is given as one half of the window width and for the two story structure as the whole window width. In both cases, the window height should be used if it is smaller than the window width.

The experimental work and the results on fire spread within and between model rooms are described more fully in Appendix B.

C. FIRE SPREAD FROM INTERIOR KINDLING FUELS

Studies of fires in interior kindling fuels were directed toward the determination of the flashover time in the enclosing room. Experiments involved furniture such as sofas, chairs, beds, etc. Items were located in an experimental room with a 12 x 12 ft. floor area, and 8 ft. high ceiling, and a window opening 48 inches high and 62 inches wide. Ignition was accomplished by wiping the exposed surfaces with a cloth dampened with JP-4 fuel.

It was determined that the fire build-up in upholstered furniture differs from that of individual samples of fabric or padding materials. Generally, sustained burning took place in joints and seams only. Except for items padded with foam rubber, most of the build-up time involved the penetration of the fire to the interior spaces. The build-up time was apparently shorter for beds than for chairs and couches. The average flashover time was 18 minutes for a living room.

The experimental work and the results on fire spread from interior kindling fuels are discussed in greater detail in Appendix C.

D. FIRE SPREAD FROM EXTERIOR KINDLING FUELS

The purpose of these experiments was to determine whether burning exterior kindling fuels can ignite combustible members of structures. Structural members used in the study consisted of wall sections, four-step stairways and railings. The kindling materials were loose paper (wind blown into a pile), excelsior or small cribs.

In fires involving walls, the experimental panel was constructed as a section of a larger, non-combustible wall in order to eliminate edge effects. The kindling material was placed against the base of the wall and ignited with the aid of kerosene. The wall-rail combinations were investigated by placing a railing at 90° near one end of the wall section. The kindling fuel was placed at the base of the wall-rail juncture. In the stairway experiments, the stairs were placed against a non-combustible wall with the kindling fuel located under the stairs.

The experiments have shown that, in general, exterior kindling fuels cannot readily ignite well-maintained combustible members of structures. An exception to this is the case of stairways which can be ignited by burning fuel containing thick and thin kindling materials. However, the compensating effect here is that the stairs offer more shielding from the weapon to such items than do the walls.

The experiments and the results on fire spread from exterior kindling fuels are described in Appendix D.

E. FULL-SCALE BUILDING FIRES

The objective of experiments with full-size structures was to verify and extend the results obtained from model studies. In total five structures were used. Two structures, the Ellis Parkway apartment building in Chicago and the dwelling in Gary, Indiana, were used exclusively to study the fire spread. Experiments with the other three structures included extinguishment studies. Because the free burning fire is of prime interest to this program, the Ellis Parkway and Gary burns were treated in detail with only pertinent information noted about the remaining three fires.

To realistically simulate actual situations, each experimental structure was furnished with contents commensurate with the designated occupancy in terms of surface area of fuel. The floor fire load of the contents was about 2.2 $lb/ft.^2$ for the Ellis Parkway building and 2.8 $lb/ft.^2$ for the Gary dwelling. The instrumentation in each burn consisted of thermocouples, anemometers, radiometers, gas tube analyzers, photographic equipment and recordings of visual observations.

In general, the results from full scale fires confirmed the conclusions reached in the model experiments. The calculations of radiation intensities using the assumed flame model, i.e., temperature, emissivity and flame area, were in good agreement with measured values. This information is of vital importance to the prediction of fire spread between structures. It has also been determined that the volumetric spread of fire through a building divided into various interconnecting spaces can be described as a succession of predictable flashovers. The relationship between the cumulative building volume subjected to flashover and the time after the first flashover is best given by an equation of the form

$$V_\tau / V_o = e^{\tau_f / m}$$

where τ_f is the time after the first flashover, V_τ is flashover building volume at time τ_f, V_o is the flashover building volume at time $\tau_f = 0$ and m is the time constant.

It is realized that all reported fires were in one way or another influenced by wind and by the chimney effects of vertical openings such as stairwells. It is believed intuitively that a certain amount of flow of fire gases is a part of all fire spread mechanisms; also, flow directions can be changed by wind and stairwells to retard the spread of fire. The volume-time flashover data on the various plots indicate three to five minute delays of fire spread due to collapse of ceiling and opening of the stairwell roof during the Ellis Parkway burn. The flow of fire gases prior to flashover is also related to the life safety aspects of fire; the lead time prior to flashover, during which a given space is filling with smoke, is important here.

Regarding the smoke problems, in the Ellis Parkway burn it was found that fire gases generated within hollow combustible partitions and furred wall spaces would flow under pressure in all directions away from the immediate fire location. While the fire originated in the second story living room, the CO concentration in the basement was detectable six minutes after flashover in that room. The conclusions reached for the Ellis Parkway burn were confirmed by other full scale fires.

The full-scale building fires are discussed in more detail in Appendix E.

F. COALESCENCE OF CONVECTIVE COLUMNS FROM FREE BURNING FIRES

Coalescence of fires into a fire storm or conflagration considerably increases their destructive potential. Hence, the prediction of fire damage requires information regarding the formation and behavior of mass fires. This was the subject of experiments dealing with the coalescence of fires. Preliminary investigations were conducted with liquid fuel fires. Both laboratory and large scale field fires were used. However, the extreme sensitivity of the liquid fuel fires to any air motion made them unsuitable for the studies. This difficulty was not encountered with the wood crib fires which were subsequently used. These experiments involved single and multiple crib fires covering an area up to 150 square feet. The crib areas ranged from 2 x 2 ft. to 6 x 6 ft. Ignition was accomplished by industrial wipers placed under the cribs. Measurements included burning rates, temperatures, radiation, and air velocities.

The results indicate that burning rates provide a more suitable description of flame coalescence than do visual observations. As the distance between individual cribs increased, the total burning rate increased until the transition from a coalesced to non-coalesced fire occurred. This transition was accompanied by a sudden drop in burning rates. The peak burning rate, just prior to the transition, was determined as

$$R_{peak} = 1.56 \cdot n \cdot R_s$$

where n is the number of cribs and R_s is the burning rate of an individual crib. The ratio of the distance between cribs to the dimension of the individual crib for peak burning of a coalesced fire was found to be:

$$\left(\frac{\text{distance between cribs}}{\text{crib dimension}}\right)_{peak} = 0.069(n \cdot R_s)^{0.4}$$

The interaction of individual fires to form a mass fire is still one of the least understood phenomena of fire behavior; however, it is believed that the experiments described above have produced a step toward such understanding. Further experiments with larger sizes and increased burning rate per unit of fire area are needed. Studies of the effects of controlled wind and reduced oxygen content on individual cribs, compared with similar studies applied to segments of full or 1/2 scale structures, can serve to relate the behavior of each crib to that of one or perhaps a group of structures comprising a city block. Information thus obtained on the criteria for coalescence can eventually be incorporated into theoretical models for the behavior of fire storms or conflagrations which presuppose that coalescence has occurred.

The coalescence studies are described more fully in Appendix F.

G. INSTRUMENTATION FOR FIRE EXPERIMENTS

The measurement of several parameters pertinent to free burning fire requires special instruments not readily available commercially.

Such instruments have been developed, involving remote recording of monitored quantities by measuring changes in voltage. The relationship between measured quantities and voltage changes is established from calibration against other standard equipment. The instruments constructed were: radiometers, hot-wire anemometers, shielded thermocouples and weighing scales.

The radiant flux was measured by comparing the temperatures of two gold disks, one of which was exposed to the flux, the other shielded from it. The shielded disk served as a reference. Both disks were housed in an enclosure covered with multiple radiation shields. A window of mica protected the exposed disk from convective cooling. The instrument was calibrated for radiant flux levels up to 0.04 cal/cm^2-sec by comparison with the reading from an Epply thermopile. Using a ten-to-one chopper, the range of the instrument was extended beyond 0.1 cal/cm^2-sec.

Velocities of air entrained by the fire were measured by a modified hot-wire anemometer. The instrument consisted of two identical tubes, one of which was electrically heated. Thermocouples were attached to the tubes in opposition so that the measured emf signal was a function only of the temperature difference between the tubes. This negated the radiant flux impinging on the tubes. Calibration of the anemometers was accomplished by rotating them in an enclosure. The air velocity was determined from the rotational speed.

The temperature sensor was developed for the open fire experiments. It consisted of a thermocouple surrounded by several radiation shields over which the gas velocity was increased by aspiration. The radiation shield consisted of seven small diameter tubes pressed into a circumscribing tube of 3/4 inch diameter.

For solids and small amounts of liquid, a direct weighing device was developed. It consisted of a commercially available unit similar to a household bathroom scale which was modified to permit remote recording by replacing the dial by a low torque potentiometer. Both the total impressed voltage to each scale and the portion spanned by the slide contact of the potentiometer were measured. Overheating of any individual scale was thus noted immediately as a variation in total voltage drop through its potentiometer. Each scale had a usable capacity of about 200 lbs. Direct weighing was impractical for large scale field fires. For these fires a float was placed in the fuel tray and its motion translated by a simple lever to a pointer.

The gas samplings of burning structures were analyzed by commercial (Hays Corporation) units. Stop motion photography (50 or 100 frames/min) was employed throughout the experimental program.

In general, the instrumentation performed satisfactorily. Difficulties were encountered in measurements of the direction and magnitude of the air entrained by the fire. The anemometers recorded only the magnitude of air velocities and were also limited to exposure to low radiant fluxes. Hence, these instruments were not suitable for application in the proximity of fires. Several smoke generating techniques were tried but results were not entirely satisfactory. Further development of a device for recording air velocities in the proximity of a fire is highly advisable.

The instrumentation developed for the experimental fires is described in Appendix G.

APPENDIX A

FLAME HEIGHTS AND BURNING RATES OF WELL-VENTILATED FIRES

I. INTRODUCTION

To evaluate the thermal damage from a nuclear attack, it is necessary to determine the spread of fire between buildings. The fire spreads between buildings primarily due to the radiative heating which depends directly on the temperature, emissivity, and size of the flames issuing from windows and other openings. The size of the flames is in turn related to the burning rate of the room contents. In well-ventilated fires, the window opening is large enough so that the surface area of fuel controls the burning rate and the flames filling the opening constitute the major portion of the thermal radiation. For large amounts of fuel and/or small window openings, the window size determines the burning rate, and an appreciable flame exists above the window opening. This situation results in higher radiation intensities per unit of window area as compared to the well-ventilated fire.

The burning rates of ventilation-controlled fires were dealt with by numerous investigators, and have been considered known with sufficient accuracy for the development of the fire spread model. This was not the case with well-ventilated fires which in the past have been examined only in a preliminary manner. Since in most fires the burning becomes well-ventilated, it must be considered in the analysis of fire spread. Of particular interest are the flame heights and burning rates. These parameters were the subject of performed investigations described in this appendix. The experiments consisted of crib fires (cross-piles of wood), burned in a free condition as well as in enclosures. All cribs consisted of Idaho white fir. The ticks were 1 x 2 or 2 x 4 inches with spacings between them 3 or 6 inches.

The cribs or enclosures were continuously weighed, and the test recorded photographically. Temperatures were recorded at various places inside enclosures and radiant flux intensities were measured at exterior locations. The burning rate, R, was calculated from the crib weight loss as a function of time, using an average slope during the active period of fire. Flame height, L, was determined from the photographic record, being averaged for the same time period used to calculate the average burning rate. The construction details of the cribs and enclosures and obtained data are shown in Tables A-1, A-2, A-3, and A-4.

II. DIMENSIONLESS PARAMETERS USED IN ANALYSIS

To correlate the burning rate and flame height data with the geometry of the cribs and enclosures, a dimensionless analysis was performed. The analysis included all pertinent parameters, some of which were used in similar investigations by Gross[1] and Thomas[2,3].

In free-burning fires, factors considered to influence the flame height (L) are: the crib width (w), crib height (ℓ), ambient air density (ρ_0), gravity (g), and the burning rate (R).

The resulting dimensionless representation is:

$$f\left(\frac{L}{w}, \quad \frac{\ell}{w}, \quad \frac{R}{\rho_0\sqrt{g}\, w^{5/2}}\right) = 0 \qquad \text{(A-1)}$$

No attempt has been made to include the crib spacing, or wood type and size, since, as indicated above, in all tests, 1 x 2 or 2 x 4 inches Idaho white fir was used, with spacings between sticks restricted to 3 or 6 inches.

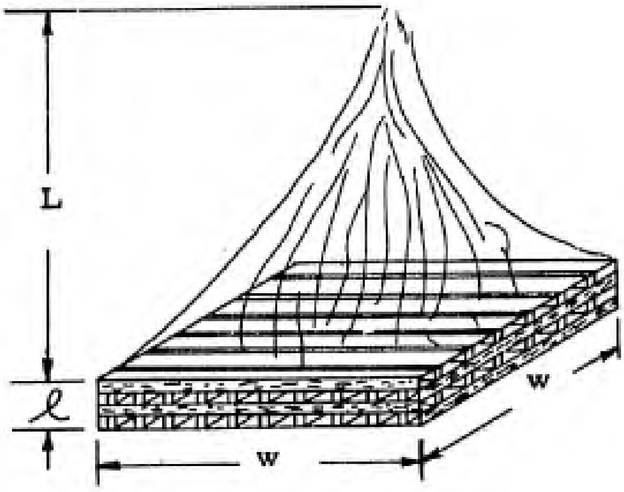


TABLE A-1 OPEN CRIB FIRES

w (ft.)	Wood Size (in. x in.)	Stick Spacing (in.)	ℓ (ft.)	Weight (lb.)	R (lb/min.)	L (ft.)	$\frac{L+\ell}{w}$
Crib Parameters							
6	1 x 2	6	0.55	68	10.0	5.45	1.00
6	1 x 2	6	1.09	137	30.0	9.81	1.81
6	1 x 2	3	0.55	139	18.0	10.45	1.83
6	1 x 2	3	0.27	69	8.0	5.23	0.92
6	2 x 4	6	1.26	279	22.0	7.64	1.48
3	1 x 2	6	1.09	34.5	6.5	5.81	2.30
3	2 x 4	6	0.55	64.5	5.5	-	-

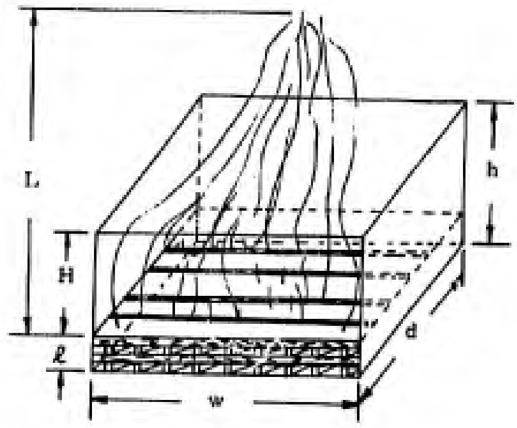


TABLE A-2 CRIBS OPEN ON ONE SIDE

Enclosure h (ft.)	Enclosure w (ft.)	Enclosure d (ft.)	Crib Wood Size (in. x in.)	Crib ℓ (ft.)	Crib Spacing (in.)	Crib Weight (lb.)	Crib A_s $(ft.)^2$	R (lb/min.)	L (ft.)
3	3	3	1 x 2	1.09	6	31	55.3	7.0	4.91
3	3	3	1 x 2	0.55	3	31.5	52.1	5.7	3.55
3	3	3	2 x 4	0.625	6	34.5	27.8	2.4	--
3	3	3	1 x 2	1.09	3	63.5	105.3	8.5	4.61
3	3	3	1 x 2	2.18	6	63	111.2	11.5	6.16
6	3	3	1 x 2	0.55	6	15.7	27.1	2.5	1.95
6	3	3	1 x 2	1.09	6	32	55.1	9.0	4.91
6	3	3	1 x 2	2.19	6	63.7	111.2	14.0	8.71
3	6	6	1 x 2	0.55	6	61.5	108.6	6.5	3.85
3	6	6	1 x 2	1.09	6	123.5	220.8	8.0	4.61
3	6	6	1 x 2	1.64	6	185.5	334	10.0	5.16
3	6	6	1 x 2	0.55	3	122.2	208	8.0	3.05
3	6	6	2 x 4	1.25	6	274	228	11.0	3.15
3	6	6	2 x 4	0.625	6	139	111	8.5	2.08
6	6	6	1 x 2	0.55	6	62.2	109	10.0	3.25
6	6	6	1 x 2	1.09	6	124.5	221	23.5	5.81
6	6	6	1 x 2	0.55	3	125.2	208	17.5	4.25
6	6	6	1 x 2	1.64	6	186.2	334	30.5	9.56
6	6	6	1 x 2	0.82	3	189	316	20.0	5.28
6	6	6	2 x 4	1.25	6	277	228	20.0	5.55
6	6	6	2 x 4	1.875	6	424.7	344	30.0	8.12
9	9	9	1 x 2	0.55	6	149	245	33.0	3.95
9	9	9	2 x 4	1.26	6	604.5	530	62.0	6.87
9	9	9	1 x 2	1.09	6	310	498	52.0	9.21
9	9	9	1 x 2	1.64	6	454.5	752	57.0	9.76

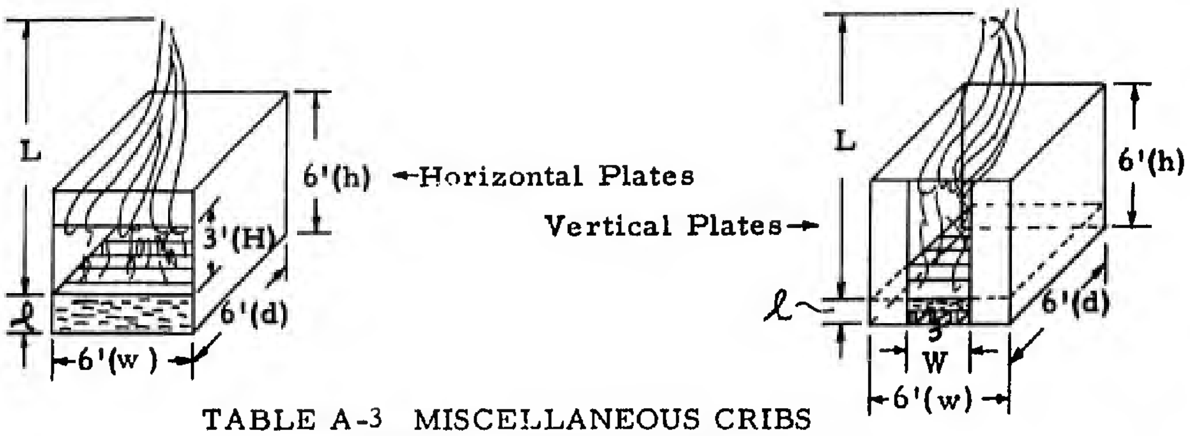
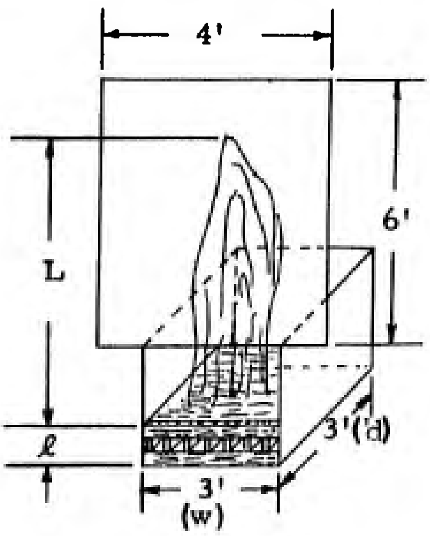


TABLE A-3 MISCELLANEOUS CRIBS

Wood Size (in x in.)	Stick Spacing (in.)	ℓ (ft.)	Weight (lb.)	A_s (ft^2)	R (lb/min)	L (ft.)
			Horizontal Plates			
1 x 2	6	1.09	123.2	221	18.0	3.4
1 x 2	6	0.55	60	108	11.0	3.3
1 x 2	3	0.55	135.5	208	14.5	2.3
1 x 2	6	1.64	208	334	19.0	5.1
1 x 2	6	1.64	207.7	334	16.5	3.6
1 x 2	3	0.82	199	316	16.0	2.9
2 x 4	6	1.20	322.5	228	14.0	2.9
2 x 4	6	1.80	476.5	344	15.5	4.1
			Vertical Plates			
2 x 4	6	1.20	326.5	228	18.0	6.7
2 x 4	6	1.80	471.5	343	21.0	11.2
1 x 2	6	0.55	66	108	14.0	4.0
1 x 2	6	1.09	135	221	21.0	7.6
1 x 2	3	0.55	139	208	15.5	5.3
1 x 2	6	1.64	202.5	334	22.0	10.0
1 x 2	3	0.88	209.5	316	20.0	6.2

Wall Above Opening



Open Front and Top

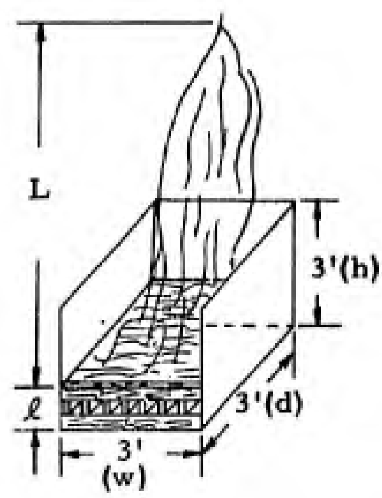


TABLE A-4 MISCELLANEOUS CRIBS

Wood Size (in. x in.)	Stick Spacing (in.)	ℓ (ft.)	Weight (lb.)	A_s (ft^2)	R (lb/min.)	L (ft.)
Wall Above Opening						
1 x 2	6	1.09	30.7	55	6.75	4.81
Open Front and Top						
1 x 2	6	0.55	14.7	27	3.0	--
1 x 2	6	1.09	31	55	7.0	5.41
1 x 2	6	2.19	64.5	111	17.0	9.31
2 x 4	6	0.625	32	28	2.0	--
2 x 4	6	1.25	63.2	57	4.5	3.35

This range is not sufficient to justify attempts of correlating the burning rate with crib geometry in terms of dimensionless parameters. The flame height representation, however, can be compared with the results of Reference 2.

Parameters similar to those in Eq. A-1 can be used to correlate the data obtained from cribs burning in an enclosure. Here, the following factors are considered to be pertinent: burning rate (R), flame height (L), crib height (ℓ), enclosure height (h), enclosure width = crib width (w), enclosure depth = crib depth (d), surface area of wood (A_s), ambient air density (ρ_o), and gravity (g). Since both h and ℓ are considered, the "opening" height, $H = h - \ell$, is automatically included. The basic form of the dimensionless representation of burning rate is then given by:

$$f\left(\frac{R}{\rho_o\sqrt{g}\,h^{5/2}},\ \frac{\ell}{h},\ \frac{w}{h},\ \frac{d}{h},\ \frac{A_s}{h^2}\right) = 0 \qquad \text{(A-2)}$$

For flame height, the correlation in terms of the burning rate and geometry is:

$$f\left(\frac{L}{h},\ \frac{R}{\rho_o\sqrt{g}\,h^{5/2}},\ \frac{\ell}{h},\ \frac{w}{h},\ \frac{d}{h},\ \frac{A_s}{h^2}\right) = 0 \qquad \text{(A-3)}$$

Considering that the burning rate in Eq. A-2 is determined by the geometric factors, and that A_s affects the burning rate only, we may attempt to correlate the flame height with geometric parameters only using the following equation:

$$f\left(\frac{L}{h},\ \frac{\ell}{h},\ \frac{w}{h},\ \frac{d}{h}\right) = 0 \qquad \text{(A-4)}$$

All parameters may also be mathematically combined to obtain the most convenient parametric form.

III. ANALYSIS OF DATA

A. Free Burning Crib Fires

Dimensionless representation of the data, as suggested by Eq. A-1, is shown in Fig. A-1. The ordinate, $(L + \ell)/w$, is the ratio of the flame height, measured from the bottom of the crib, to the crib width. The abscissa in Fig. A-1 is the burning rate reduced to the dimensionless form. The ambient air density, ρ_o, is taken as $1.3 \times 10^{-3} g/cm^3$. The correlation of Fig. A-1 is identical to that used by Thomas[3], who also reduced the experimental data of Gross[1] into similar form. To eliminate the case of laminar flame, Thomas used Gross' data only where flame height was larger than two feet. Figure A-1 represents these results as well as those obtained by IIT Research Institute.

To relate the data to the Reynolds number, consider the top of the crib to be an orifice of the area w^2. Then, if V is the velocity, ρ the density, and μ the viscosity of gases leaving the top of the crib, the Reynolds number is:

$$N_{Re} = V w \rho / \mu \qquad \text{(A-5)}$$

Furthermore, assuming that the gases leaving the top of the crib are volatiles only, the rate of weight loss of wood, $R = V \rho w^2$, can be introduced in the above equation, so that:

$$N_{Re} = \frac{R}{\mu w} \qquad \text{(A-6)}$$

Since, in deriving Eq. A-6, the air was not included in the flow leaving

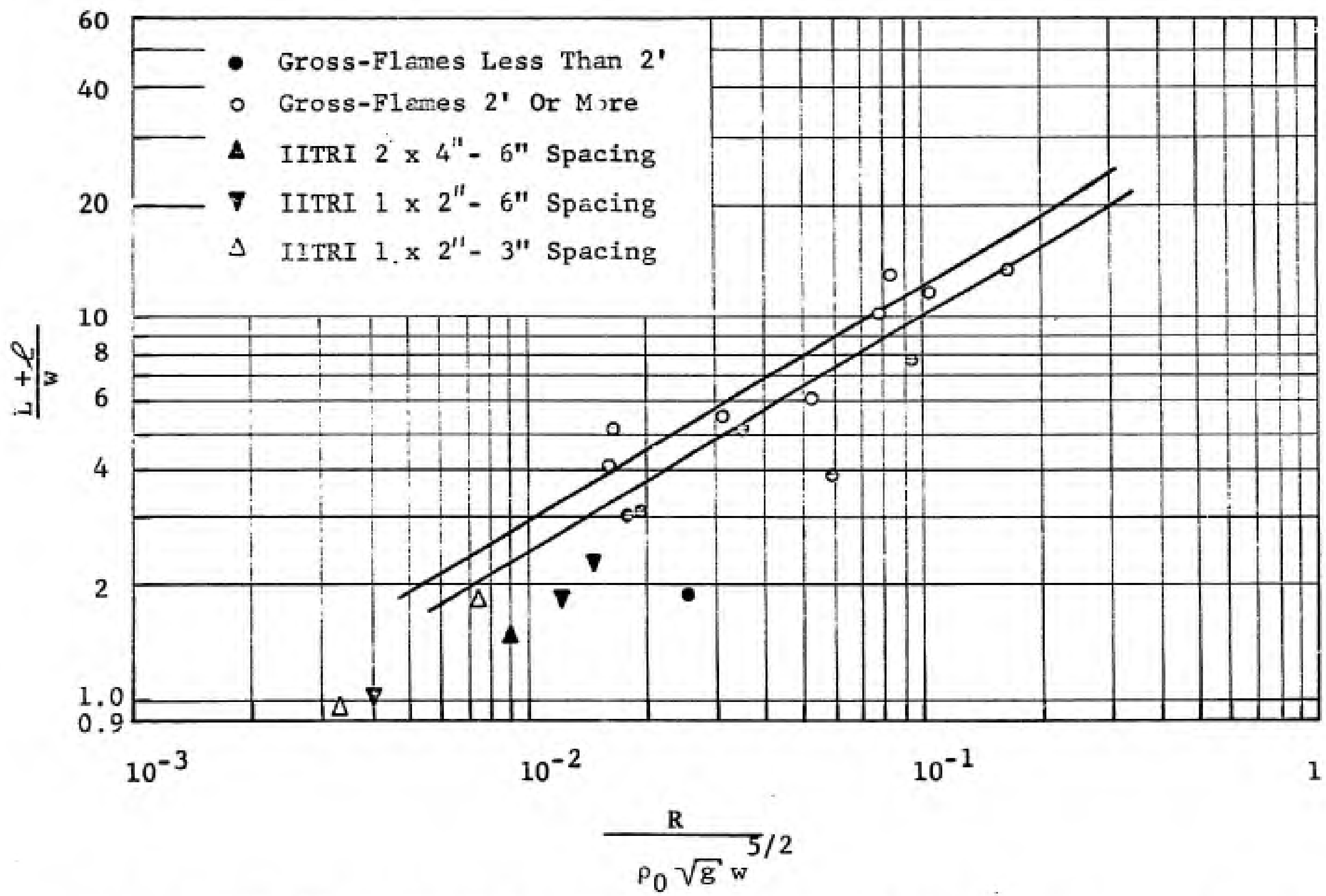


Fig. A-1 EFFECT OF BURNING RATE ON FLAME HEIGHT FOR FREE BURNING FIRES the top of the crib, the actual Reynolds number is probably larger than the one given by Eq. A-6.

Considering, as did Thomas, the viscosity of the volatiles, μ, to be 10^{-4} gm/cm-sec, the Reynolds number for Gross' data range from 13 to 6400. The Reynolds number for the IITRI data lies between 3,000 and 13,000, and thus should be well into the turbulent regime. Figure A-1 shows, however, that the IITRI data is somewhat lower than the results of other investigators. This difference can be reduced to some degree by using a flame height measured from the top of the crib. Gross' experiments were for cubical cribs so that $\ell/w = 1$ in all cases. For the IITRI data ℓ/w was between 0.05 and 0.35 so that Gross' data will be displaced downward to a greater degree than the IITRI data. This is not sufficient, however, to explain the difference in values. It is felt that one of the more important factors is the spacing of the wood in the crib. The cribs used by Gross were more closely packed than those used by Thomas or IITRI. In Gross' cribs the spacing was of the order of the stick width. As well as can be determined, Thomas used 1 x 1 inch sticks spaced 3 inches apart; the IITRI cribs were 1 x 2 inch sticks spaced 3 inches and 6 inches apart. The IITRI points showing greatest difference with results of other investigators are those where the spacing was 6 inches. This may be explained by considering that the larger spacing results in improved air flow conditions inside the crib. Thus, more of the fuel is burned within the crib rather than in the flame and consequently results in a reduced flame height. Figures A-2 and A-3 show the effects of crib height and wood surface area on the burning rates obtained from 6 x 6 ft. cribs. This information also indicates the most economical types of

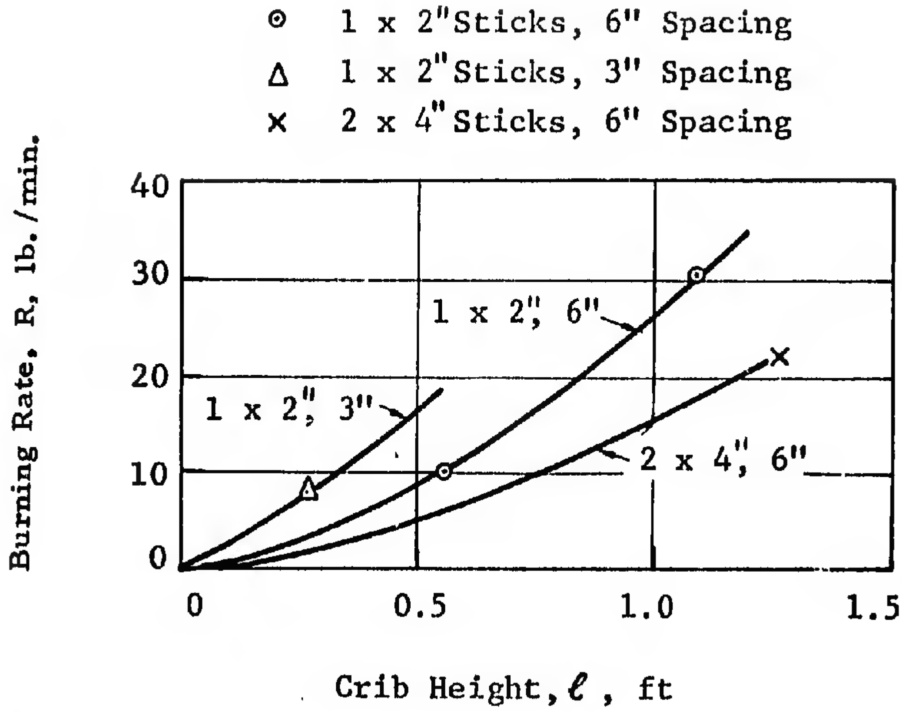


Fig. A-2. EFFECT OF CRIB HEIGHT ON BURNING RATE FOR 6' x 6' CRIBS

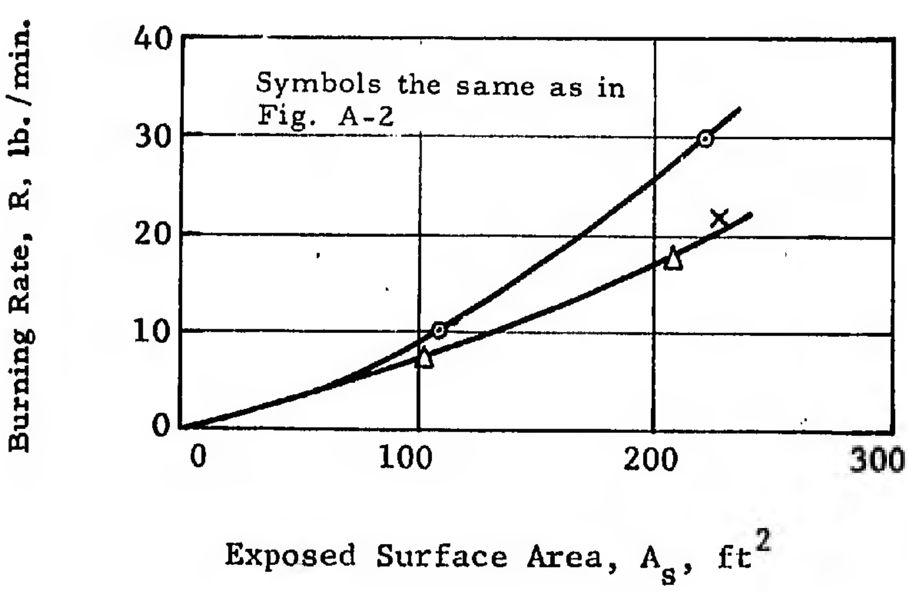


Fig. A-3. EFFECT OF WOOD SURFACE AREA ON BURNING RATE FOR 6' x 6' CRIBS

cribs for future experimental investigations.

The most important data are obtained during the peak burning period where, for a short time, the burning rate is reasonably constant. This period is also of importance in determining conditions necessary for coalescence of individual fires. The duration of each fire is from initial fire buildup until the wood char layer is approximately 1/2 inch thick, after which the layer offers appreciable resistance to the release of combustible gases. Much of the wood contained in the 2 x 4 inch sticks is left after the peak fire; consequently it is more economical to use the 1 x 2 inch sticks. Some heat is also lost with the 2 x 4 inch sticks due to the heat capacity of the wood not burned. The present data indicate that in terms of required wood, the most economical means of increasing the burning rate of 6 x 6 ft crib is to increase the crib height and to use a stick spacing in the neighborhood of 6 inches. Smaller spacings appear to offer too great a restriction to the air flow through the crib. This effect is not as great with the 3 x 3 ft. cribs, and the 3-inch spacing is adequate.

B. Crib Fires in Enclosures

Enclosure sizes of 3 x 3 x 3, 6 x 6 x 6, 9 x 9 x 9, 6 x 3 x 3, and 3 x 6 x 6 ft. were used. The first, second, and third numbers refer to height, width, and depth respectively. The flame height, L, is measured from the top of the wood in the crib, which differs from the previous work of other investigators who considered flame heights from the bottom or top of the enclosure. The wood cribs were constructed of 1 x 2 inch sticks spaced on 3 or 6 inch centers or 2 x 4 inch boards spaced on 6 inch centers. As in the case of wood cribs burning in the open, the 3 inch spacing resulted in a smaller burning rate than the 6 inch spacing for the same fuel load.

Figure A-4 shows the effect of the fuel surface area on the burning rate. The region where the burning rate increases only slightly with increasing fuel surface indicates the start of transition from fuel controlled to ventilation controlled burning. Figures A-5 and A-6 illustrate this characteristic in terms of the ratio of fuel surface to the total enclosure opening, A_s/wh, and the opening above the crib, A_s/wH. If A_s/wH is greater than twelve, the fire appears to be approaching a ventilation controlled condition. However, the ventilation control is not necessarily that of the compartment opening, but also reflects the restriction to airflow into the depths of cribbing.

For correlation of the data in terms of dimensionless parameters, we write Eq. A-2 in the form:

$$f(R/\rho_o\sqrt{g}\ wh^{3/2},\quad A_s/wh,\quad \ell/h,\quad w/h,\quad w/d) = 0 \qquad \text{(A-7)}$$

where the parameters have been combined to obtain more convenient forms. For cubical enclosures, $w/h = 1$ and $w/d = 1$, the correlation reduces to that of only three parameters. Since $\rho_o\sqrt{g}$ is constant, it is only necessary to consider $R/wh^{3/2}$ for the first parameter. (Thomas has indicated that this group is constant for ventilation controlled fires.) Fig. A-7 shows the effect of A_s/hw on $R/wh^{3/2}$ for the cubical enclosures. The lines plotted on Fig. A-7 are based on the fire being fully fuel surface controlled and having a burning rate of 0.09 lb/min-ft^2 of fuel surface. Reasonable agreement can be noted over the range of crib loadings studied. Extension of the data to the right would undoubtedly

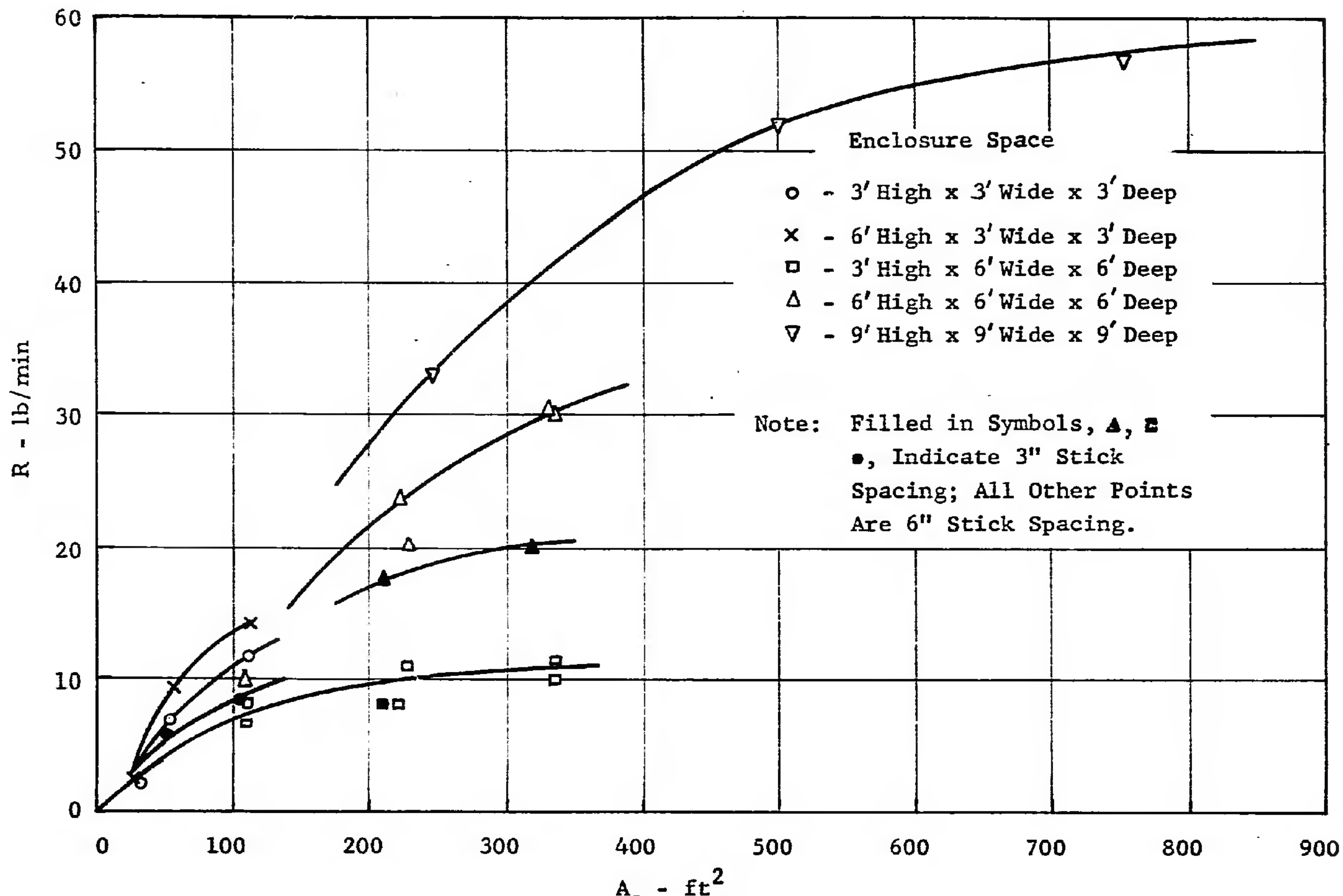


Fig. A-4. EFFECT OF WOOD SURFACE AREA ON BURNING RATE FOR FIRES IN ENCLOSURES

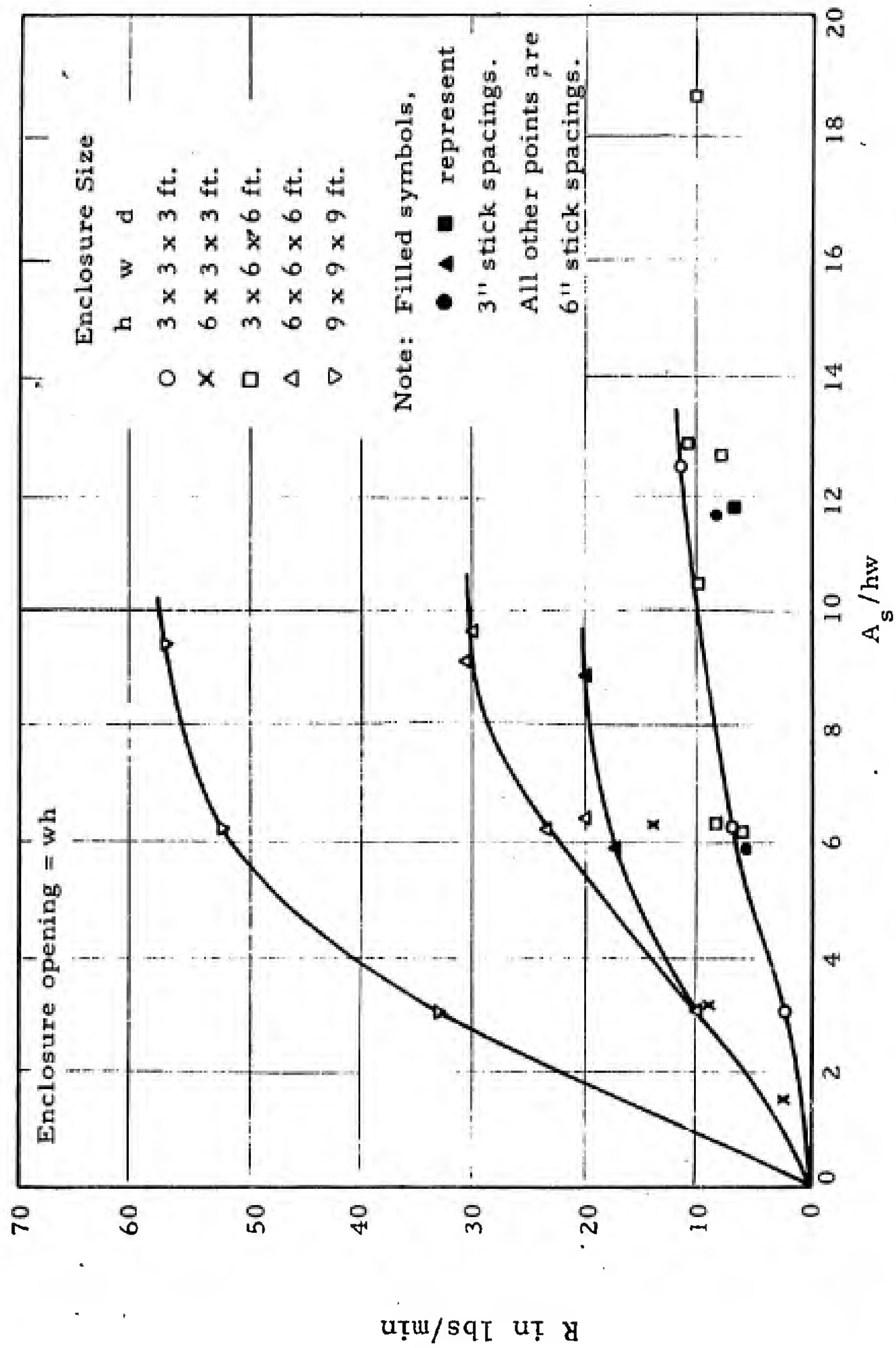


Fig. A-5 BURNING RATE AS A FUNCTION OF THE RATIO OF SURFACE AREA TO ENCLOSURE OPENING

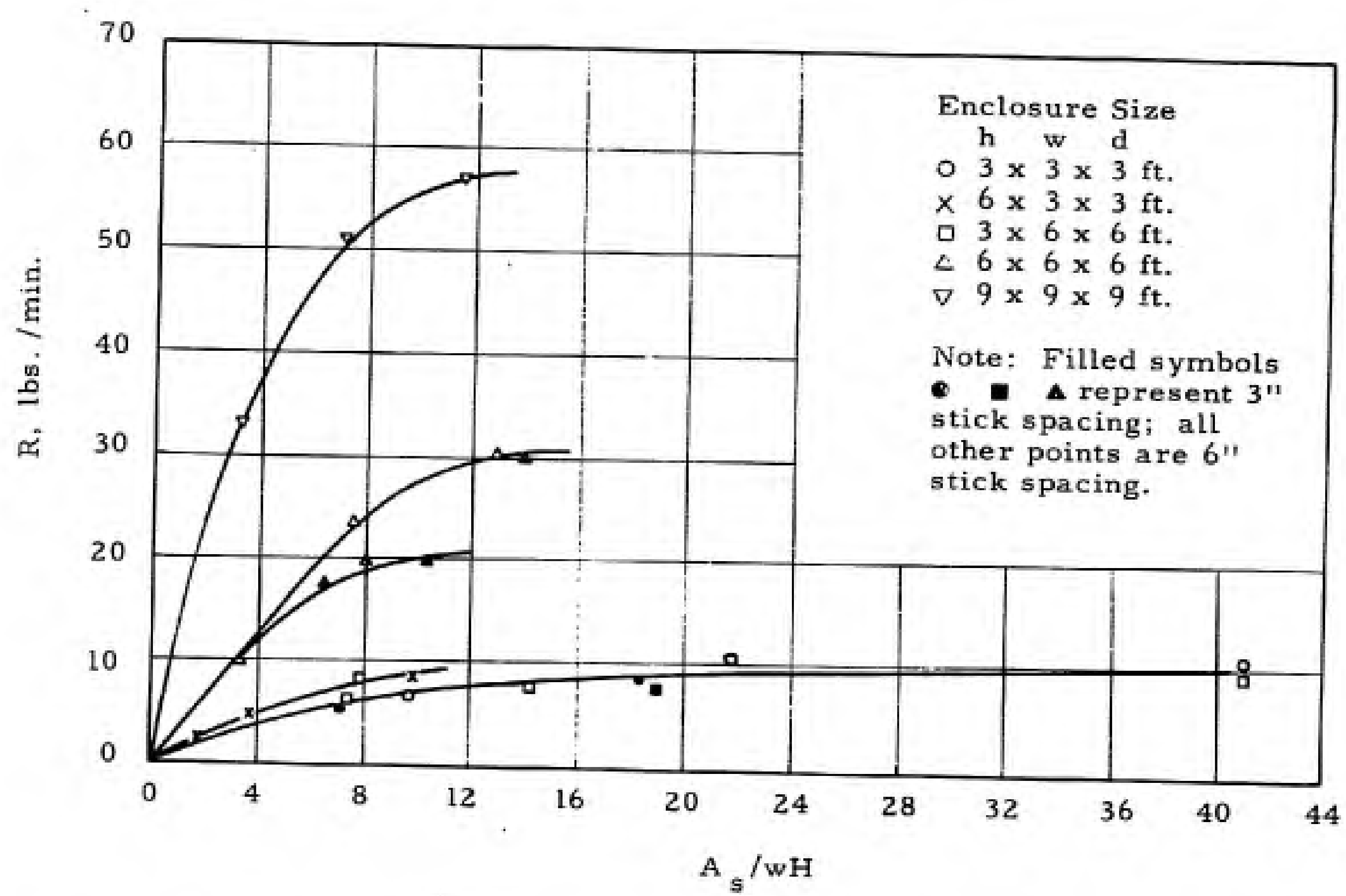


Fig. A-6 BURNING RATE AS A FUNCTION OF THE RATIO OF WOOD SURFACE AREA TO THE ENCLOSURE OPENING

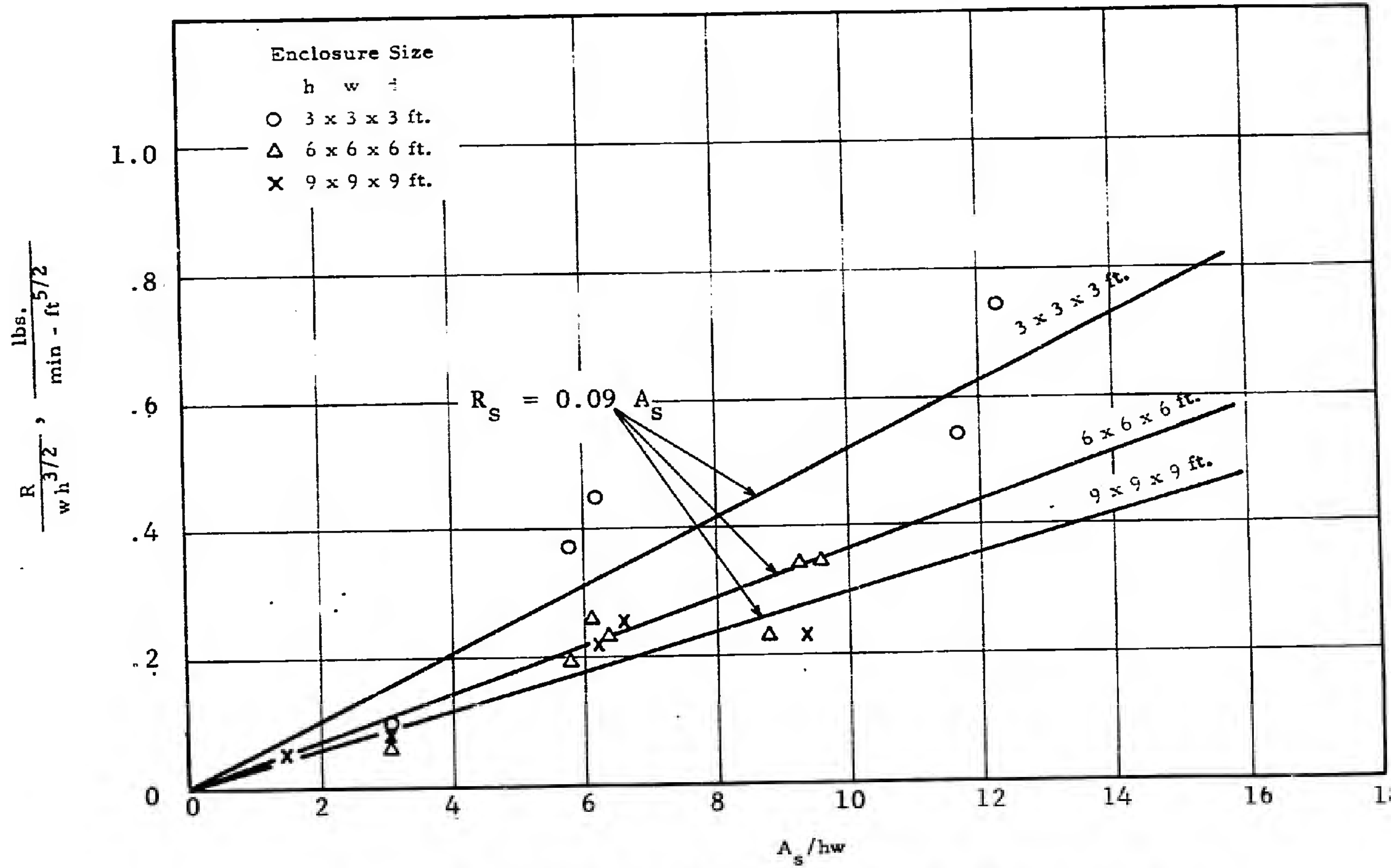


Fig. A-7 EFFECT OF WOOD SURFACE AREA ON BURNING RATE produce a drop in the results below those predicted by using $R_s = 0.09\ A_s$, until at some point further loading would not increase the burning rate and the fire would become ventilation controlled. As mentioned earlier, the sharpness of this transition is masked in crib fires by the ventilation restriction of fuel members themselves.

Figure A-8 shows the effect of the burning rate on the flame height in terms of the parameters $(L + \ell)/h$ and $R/\rho\sqrt{g}\ wh^{3/2}$. These parameters can be obtained by rewriting Eq. A-3 so that:

$$f(L/h,\ R/\rho_o \sqrt{g}\ wh^{3/2},\ \ell/h,\ A_s/wh,\ w/h,\ w/d) = 0 \qquad (A-8)$$

In Fig. A-8, $w/d = 1$ for all tests plotted. The points are compared with the curve given by Thomas for flames from windows and when burning is ventilation controlled ($R/wh^{3/2}$ = const.). The data are too widely scattered to justify a correlation only in terms of the above parameters. A better means of representing the results, in terms of the geometrical factors as in Eq. A-4, is shown in Figures A-9 and A-10 in logarithmic and linear coordinates. The parameters used are $L/H = L/(h - \ell)$ and $\ell/H = \ell/(h - \ell)$. This correlation appears to reduce the scatter and indicates a definite effect of the crib height, relative to the opening above the crib, on the height of the issuing flames. The best slope was found to be about 2/3.

As was shown by Thomas[3], for ventilation controlled fires:

$$R \sim wH^{3/2} \qquad (A-9)$$

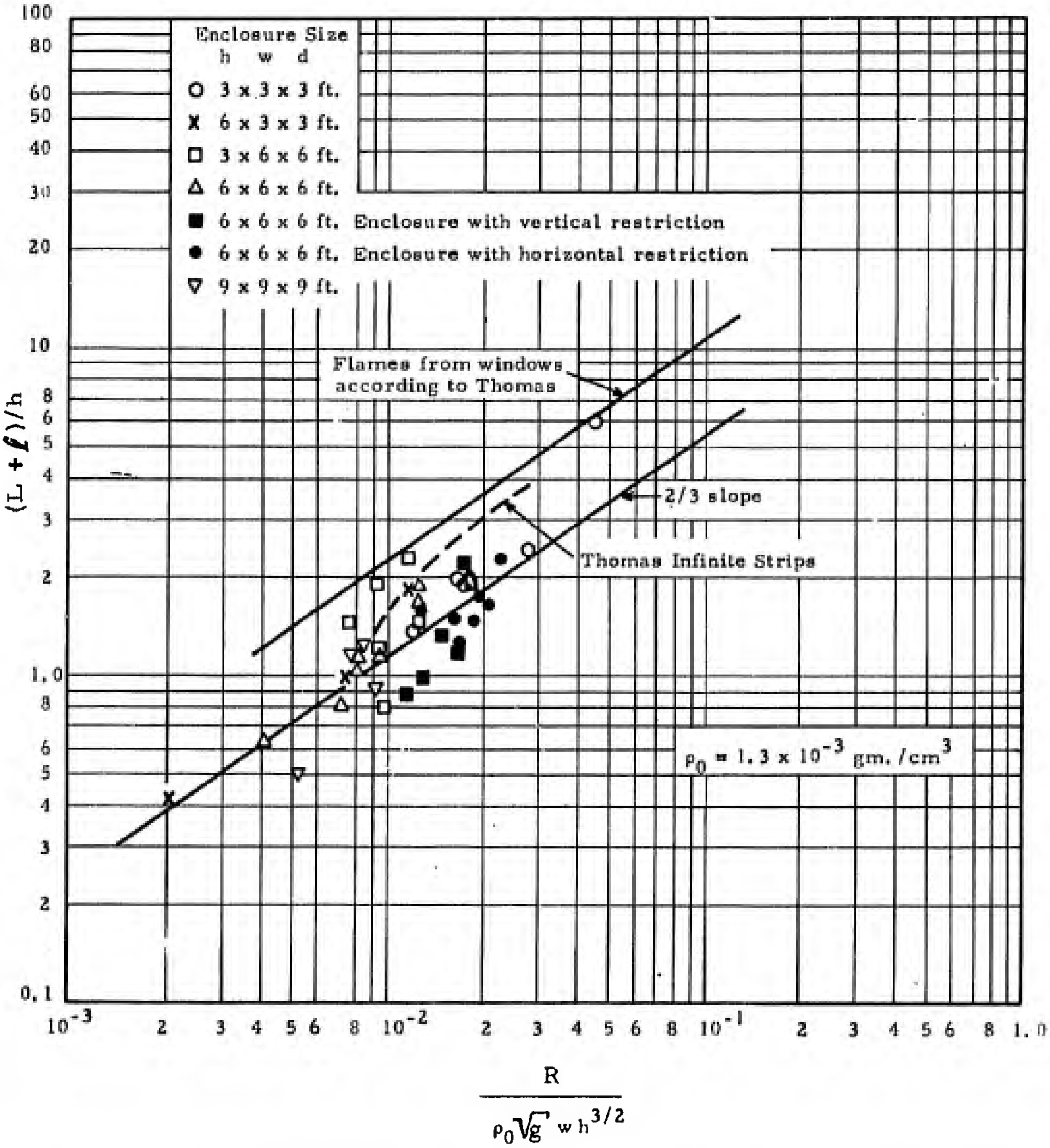


Fig. A-8 EFFECT OF BURNING RATE ON FLAME HEIGHT FOR FIRES IN ENCLOSURES

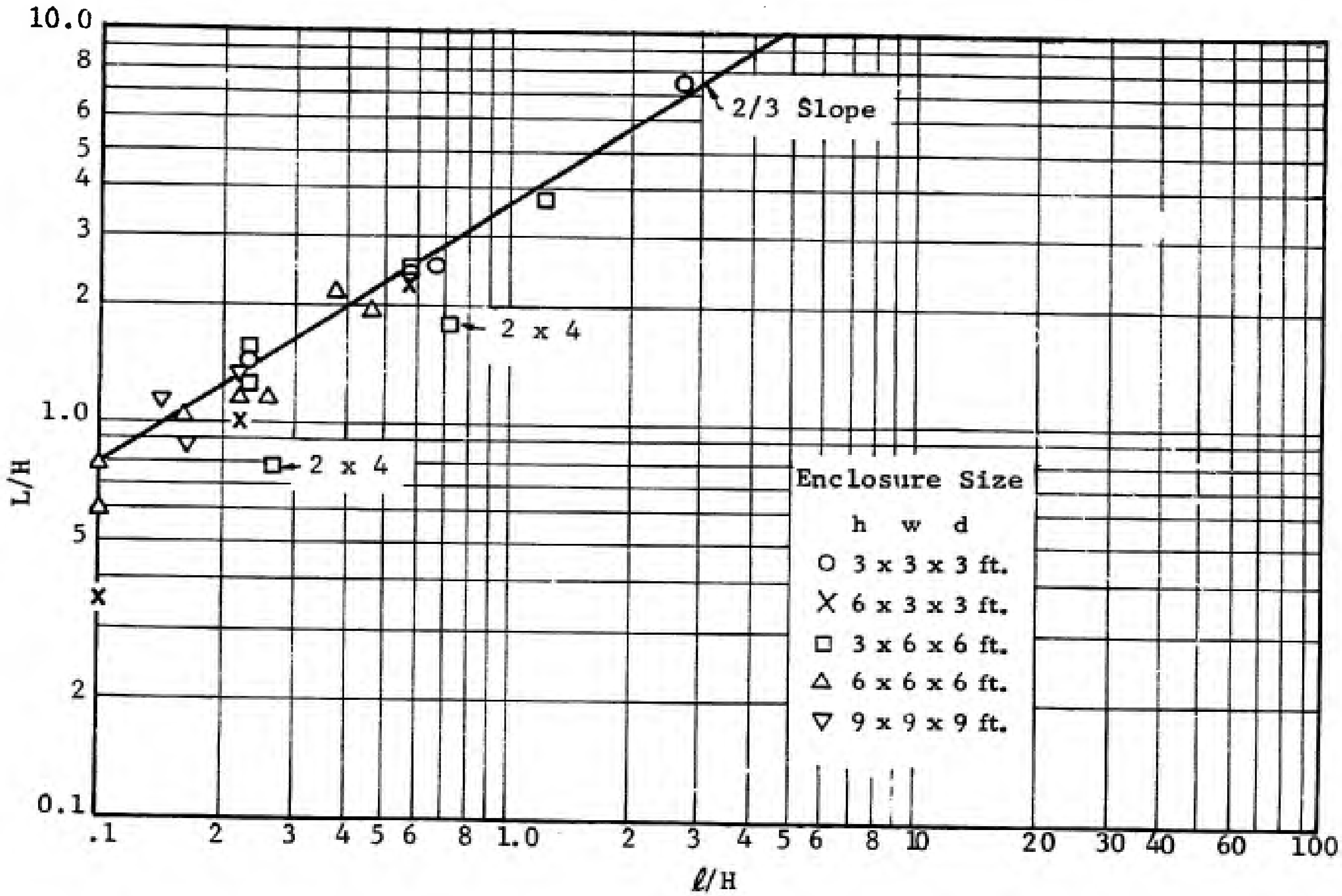


Fig. A-9 CORRELATION OF FLAME HEIGHT, CRIB HEIGHT AND OPENING HEIGHT, L/H VS. ℓ/H, IN LOGARITHMIC COORDINATES

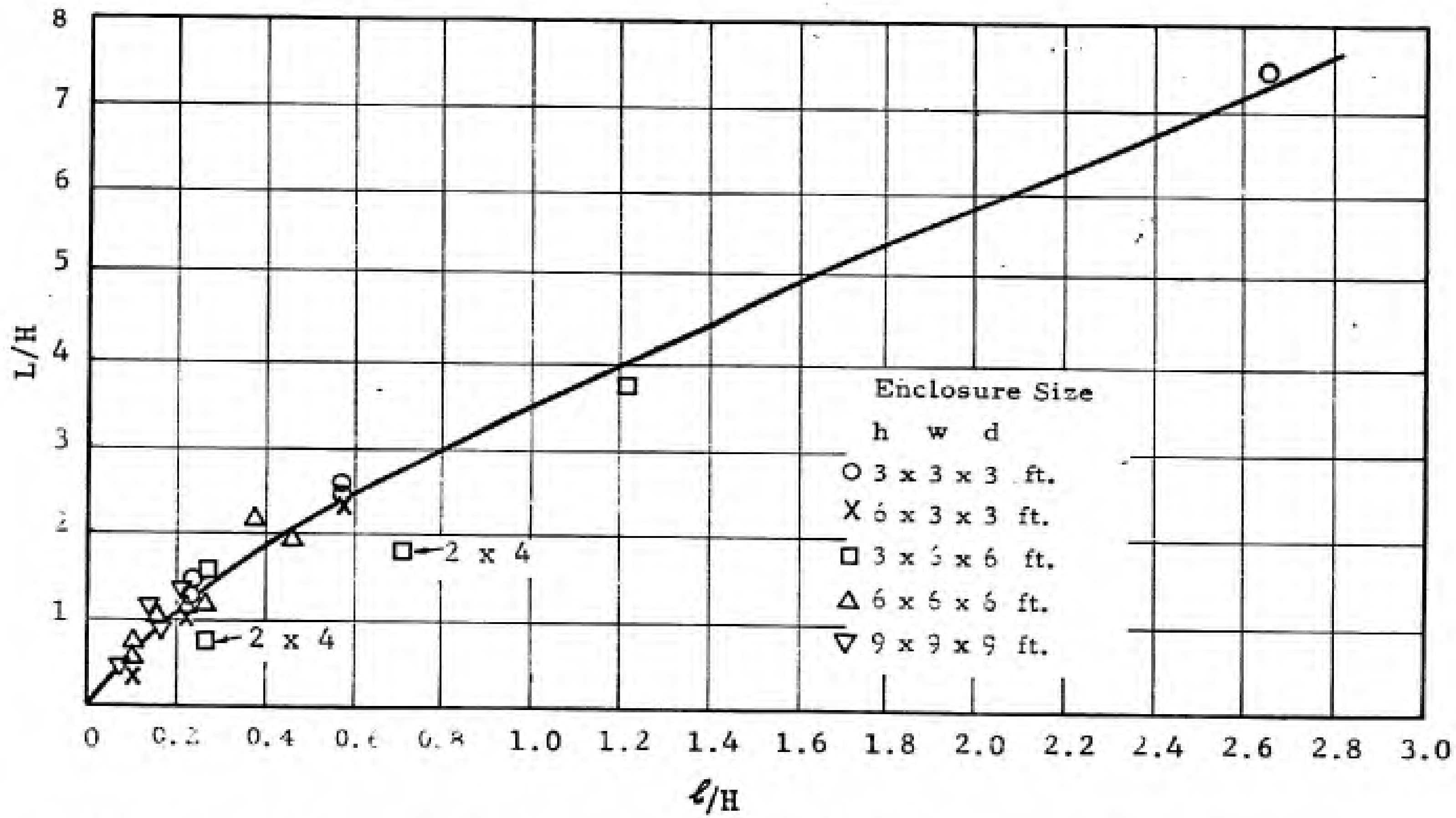


Fig. A-10. CORRELATION OF FLAME HEIGHT, CRIB HEIGHT AND OPENING HEIGHT, L/H VS ℓ/H IN LINEAR COORDINATES.

and with the 2/3 slope from Fig. A-8:

$$L/H \sim (R/wH^{3/2})^{2/3} \qquad \text{(A-10)}$$

or

$$L \sim H \qquad \text{(A-11)}$$

Hence, flame and window heights are proportional for ventilation controlled fires.

For the crib fires in enclosures which are mostly fuel controlled, the data indicate:

$$L \sim H(\ell/H)^{2/3} \qquad \text{(A-12)}$$

To verify this conclusion, more data are necessary in the region where $\ell/H > 1$; it is believed that ℓ/H represents the combined effects of increased fuel load and a changing air flow pattern as the openings in the exposed side of the crib attain the same order of magnitude as the opening of the enclosure above the crib.

C. Crib Fires in Enclosures with Restricted Air Flow

In this series of experiments, the open side of the enclosure was partially restricted by 1.5 ft. wide plates. The enclosures were 6 x 6 x 6 ft. having an opening of 3 ft. for the vertically restricted case. The horizontally restricted case gave a better approximation of a window in a structure, than the previous experiments where the entire side was left open. All sides of the wood crib were confined and the air flow was restricted to that only induced through the opening above the crib.

Values of $R/wH^{3/2}$ were generally larger for the vertically restricted enclosures. However, using $R/wh^{3/2}$ reduced the values to the extent that they were generally lower than the horizontally restricted case. It is believed that this is an effect of the exposed portion of the crib. The data points have been added to Fig. A-8 for purposes of comparison with enclosures completely open on one side. Again, the parameters $R/\rho_o\sqrt{g}\,wh^{3/2}$ and $(L + \ell)/h$ are not sufficient for correlation, although the results tend to group together slightly below those for the unrestricted openings.

D. Other Tests Using Enclosures

A 4 ft. wide and 6 ft. high wall was placed above the opening in a 3 x 3 x 3 ft. enclosure. Comparison of the results for the same wood crib with and without the wall indicates approximately the same burning rate and flame for both configurations. The radiant flux emitted was about 30% lower than that obtained without the wall due to the short duration of peak fire which did not permit the wall to reach a steady temperature.

Experiments were also performed with 3 x 3 x 3 ft. enclosures where both one side and the top of the enclosure were open. For the same crib type, the burning rate was approximately the same as when only one side of the enclosure was open or when no enclosure was used. The three-foot dimension apparently does not offer significant restriction to air flow at the stick spacings used. This effect was also noted in the coalescence studies where one 6-foot crib burned at four times the rate of a 3-foot crib, although one 12-foot crib did not burn at four times the rate of the 6-foot crib.

The enclosure of the crib in either form, open side or open top and side, produces a more stable peak fire than that obtained for open cribs.

IV. RADIATION FROM CRIB FIRES

Several experimenters have measured temperatures attained in enclosures for different values of ventilation. Simms and Wraight[4] have correlated temperatures obtained for various values of $A\sqrt{h}$, where A is the area of the opening and h is its height. The fire load was found to affect the results below a value of about 8 lbs/ft^2 of floor area. Other experiments with cribs[5] have yielded correlations of peak radiant intensity and fire load for a limited number of small cubical enclosures. IIT Research Institute experiments with model rooms have lead to a radiation model for fully ventilation controlled fires (Appendix B). The model gives average flame area and emissivity during the duration of peak fire. In order to establish a similar radiation model for fuel surface controlled fires, the crib data have been correlated in terms of the ratio of measured radiant intensity, I, to configuration factor of the opening, $\phi_{opening}$, ($I/\phi_{opening}$ vs $R/A\sqrt{h}$). Figure A-11 presents this correlation and includes results of several model rooms. The relationship between radiation intensities and burning rates for ventilation and surface controlled fires are also shown in Fig. 11. The right hand ordinate, I/I_v, was obtained by [illegible] that for the ventilation controlled fire (See Appendix B):

$$I_v / \varphi_{opening} = 2.86 \text{ cal/cm sec.} \qquad \text{(A-13)}$$

The abscissa, R_s/R_v, was generated by assuming that a fire is fully ventilation controlled (Appendix B) at:

$$R / A\sqrt{h} = 1.5 \qquad \text{(A-14)}$$

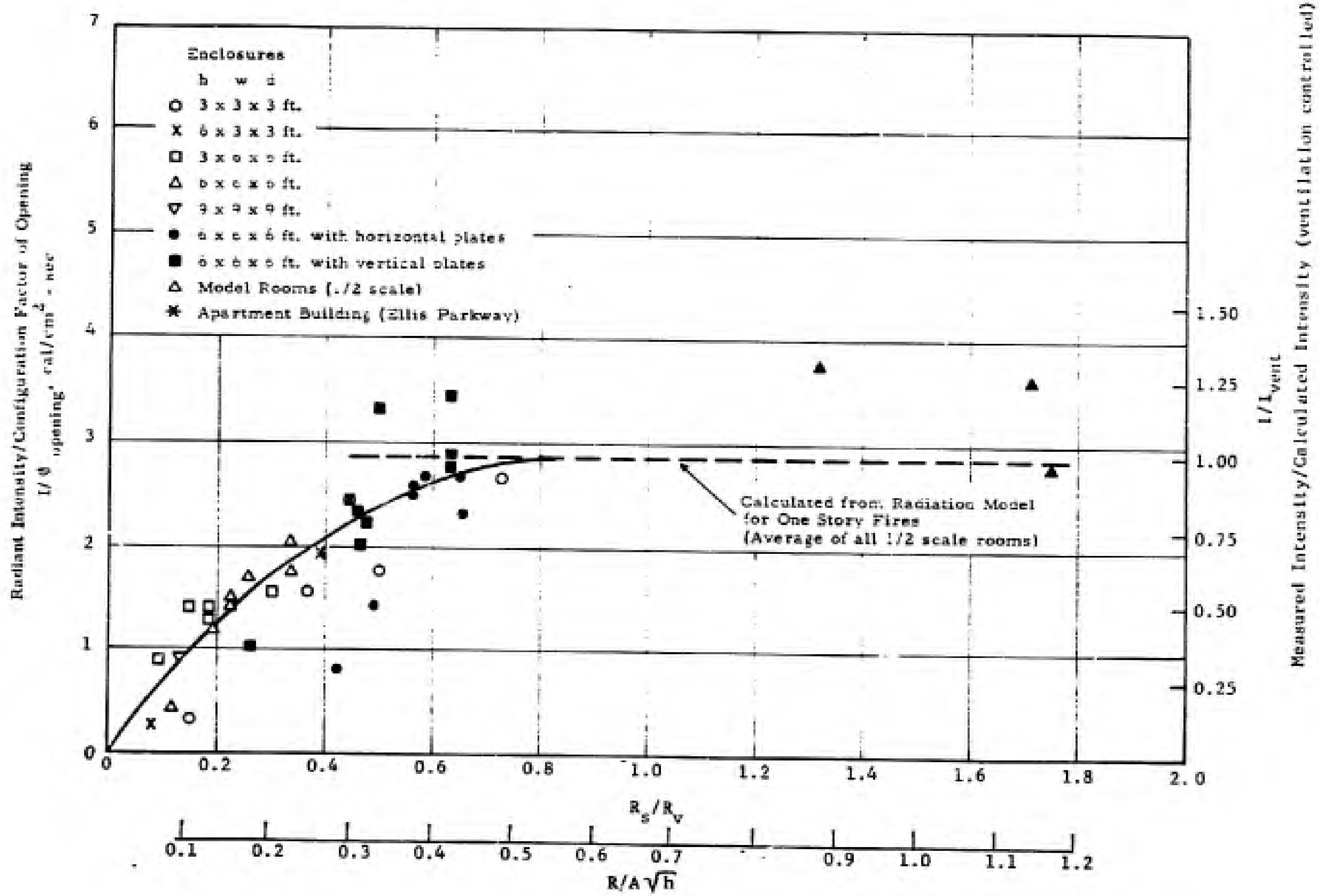


Fig. A-11 RADIATION FROM CRIB FIRES AS A FUNCTION OF BURNING RATE where R is the burning rate, A is the area of the opening, and h is the opening height.

The value of I/I_v compares the measured intensity to that predicted on the assumption that the fire is ventilation controlled. The ratio R_s/R_v indicates the degree to which this control has been established. The measured intensity of the peak fire on the second story of the Ellis Parkway apartment burn (Appendix E) is included as a function of the ratio R_s/R_v where R_s (the fuel controlled burning rate) was obtained from the estimated fuel surface area, and R_v (the ventilation controlled burning rate) was based on the window areas alone, neglecting the interior door opening.

REFERENCES

1. Gross, D., "Experiments on the Burning of Cross-Piles of Wood", Journal of Research of the National Bureau of Standards, Engineering and Instrumentation, Vol. 66C, No. 2, April - June 1962.

2. Thomas, P. H. "Modellbrandtechnik, Some Studies of Models in Fire Research", 7. 01, Reprinted from VFDB List, 1960, 9 (3).

3. Thomas, P. H. "The Size of Flames from Natural Fires", Ninth Symposium (International) on Combustion, 1962, pp. 844-859.

4. Simms, D. L. and H. Wraight "The Temperature and Duration of Fires, Part II. Analysis of some Full-Scale Tests", "Fire Research Note 413, 1959.

5. Webster, C. T. and M. M. Raftery "The Burning of Fires in Rooms - Part II", Department of Scientific and Industrial Research and Fire Offices' Committee, Joint Fire Research Organization, Fire Research Note No. 401, 1959.

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APPENDIX B

FIRE SPREAD WITHIN STRUCTURES, MODEL ROOM EXPERIMENTS

I. INTRODUCTION

As previously indicated, the spread of fire between structures can be directly related to the radiating areas of the burning structure or structures. In turn, these areas depend on the fire spread within structures. For example, the existence of flames above a window in a burning structure is determined by the integrity of the structure (in regard to the penetration by fire), the direction of the prevailing wind and the remaining fuel load (burning rate).

In the early phases of the program, various means were developed for predicting the time history of structural fires. Since they form the backbone of the entire spread model, it was felt advisable to undertake an experimental study to verify or correct the developed methods. The experiments consisted of burning model rooms in various combinations, under controlled laboratory conditions, where temperatures, radiation levels, flame areas, and burning rates could be monitored as a function of time. The following sections describe these models and their fire behavior.

II. MODEL ROOMS

Quarter, third and half-scale rooms were constructed, scaled from a 12 x 12 ft. room with an 8 ft. ceiling and having a single window 4 ft. high by 5 ft. wide on one wall. The scaling of furniture was patterned after that of Hird and Fischl[1] who successfully studied the fire build-up in models down to 1/10 scale. The construction of the various furniture items is shown in Section X. In general, the height and width of the items were scaled directly, with the thickness held to the full scale equivalent. In this manner the total surface area was properly reduced while the burning time was held equal to that of full scale items. The layout of furniture in a typical room is shown in Section X. Ignition in each case was accomplished by use of a small crib on the lower shelf of the bookcase.

Walls were in every case constructed of 2 x 4's on 16 inch centers. The ceiling and floor construction generally used 2 x 8's on 16 inch centers although 2 x 4's were used in several cases. Thus, the unsupported distances on covering materials were kept equal to those of full scale structures. The fuel loading of the structural members was properly scaled by this means. Had the spacing been scaled, (i.e., 8 inch centers for 1/2 scale, etc.) the members would also have been scaled (i.e., 2 x 4's would be 2 x 2's for 1/2 scale) so that the total fuel weight would be the same. The importance of retaining the full scale type of support was demonstrated quite decidedly in a 1/2 scale wall penetration study where a single sheet of drywall formed the entire wall and showed unexpected fire resistance due to the lack of butt joints. Due to the problem of the unsupported distance plus a tendency for the flames to remain laminar on the smaller scale models, the 1/3 and 1/4 scale experiments were eliminated after the preliminary burns and all further work was with 1/2 scale structures. A typical construction is shown in Section X. With the exception of those experiments specifically aimed at studying the effect of different wall and ceiling materials, the interiors of walls and ceilings were 1/2 inch drywall and the floors were 3/4 inch plywood. The exterior of the structure was covered with a minimum of one layer of drywall with additional layers placed over strategic areas in order to retain the integrity of the ignition room until the desired fire spread path was accomplished.

III. INSTRUMENTATION

In all rooms several thermocouples were installed one inch from the surface of the walls, ceilings, and floors. Also, thermocouples were placed in the stud spaces and against the specific surfaces expected to be penetrated by the fire. In this manner, the build-up and spread of flames and hot gases could be followed throughout the models.

Radiometers were placed to measure the flux intensity of the window flames from both head-on and side locations. Photographic records permitted the evaluation of these intensities in terms of flame height and area as well as offering an event time check on the visual and temperature records.

Experiments were also performed on skeletal structures with and without the influence of wind. In these cases the entire structure was weighed to determine burning rate. The use of a skeletal structure was necessary in order to decrease the over-all weight to such a level that the portion burned was a measurable percentage of the total. The weighing devices consisted of ordinary scales with the indicator dial replaced by a potentiometer providing a means of remotely recording the dial rotation. Details of this and other instruments are presented in Appendix G.

IV. IGNITION TO FLASHOVER TIME

An important parameter determining the fire spread within structures is the time after ignition at which the entire room becomes filled with flames, i.e., the flashover takes place. In a series of full scale room burns dealing with this subject, Bruce[2] found a difference in the build-up time under identical room conditions. He used as the source of ignition a dining room chair placed slightly under a table. The difference in fire build-up time was also confirmed in several ignition trials performed by IITRI using a model chair. The results were quite varied and depended entirely on the vagaries of the flames during the early stages of build-up.

The bookcase-cupboard was then examined for reproducibility and was found to be quite good at 1/2 scale. However, since the material, 1 inch lumber, required the reinforcing effects of the shelves to sustain burning, variation in the space between shelves caused variation in the fire build-up rate for bookcase fires smaller than 1/2 scale. The 1/4 scale bookcase had shelves so close together that very slow spread occurred. This problem was not encountered by Hird and Fischl[1] as the ignited item was a cupboard of 1/8 inch plywood placed near a fiber board chair. These items burn readily independently of size. The addition of fiber board strips to our bookcase front created sufficient active flaming to increase the build-up rate and this approach was used on the early burns. However, as previously stated, the behavior of single rooms in the 1/3 and 1/4 scale lead to their elimination from the experimental series and all multiple room fires were conducted at 1/2 scale. In these rooms, as mentioned above, the bookcase was ignited by a small crib placed on the first shelf. The build-up time for identical rooms was quite constant as indicated in Table B-1.

Table B-1

FLASHOVER OF 1/2 SCALE MODEL ROOMS

Experiment Number	Wall and Ceiling Covering	Time from Ignition to Flashover (min.)
8	Plasterboard	12.4
9	Plasterboard	14.2
10	Plasterboard	15.0
11	Plasterboard	14.3
12	Plasterboard	13.0
12A	Plasterboard	17.8
13	Plasterboard	14.2
15	Plasterboard	12.0
17	Plasterboard	14.0
18	Plasterboard	15.5
4	Fiberboard	7.6
4A	Fiberglass	8.9

Table B-1 also shows that the times from ignition to flashover for a room with a combustible fiberboard lining and for a room lined with incombustible unbonded fiberglass do not differ significantly. These results indicate that a description of the combustibility of the wall covering materials of a room does not adequately describe the effect on the build-up of a room fire. The insulating value of the covering material reduces heat losses from the room interior and thus also shortens the flashover time. This effect has also been noted in the studies performed in England by the Joint Fire Research Organization.[3]

A series of preliminary experiments was performed to obtain an indication of the fire spread in a large room. The experimental setup included quarter and third scale rooms of floor area equal to four single rooms. The furniture was arranged in the standard pattern in the area associated with a single room. The resulting arrangement was equivalent to four rooms with no partition. The window was equivalent in area to four standard windows. The fire was ignited in the bookcase in the left rear corner of the room assembly. In both the quarter and third scale case, the first flashover involved only the furniture of the ignited room. The room area towards the window then flashed followed by a flashover of the remaining furniture on the right side. The reason for this fire behavior can be seen from the following consideration.

The fire spread forward first due to the relative location of the window and the initially flashed area. The flames followed the ceiling toward the window which was the exit of the combustion products. Thus the area on the left side was heated to a greater degree than the right side. Once the entire space was aflame, the fire near the windows consumed the majority of available air and a reduction in burning of the furnishing near the rear was observed.

A further indication of this "local flashover" concept was noted where a model of two rooms, side by side with no separating partition, flashed first over one half the room and then some 2-1/2 minutes later, over the remainder. In the second experiment, a sliding gypsum wall-board partition separated the two rooms before the first flashover. Removal of the partition produced a second flashover in three minutes. Since several seconds were required to remove the panel, the results of the two experiments are in excellent agreement. Similar behavior was also observed in a full scale fire involving a large schoolroom furnished as a furniture store. This behavior, as well as an analogous behavior for well established fires involving rooms separated by open doorways, are dealt with in more detail in the section on full scale building fires of Appendix E.

V. EFFECT OF BARRIERS ON FIRE SPREAD

Table B-2 indicates the time from flashover of a room to penetration of a partition and/or the flashover of a second room for various single and two story half-scale model structures. Penetration was considered to be the appearance of flame on the unexposed side.

Roof constructions consisted of 2 x 4 inch or 2 x 8 inch joists with one layer of 1/2 inch gypsum wallboard on the interior and two layers on the exterior. The average penetration time was forty minutes; the 2 x 4 inch joists case indicated penetration a minute or two shorter than when 2 x 8 inch joists were used. This is due to the extra rigidity achieved with the 2 x 8's.

The penetration time for a finished type floor-ceiling construction, consisting of a 3/4 inch plywood floor, 2 x 8 inch joists, and 1/2 inch drywall ceiling, was approximately 25 minutes for upward spread and 29-1/2 minutes for downward spread. For a basement type situation, where there was no drywall ceiling protection, penetration upward was 10-1/2 minutes and downward, 12-1/4 minutes. The difference between upward and downward spread is not the same for both cases which is attributable to the absence of drywall in the basement type ceiling. For a finished type floor-ceiling construction, the difference appears

Table B-2

PENETRATION AND FLASHOVER TIMES IN 1/2 SCALE MODEL ROOMS

	Reference Burn No.	Partition Penetrated	Flash to Penetration (min.)	Flash to Flash (min.)
1 Story	5	roof*	38.8	
	8	roof	41.5	
	9	1/4" ply door****	5.3	9.87
		roof	40.0	
	10	roof	42.0	
2 Story	12	finished ceiling**	24.5	25.5
	12A	finished ceiling		27.4
	13	finished ceiling (downward spread)	29.5	35.0
	14	basement ceiling***	10.5	16.0
	14A	basement ceiling		16.7
	15	basement ceiling (downward spread)	12.25	15.7
	17	1/4" ply door finished ceiling	5.1 24.0	26.0

* Roof: One layer 1/2" drywall on underside, two layers topside

**Finished ceiling: One layer 1/2" drywall on underside, 3/4" plywood topside.

*** Basement ceiling: No protection on underside, 3/4" plywood topside

****Structure: Two adjacent rooms.

to be approximately two minutes for the wood, leaving a 2-1/2 minute difference between upward and downward penetration through 1/2 inch drywall. Rating with a standard time-temperature curve by Davey and Ashton[4], using 1 inch nominal tongue and groove boards, 1/2 inch drywall and 2 x 9 inch joists, resulted in penetration of the wood by flame after 27 minutes. The rating also indicated some plasterboard fell at 18 minutes and several further falls occurred at 19 minutes, approximately the same as obtained for our basement type ceiling.

The rather fast downward spread occurring in the models will not be found in most real situations. One reason for this is that standard floors normally consist of two layers, flooring and sub-flooring, which offer much higher resistance to penetration into the joist space. Thus, the fire from below reaches the joist area quickly and the subsequent weakening and sag of the joists aids in the further upward spread. Downward, the double flooring delays this sag for some time. A second effect is the collapse of room contents which tend to further protect the floors in real structures. This effect was noted in the Ellis Parkway building burn (Appendix E) to the same extent that the lower (1st) floor was not involved until the fire spread down the stairway. Floor penetration from above did occur in the full-scale school fire in Plato Center, Illinois; however, in this case the room size was extremely large and as such did not flash over for an extended period. The initially ignited couch, placed near an interior wall, burned actively on the bottom and back for some time with little or no other burning. It did not collapse before the fire penetrated the wall-floor juncture and extended to the basement. This occurrence is not considered typical and in the computer program, the prediction of downward fire spread will continue to be limited to the stairwells.

Two experiments indicate penetration of a 1/4 inch plywood door in approximately five minutes. "Fire Resistance of Timber Doors", in the British series[5], contains information concerning the behavior of various doors when exposed to the standard time-temperature heating curve. For a door with a 3/8 inch soft wood panel, which is considered comparable to the 1/4 inch plywood, flame appeared on the unexposed face of the panel after four minutes and the door ceased to be of use as a fire stop after ten minutes. Similar ratings were attained by wall panels faced on one side with 1/4 inch plywood. The difference between measured penetration resistance and rated resistance is given in Figure B-1 as a function of rated resistance. Included with this is a second curve of the same nature for flashover times.

Two story structures were examined to determine the effects of both stairwells and interior stairways on fire spread. In the first case the stairwell was attached to the exterior of the structure, with 1/4 inch plywood doors separating the stairwell from the rooms. Two tests were performed, one with no ventilation in the stairwell and one with a 24 inch high by 15 inch wide window in the stairwell at the second story level. In both cases the fire was ignited on the first story. The models are shown in Figure B-2. Three walls and the ceiling of the second story room were omitted from the model with the window to allow better observation of the fire penetration. In both experiments, the first story door was penetrated by flame about 5 minutes after flashover of the room. With the non-ventilated stairwell, however, the fire spread to the second

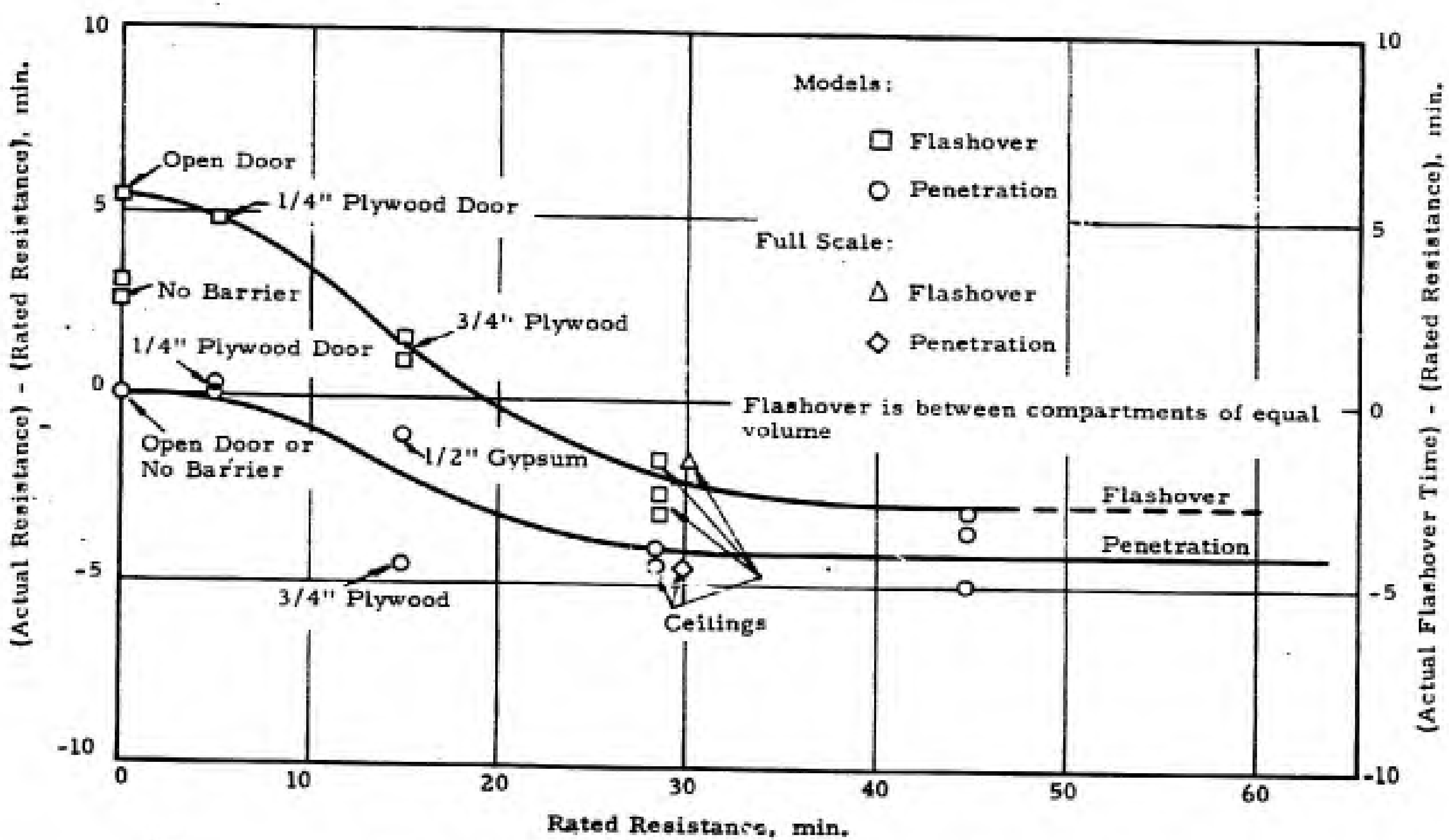


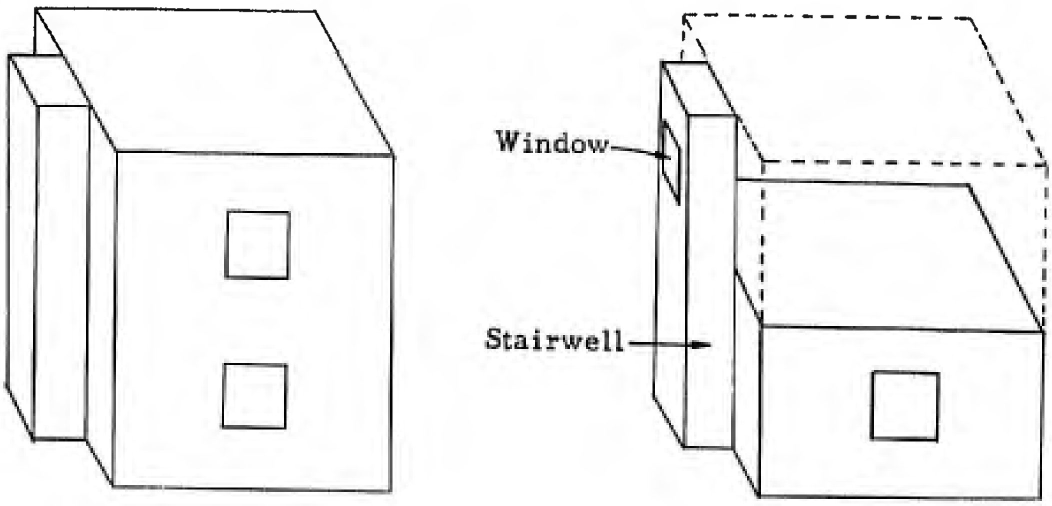
Fig. B-1 A COMPARISON OF ACTUAL FIRE BEHAVIOR OF VARIOUS BARRIERS TO THEIR FIRE RESISTANCE RATING story through the ceiling, causing a flashover 26 minutes after flashover of the first story. With a window in the stairwell, the first story door collapsed and a flashover occurred in the stairwell approximately 8-1/2 minutes after flashover of the room. Flames were then observed exiting from the stairwell window. The door at the second story level was penetrated by flame 13 minutes after the first story flashover. Thus, ventilation in the stairwell sufficiently enhanced the fire severity on the 2nd floor door to change the prime path of fire spread.

The interior stairway found in many frame dwellings was simulated by an opening of 5 $ft.^2$ in the first story ceiling, approximately 1/5 of the ceiling area. Two tests were performed, ignition on the first story and ignition on the second story. This was done to examine both upward and downward fire spread. This model is shown in Figure B-3.

For the configuration simulating an interior stairway, ignition on the first story resulted in sumultaneous flashover at both the first and second stories. When the fire was ignited on the second story, a flashover occurred in the first story approximately 3-1/2 minutes after flashover of the second story. However, approximately two minutes after flashover of the second story, it was observed that the bookcase fell over, dumping burning debris through the opening to the first story. As this mode of fire spread is not characteristic of the fire spread down a stairwell, the observed flashover to flashover time is much lower than can be expected in the actual case.

VI. WIND EFFECTS

Half scale single and two story structures were burned to determine the effect of wind on the burning rate. Skeleton wall and roof constructions



Without window

With window

FIG. B-2 SEPARATED STAIRWELLS, TWO STORY MODELS

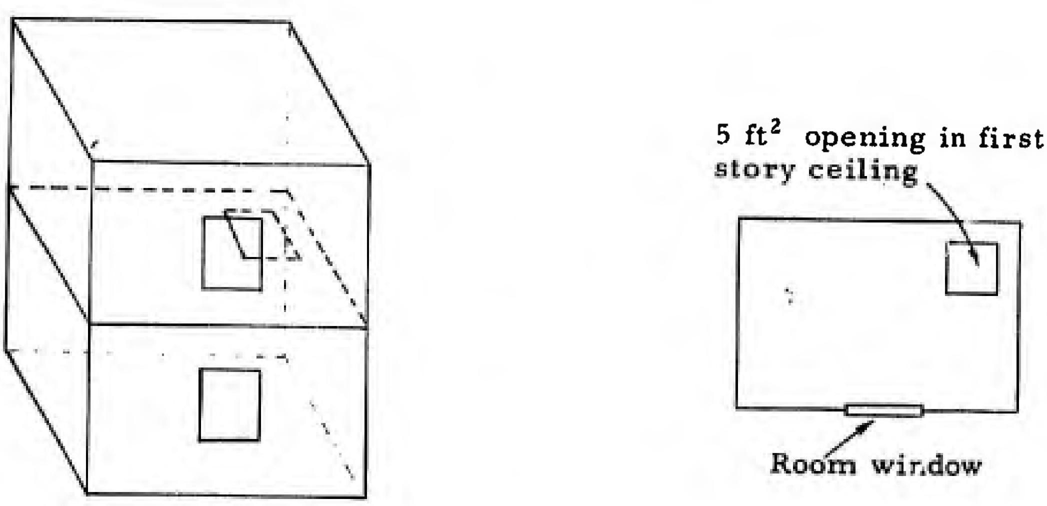


FIG. B-3 SIMULATED INTERIOR STAIRWAY, TWO STORY MODEL were used to reduce the total structural weight. A single layer of drywall was used on the interior with an external wood frame just sufficient to hold the structure and drywall in place. The interior was furnished in the standard half-scale manner. Table B-3 indicates the average burning rates obtained for the various wind and window location conditions.

A comparison of Experiment 31, having a window on one side, with Experiment 34, where two windows of the same height but half the width were on opposite walls, indicates approximately the same burning rate. For the windows on opposite walls, the films show the same flame pattern from both windows, indicating air drawn in the bottom portion and volatiles and combustion products leaving through the top. The window areas of these experiments are in the region where ventilation controlled burning is expected, i.e., where the burning rate is directly proportional to the window width ($R \propto w h^{3/2}$). The experiments support this conclusion in terms of the width, and indicate that the total width of all windows in a room can be used to assess reasonable burning rate criteria.

Experiments 32 and 33 indicate the increase in burning rate when a relatively strong wind is present.

The flame pattern, obtained from the two windows on opposite walls in Experiment 35, was similar to that obtained in Experiment 34. The burning rate is not quite double that obtained in Experiment 34, indicating the start of transition to fuel controlled burning due to the relatively large window sizes. Experiment 36 indicates the increase in burning rate for a 35 ft/sec wind. For Experiment 37, where the windows were on adjacent walls and a 38 ft/sec wind was imposed, the burning rate was lower than expected, being on the order of that obtained in Experiment 35,

Table B-3

EFFECTS OF WIND ON BURNING RATES

(Burns 31 - 40)

Burn No.	Wind Conditions (Wind was commenced after flashover)	Number of Stories	Average Burning Rate lb/min	Window Arrangement
31	None	1	12.5	One
32	15 ft/sec	1	20.3	Two windows, 1/2 the normal width, on opposite sides of room
33	32 ft/sec	1	23.0	
34	None	1	12.0	
35	None	1	19.8	Two windows on opposite sides of room
36	35 ft/sec	1	27.8	
37	38 ft/sec	1	20.7	Two windows on adjacent walls
38	None	2*	35.3	Two windows, one per story, on opposite walls
39	54 ft/sec into 1st story	2*	40.3	
40	28 ft/sec into 2nd story	2*	15.0	

* In the two-story burns, an internal stairway opening was provided between stories.

where no wind was imposed. The wind forces air in one window and increases the burning rate by increasing the stagnation pressure at the inlet window. If this were the primary mode of augmentation, one would expect the location of the window not facing the wind to have little effect on the burning rate. The two experiments performed indicate that this conclusion is not exact, since the burning rate obtained with the exit window on a wall parallel to the wind was lower than that obtained with a window on the downwind side. This indicates that the difference is due to effects such as internal mixing not taken into account by the simplified theory. In Experiment 37, the windows were in close proximity to a corner and all the fuel in the room may not have been involved.

In a room with high ceilings and windows at two elevations, air is induced through the lower window and flames emerge from the higher one. This is also the situation that occurs when the ceiling collapses between two stories. Experiments 39 and 40 as compared with 38, indicate the effect of a wind in each window, showing the suppression of the burning rate when the wind is in the higher window opposing the buoyancy forces, and the increase when wind is in the lower window thus augmenting the buoyancy forces. The magnitude of the measured effect is less than the calculated one and is probably due to the fact that fires are becoming fuel surface controlled.

VII. BURNING RATES AND FIRE DURATION

Previously, the burning rate in a room with a small window, where the fire may be considered ventilation controlled, was determined from the relation

$$R = 0.678 A\sqrt{h} \qquad \text{(B-1)}$$

where A and h are the window area and height, respectively. The constant

0.678 lb/min $ft^{5/2}$ was based on a correlation of the exper mental results of several investigators given by Thomas(6). The result represents a mean value of the data. The data spread indicates constants varying from 0.5 to 1.5 lb/min $ft^{5/2}$.

The burning rates obtained from the half scale rooms of the type used in the wind experiments (Burns 31, 34, and 35) indicate values of 1.76 and 1.4 lb/min $ft^{5/2}$. The value of 1.4 was obtained for Burn 35 where two windows were used and where burning is believed to be in the transition region of fuel to ventilation control. An experiment with a one-third scale room of standard construction resulted in a value of 1.6 lb/min $ft^{5/2}$. These results indicate that the constant based on values given by Thomas is too low to truly represent ventilation controlled fire in a room.

It is believed that the variation in the ratio $R/A\sqrt{h}$, indicated by the Thomas correlation is due to the use of data from both fuel and ventilation controlled fires. As the amount of fuel in a room with a given opening is increased, the burning rate increases until a maximum constant value is reached. It then seems more reasonable to consider the highest value of R as being in the ventilation controlled regime. With this consideration, the values of $R/A\sqrt{h}$ from the data of other investigators and those obtained here are in close agreement and the value of 1.5 lb/min $ft^{5/2}$ is recommended.

The peak fire duration for Burns 31 and 32 was approximately 8 minutes. Calculation ($R = 1.5A\sqrt{h}$) gives the burning rate of 10.5 lb/min which represents 84 pounds of fuel. The weight of the fuel in the room, consisting of wood furniture, a plywood floor, and 25 pounds of paper was approximately 185 pounds. Thus, about half the fuel was consumed during the peak fire. A few of the half scale rooms, where the burning rate was not measured because of the high initial weight of the room, also indicated peak furniture fire durations of 8 minutes. This indicates the burning rate could be considered the same as in the measured cases. For these rooms, stud involvement also occurred at approximately the same time the peak furniture fire began to decay. Figure B-4 indicates the peak fires that attributed to stud and joist involvement for a half-scale room. The durations indicated on the figure are 8 minutes for the furniture and 16 minutes for the studs and joists. The studs, floor joists and ceiling joists weighed approximately 330 pounds. Again, considering the burning rate to be 10.5 lb/min, the fuel consumed during this stage was 50% of the total weight. This particular test was not entirely typical of all the half-scale rooms in that the time lag between the peak fires was longer than normally encountered. It was chosen to demonstrate the two stages of the fire. In the case of full-scale buildings, this time lag, if any, will depend on the type of wall covering used on the interior. Involvement of the studs requires opening of the interior room lining. In rooms using both wallboard and plaster, the time lag may be longer than encountered in the test shown here.

VIII. SCALING

An additional note on modelling and scaling effects is worth some attention at this time. As mentioned in Section II, the furniture was scaled in two dimensions following the procedure indicated by Hird and Fischl[1]. If the furniture weight is W_f for full scale, then k^2W_f is the weight for some scale k. Considering the windows to be scaled also, the area is k^2A_f and the height is kh. For ventilation controlled conditions ($R = CA\sqrt{h}$), and for any percentage of W_f burned during the peak fire, it can be shown that the

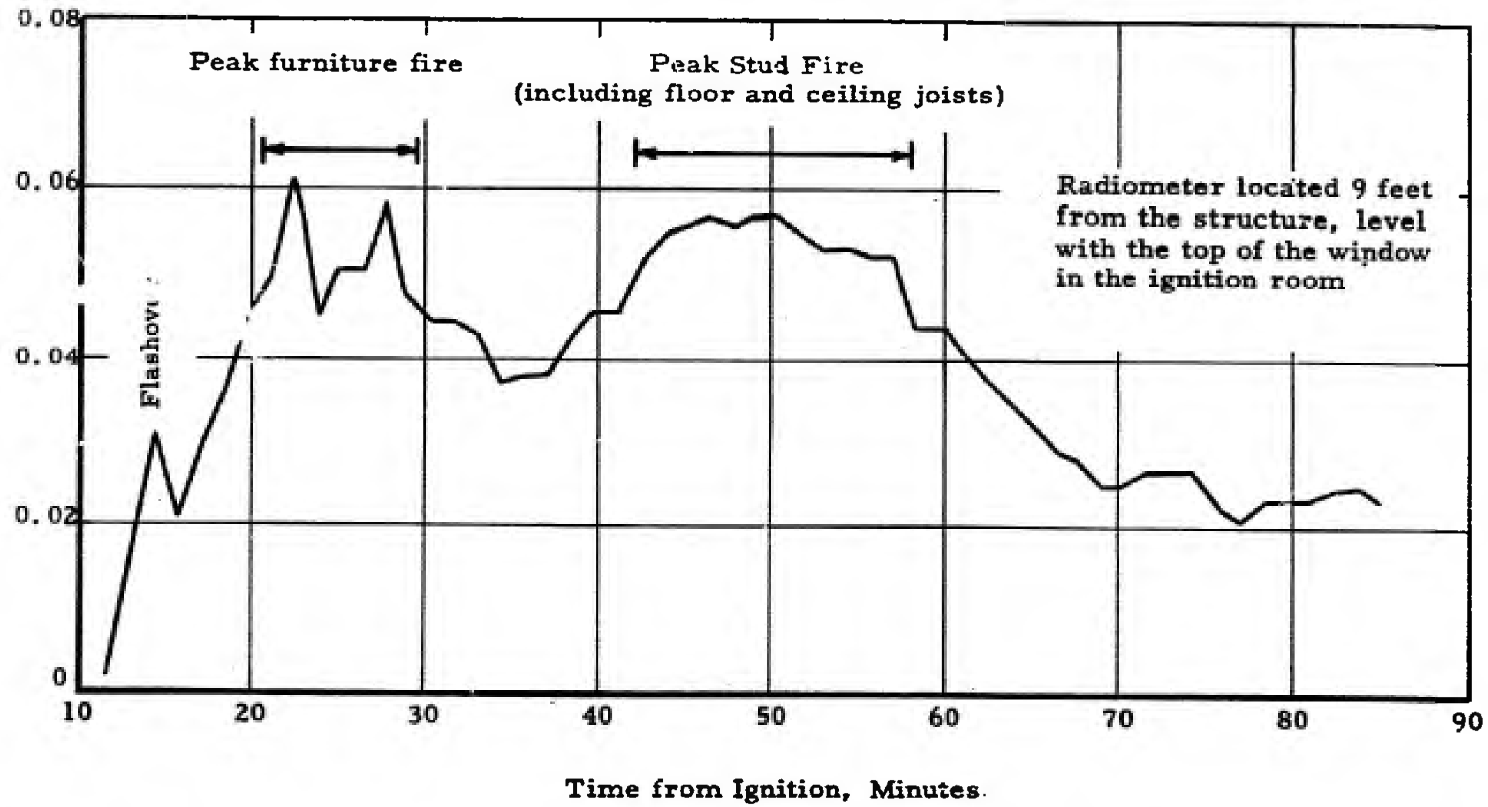


Fig. B-4 PEAK FURNITURE AND STUD FIRES (BURN 11) ratio of the fire durations, d/d_f, is $1/\sqrt{k}$ where the subscript f refers to full scale. Since k is less than one, the full scale fire duration is less than indicated by a model test. The peak fire duration of 8 minutes for a half scale room is comparable to a duration of 5.7 minutes for a full scale room.

It can also be shown that modelling tends to improve conditions necessary for a ventilation controlled fire. Conversely, a ventilation controlled fire in a model room does not necessarily imply that the comparable full scale room will have a ventilation controlled fire. We consider the burning rate, R_s, associated with a surface controlled fire to be directly proportional to the fuel surface area. Since, for thin boards, the surface area of the fuel is scaled to the degree k^2, the ratio of burning rates is $R_s/R_{s,f} = k^2$. For ventilation controlled conditions, the ratio is $R_v/R_{v,f} = k^{5/2}$. Suppose that the full scale condition is marginal in that $R_{s,f} = R_{v,f}$. Then, $R_v/R_s = \sqrt{k}$ which is less than one, since for modelling, k is less than one. This shows that R_v is less than R_s and the fire in the model room is ventilation controlled. Conversely, if the conditions in the model are marginal, then, $R_{v,f}/R_{s,f} = 1/\sqrt{k}$, which is greater than one, illustrating that the comparable full scale room would have a surface controlled fire.

IX. FLAME RADIATION MODEL

Studies of the radiation data from model rooms indicate that for a single room, the radiation from the window opening for an intense fire is well approximated by considering the opening to have an emissivity of one and temperature of 1500°F. During the peak fire the flames above the opening are about equal to the window height for those cases where the wall extends to this height or more. In the single story models, the height from the top of the window to the roof was one foot, and the window height was two feet. Thus, a portion of flame received air on both sides and was shortened. Since, for most structures, the walls will probably extend at least the window height above the top of the window, a reasonable radiation model may be obtained by considering a rectangle above the window the same shape and size as the window but with an emissivity of 1/2. The model is shown in Figure B-5. Using a temperature of 1500°F results in a good comparison with the measured radiation levels.

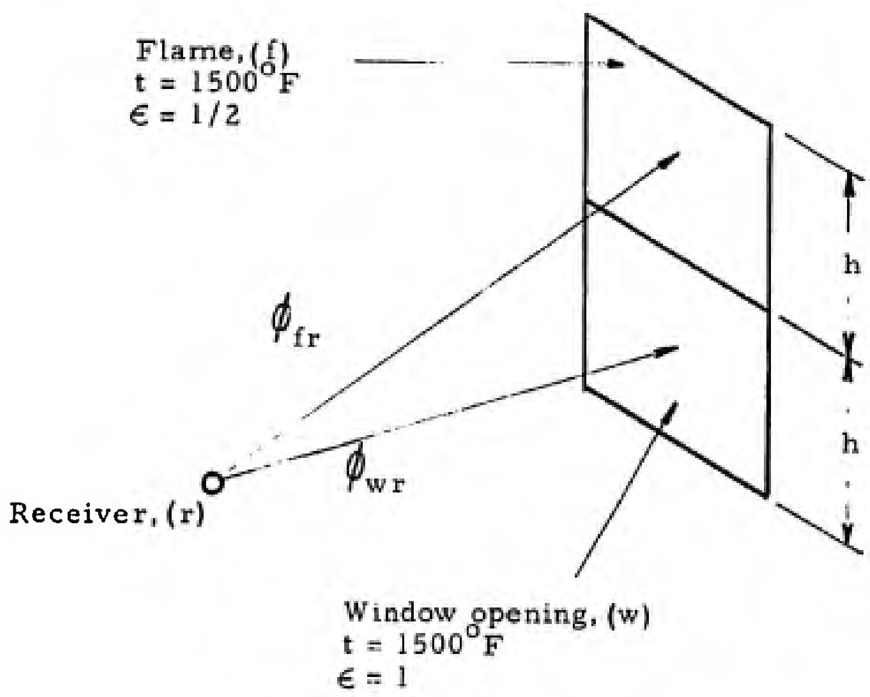


Fig. B-5 Radiation Model During Peak Fire from a Room

This model approximates the actual flame size, for the purpose of determining angle factors to receivers in close proximity to the window. For large distances, where geometric angle factors from both rectangles to the receiving surface are approximately the same, one may simplify the expression slightly and use a fictitious emissivity of 1.5 in conjunction with the angle factor of the window opening only. Thus, for short distances, $I_r = \sigma(\phi_{wr} + 1/2\,\phi_{fr})T^4$, and for relatively large distances, $I_r \approx 1.5\sigma\,\phi_{wr}T^4$. The temperature, T, is 1960° R in both cases and meaning of symbols is shown in Fig. B-5.

These model results can be directly scaled to full size room fires. Thomas[7] has shown that the flame height, L, from cubical enclosures having one side open can be expressed in terms of the opening height, h, as

$$L/h = C_1\,(R/wh^{3/2})^{2/3} \qquad \text{(B-2)}$$

Since the burning rate, R, for ventilation controlled fire is given by

$$R = C_2 wh^{3/2} \qquad \text{(B-3)}$$

the flame height becomes

$$L = C_1 C_2^{2/3} h \qquad \text{(B-4)}$$

or, as C_1 and C_2 are constants,

$$L \sim h \qquad \text{(B-5)}$$

and the results of the models in terms of flame size can be considered representative of full scale fires having ventilation controlled burning conditions.

After ceiling collapse in two story models, air is induced into the first story window and combustion products leave from the second story window. The flames emerging from the second story window are much larger than those obtained for a single room. The temperatures for these conditions are higher than for a single room burn and 1600°F appears to be the best temperature to use for radiation calculations. At the first story only the window opening radiates and the radiant flux can be determined using ϵ = 1. The size of the flames issuing from the second story window depended on the location of the window relative to the location of the first story window. When the first and second story windows were vertically aligned, the flame above the window could be represented by a rectangle 1.5 windows wide and three windows high. When the windows were on adjacent walls, the flame width was equal to the window width. The photographic records show that flames are much thicker than from the single rooms, and an emissivity of one should be used for radiation calculations. The radiation models for the two situations are shown in Figure B-6, and represent the projected area of the flame in the plane of the window.

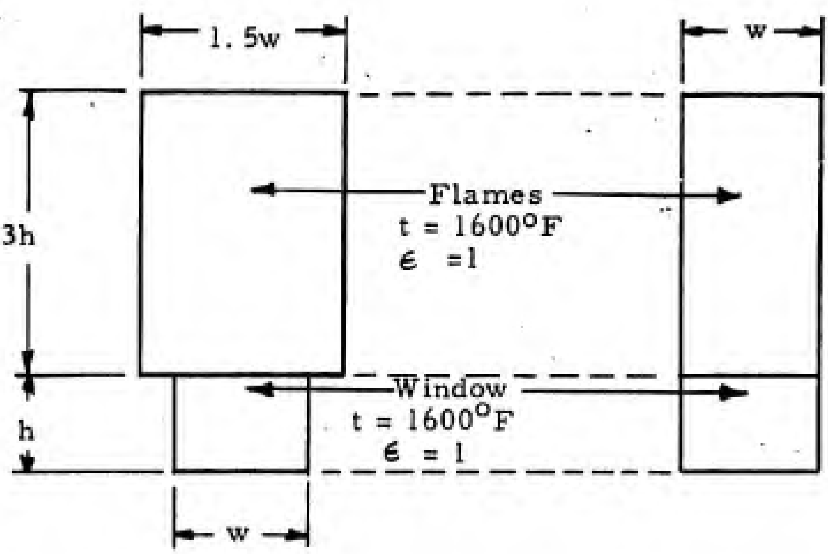


Fig. B-6 Radiation Model for Second Story Windows after Ceiling Collapse

The model for cases where the windows are on opposite sides is expected to be the same as the case where they are aligned in the same side. For large distances from the windows, where the angle factor is not greatly affected by the shape of flames, the radiant flux received per unit area of the receiver may be obtained from $I_r = 5.5\,\sigma \phi_{wr} T^4$ for windows aligned or $I_r = 4\sigma \phi_{wr} T^4$ for windows on adjacent sides. The angle factor, ϕ_{wr}, is for the window opening.

The films show that the flames actually leave the window at an angle of approximately 45° from vertical. Due to the thickness of the flame, there is a radiation to the side that must be taken into account. Calculations based on radiation measurements in the plane of the window indicate that the model for a single room may be modified to include the side radiation by considering the flame above the window to have a thickness of one-half of the minimum window dimension and an emissivity of one. For a second story window after a ceiling collapse, the thickness of the flame equal to the minimum window dimension and an emissivity of one are appropriate. The modified models are shown in Figure B-7.

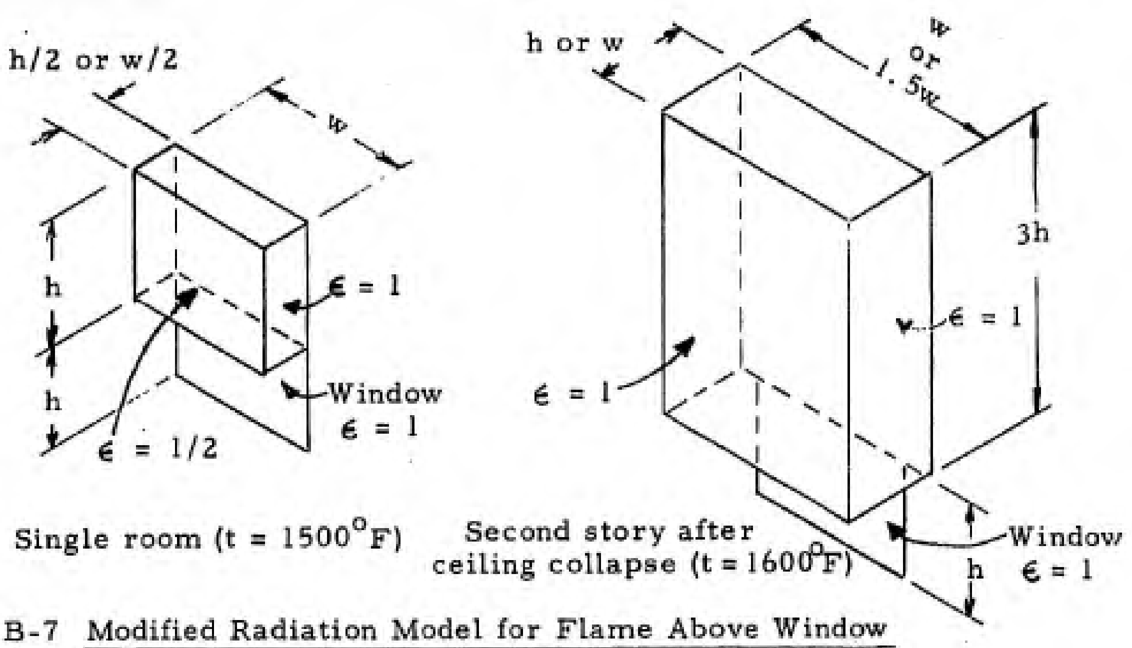


Fig. B-7 Modified Radiation Model for Flame Above Window to Include Radiation to the Side

Some radiation data are shown in Figures B-8 and B-9, as measured by a radiometer even with the top of the appropriate window, and nine geet away. The radiant intensity levels from calculations using the models are shown for comparison. For the single room case, the calculated intensity at the radiometer location is 0.054 cal/cm^2-sec. For the two story case, with windows aligned, the calculated level is 0.23 cal/cm^2-sec. which includes the contribution of the first story window. Where the windows are on adjacent sides, the level is 0.15 cal/cm^2-sec.

Figure B-8 also shows the radiation levels achieved by a room lined with fiberboard (Burn 4) and one lined with unbonded fiberglass (Burn 4A). The combustible lining added no appreciable intensity to the radiation level over that resulting from the drywall lined rooms. The insulating quality of the fiberglass apparently aided the build-up of the fire in Burn 4A and for a short period early in the fire the level averaged about 30% above that predicted. The more important result, however, concerns the behavior of the fiberboard room since previous experiments, reported in the literature, show appreciable increases in radiation level from such rooms as well as increased temperature levels within the rooms. This difference can be attributed to the lack of combustible contents within the rooms which in turn permitted the combustibility of the wall and ceiling covering material to become significant. In our experimental series, all rooms were furnished to a typical residential level both in terms of the weight and surface area of combustibles and thus were not as sensitive to wall and ceiling combustibility. It is therefore recommended that, for radiant flux calculations, the radiation models given in Figure B-7 be used for both combustible and noncombustible lined rooms.

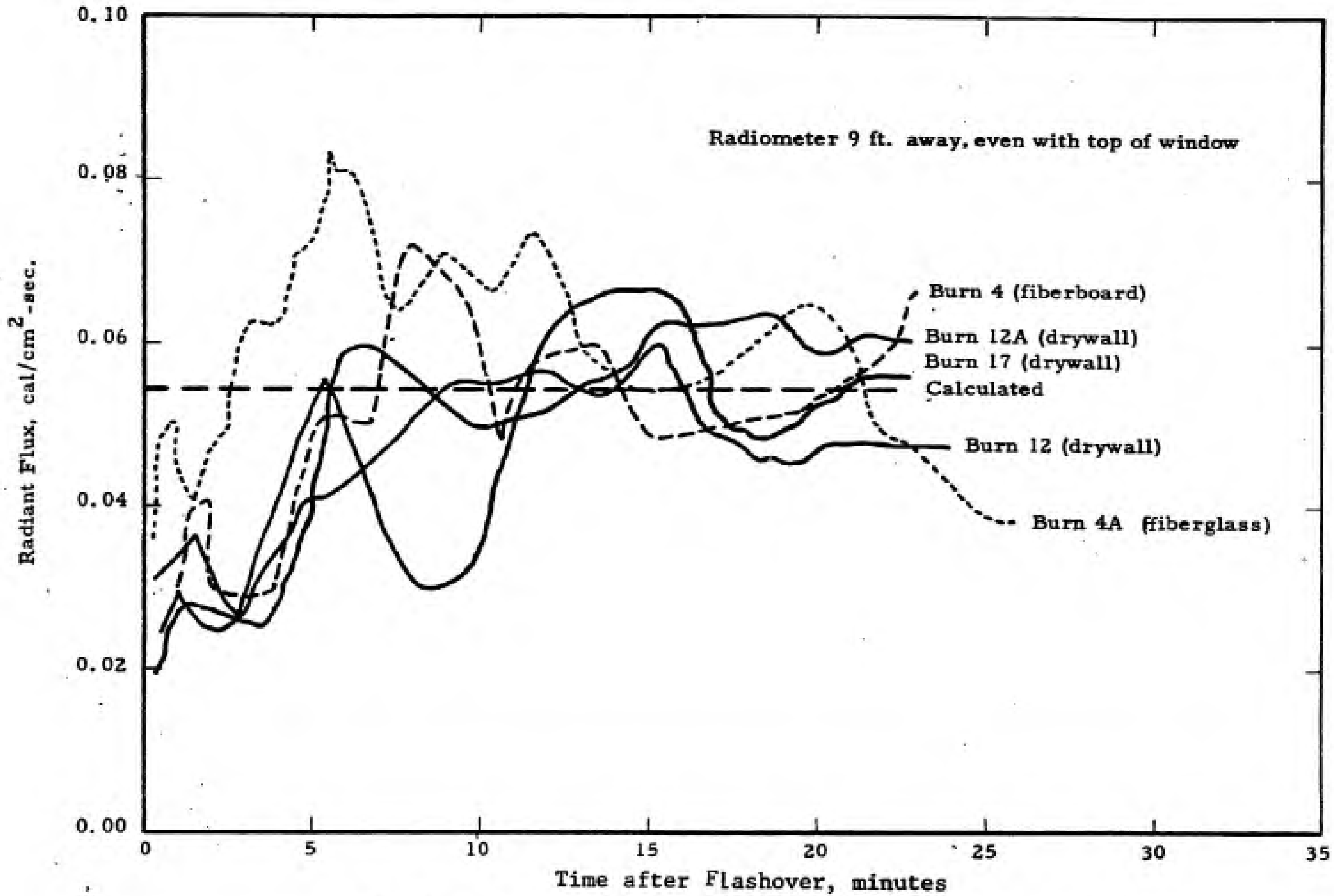


Fig. B-8 RADIATION FROM FIRE INVOLVING A SINGLE ROOM

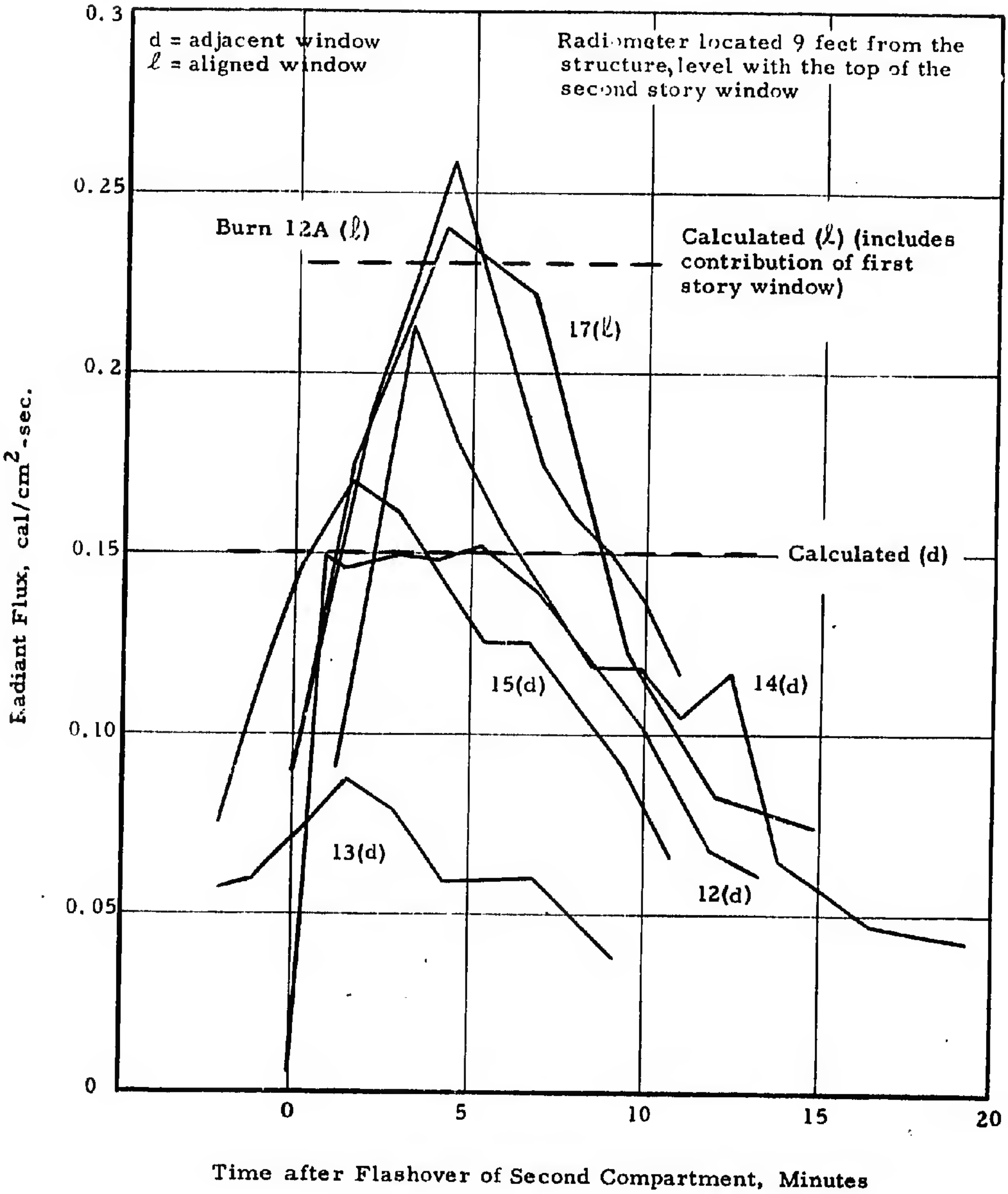


Fig. B-9 RADIATION FROM FIRES INVOLVING TWO-STORY STRUCTURES AFTER CEILING PENETRATION

The size of the flames encountered with the model room burns was generally larger than that observed in the full-scale experiment of the three story apartment building (Appendix E, Ellis Parkway Burn). During the peak fires in the second story living room, the flames above the windows were only half the height of the window and quite thin. A comparison of calculated radiation levels with those obtained from the instruments indicates the best correlation with a flame temperature of 1500°F, an emissivity of one for the window openings and no flames above the windows. The difference in the flame size and temperature, as compared to the model rooms, is attributed to the relatively large window areas compared to the room size of the full-scale building. According to the presently used equations the burning rate is given by $R_v = 1.5\ A_w\sqrt{h}$ for a ventilation controlled fire in a room or $R_s = 0.09\ A_s$ for fuel controlled fire. The fuel area in the second story living room of the full-scale test was estimated as 496 ft^2, including the wood floor area. The window area was 48 ft^2 with a window height of 5.8 ft. For these data, one obtains R_v = 175 lb./min and R_s = 45 lb/min., which indicates that the fire in the room was fuel controlled. For a fuel controlled fire in a room with extreme excess ventilation, no flame will be present above the window since the entire combustion would occur inside the room. As the amount of fuel is increased (or window area decreased) flames will appear above the window as a result of combustibles not burned inside the room. In the transition region, the flame increases in height until it reaches a maximum as ventilation controlled conditions are approached. Appendix A relates this behavior for the crib fires burned in enclosures. Radiation levels from the cribs reached those of the model rooms at values of $R_s/R_v \approx 0.5$. The results from the three story apartment building during the peak fire of the second story living room is in good general agreement. Other full scale building fires where the windows were smaller compared to the room size (and loading) evidenced behavior similar to the models.

After flashover of the third story living room and collapse of the second story ceiling during the Ellis Parkway (Appendix E) apartment building burn, a situation analogous to the two story models was observed. The air flow was induced through the second story living room windows and flames left through the third story living room windows. In the model experiments, such a situation resulted in flames three times the window height above the opening, while in the full scale experiment, the flame height was only slightly greater than the window height. The radiation levels indicated by the radiometers could be calculated using a temperature of 1600°F and emissivity of one for both the opening and flames above the window, which is the same as found in the half-scale models. The major discrepancy is the size of the flame above the window. It is believed that this is again due to the relatively large window areas in comparison to the available fuel. There is also another source of air through the doorway to the living rooms which would further increase the opening through which air may reach the fire. Due to this tendency for many full scale structures to be only marginally ventilation controlled, the use of the "adjacent wall" radiation model (flame width = window width) is recommended for all cases. This recommendation, rather than that of the wider flame, is further indicated as the observed flame width increase in the models will certainly not scale as a function of window width for groups of windows side by side (a common occurrence).

X. SYNOPSIS OF MODEL ROOM EXPERIMENTS

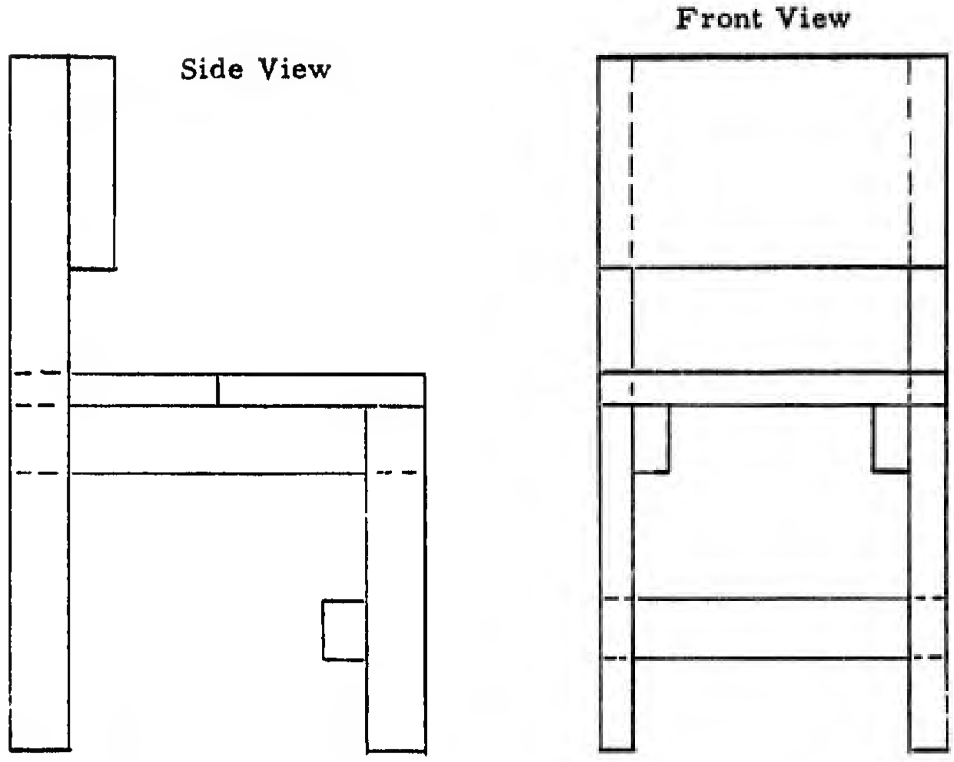
The construction of the model furniture and the layout in a typical room are shown in Figures B-10 to B-20. Unless otherwise noted, burns were 1/2 scale, and the interior walls and ceiling made from one layer of drywall.

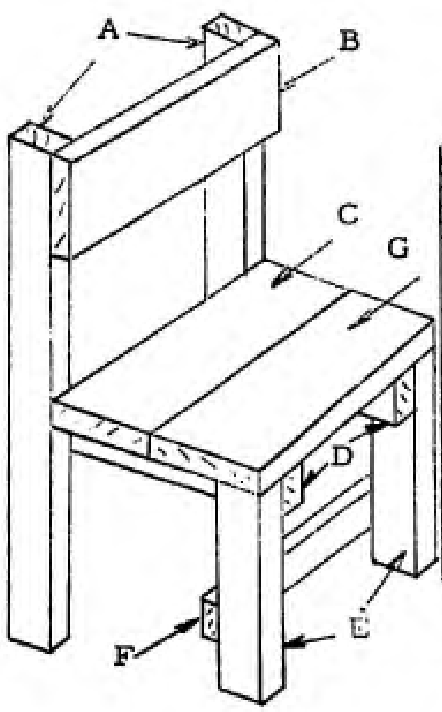
In Burns 1 - 7, the 2 x 4's were used for roof-ceiling-floor construction and exteriors were covered with one layer of drywall. In Burns 8 - 40, the 2 x 8's were used for roof-ceiling-floor construction and exteriors were covered with two layers of drywall, at least over the ignited room.

The details of performed experiments are described below.

BURN 1 - SINGLE ROOM, TOP TWO-THIRDS OF WINDOW COVERED WITH DRYWALL

It was planned to remove the window covering at flashover; however, due to the tightness of the room (as compared to one room of a series in a real structure) the interior became very oxygen starved, filled with thick black smoke and gradually increased in temperature rather than undergoing a rapid change as the entire contents became involved. Upon removal of the window covering, flames belched forth from the opening, fire having fully involved the interior. It can be noted that the penetration of the walls and ceiling indicate an equivalent to flashover some twenty minutes earlier which is substantiated by the temperature records.





Chair Dimensions
(In Inches)

Scale	Half		Third		Quarter	
Part	TxW	L	TxW	L	TxW	L
A	1x2	18	1x1-1/3	12	1x1	9
B	1x6	9	1x4	6	1x3	4-1/2
C	1x4	9	1x2-1/2	6	1x4-1/2	4-1/2
D	1x2	11	1x1-1/3	7-3/8	1x1	5-1/2
E	1x2	9	1x1-1/3	6	1x1	4-1/2
F	1x1-1/2	9	1x1	6	1x1	4-1/2
G	1x6	9	1x4	6	---	---

T = Thickness
W = Width
L = Length

Fig. B-10 MODEL CHAIR

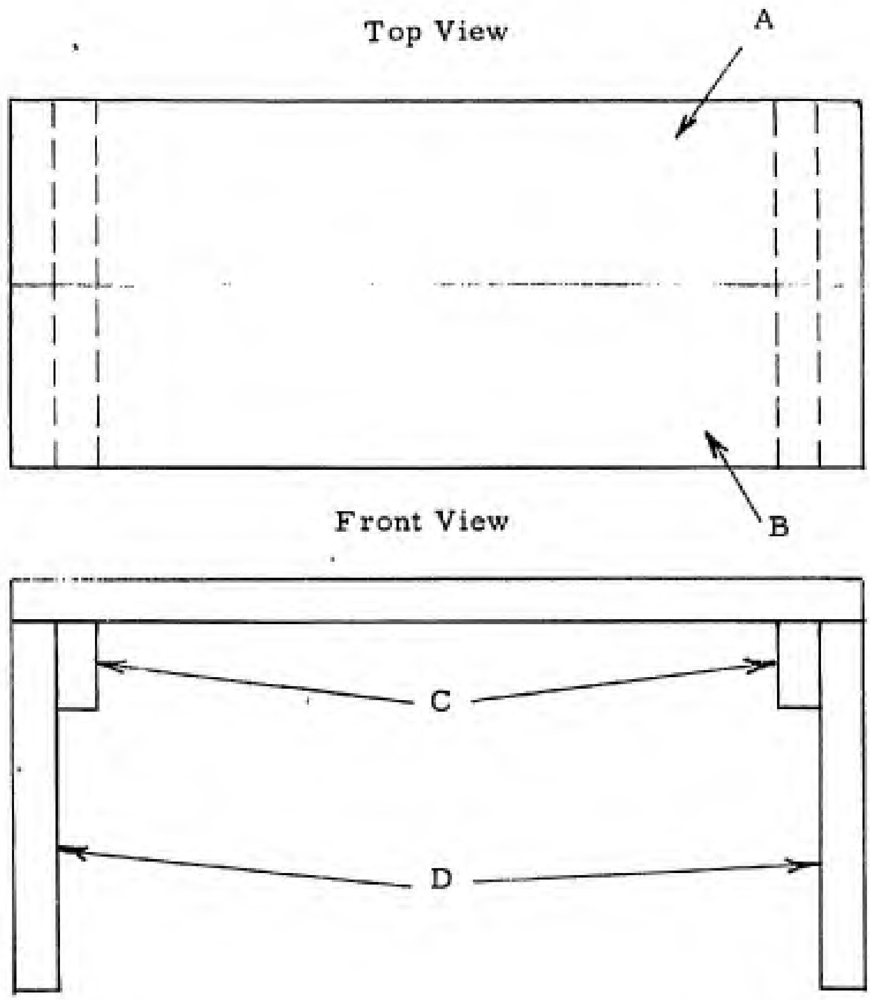
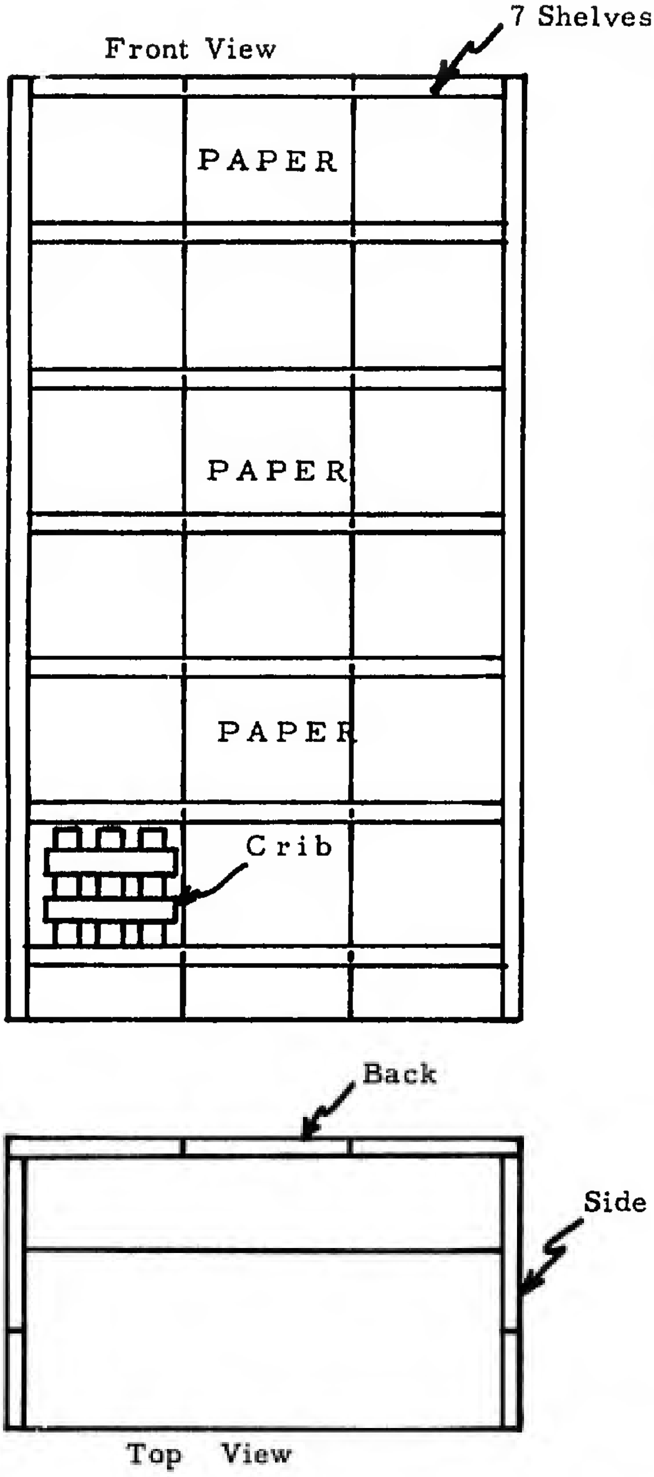


Table Dimensions
(In Inches)

Scale	Half		Third		Quarter	
Part	T x W	L	T x W	L	T x W	L
A	2 x 8	36	2 x 8	24	2 x 8	18
B	2 x 8	36	2 x 2-2/3	24	- - -	--
C	2 x 4	15	2 x 2-2/3	10	2 x 2	7-1/2
D	2 x 2	15	2 x 1-1/3	10	1 x 2	7-1/2

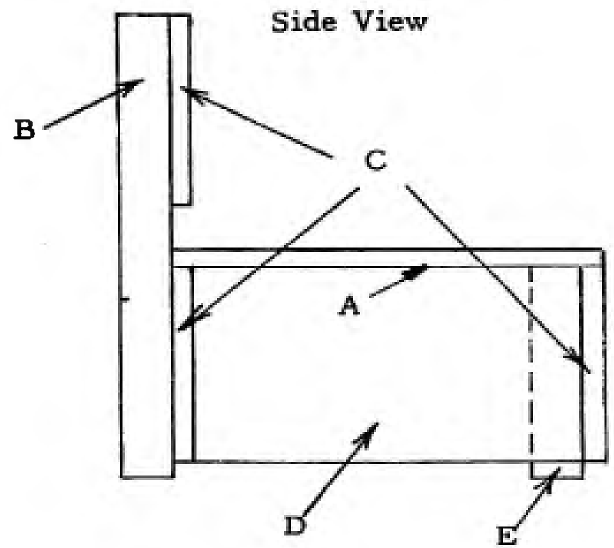
Fig. B-11 MODEL TABLE

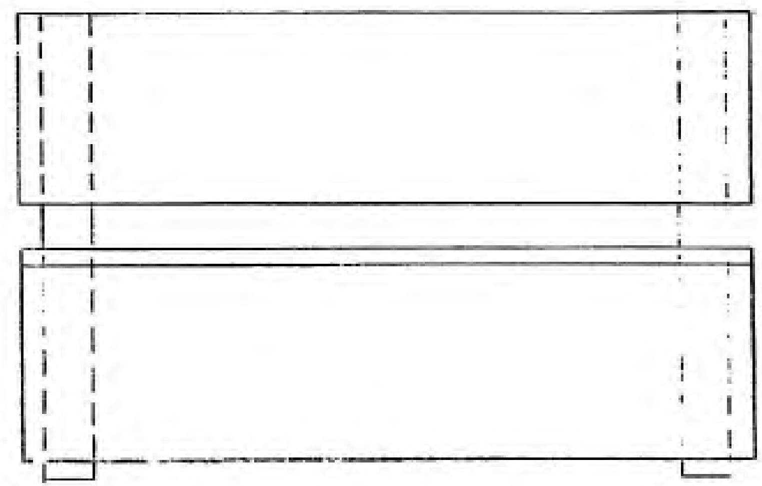


Cupboard Dimensions
(In Inches)

Part	No. of pcs.	T x W	L
Half Scale			
Shelf	2	1 x 8 1 x 4	20-3/4
Back	3	1 x 8	39
Side	2	1 x 8 1 x 4	39
Third Scale			
Shelf	1	1 x 8	13-1/4
Back	2	1 x 8	26
Side	1	1 x 8	26
Quarter Scale			
Shelf	1	1 x 6	9.5
Back	2	1 x 8 1 x 4	19.5
Side	1	1 x 6	19.5

Fig. B-12 MODEL BOOKCASE-CUPBOARD

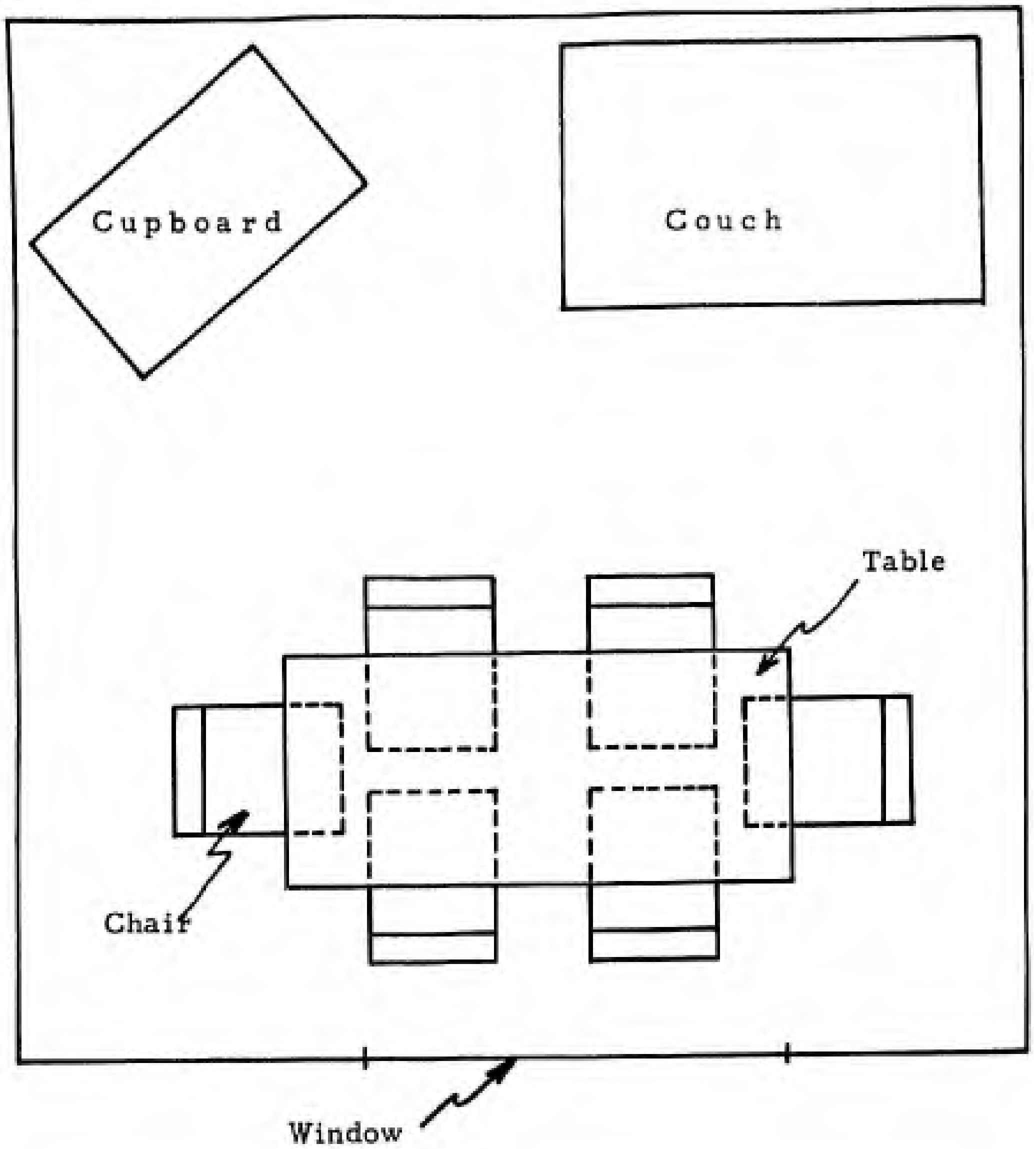




Couch Dimensions (In Inches)

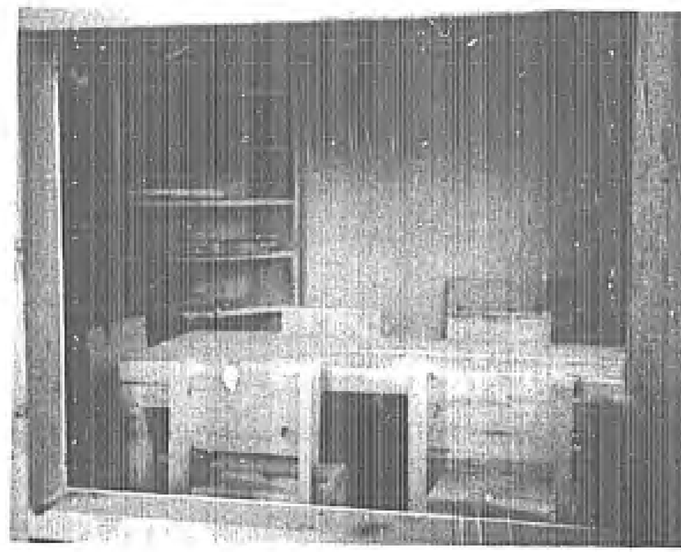
Part	Half Scale			Third Scale			Quarter Scale		
	No. of pcs.	T x W	L	No. of pcs.	T x W	L	No. of pcs.	T x W	L
A	2	1 x 8	30	2	1 x 8 1 x 2-2/3	20	1	1 x 8	15
B	1	2 x 2	18	1	2 x 1-1/3	12	1	1 x 2	9
C	1	1 x 8	30	1	1 x 5-1/3	20	1	1 x 4	15
D	1	1 x 8	13-1/4	1	1 x 5-1/3	8-1/4	1	1 x 4	5-3/4
E	1	2 x 2	8	1	2 x 1-1/3	5-1/4	1	1 x 2	5-3/4

Fig. B-13 MODEL COUCH



Item	Weight, (lb.)		
	1/2 Scale	1/3 Scale	1/4 Scale
Table	16.0	7.1	4.0
6 Chairs	16.8	7.5	4.2
Couch	15.2	6.7	3.8
Cupboard	34.5	15.3	8.9
Cpbd Load	25.0	11.0	6.25

Fig. B 14 ROOM LAYOUT



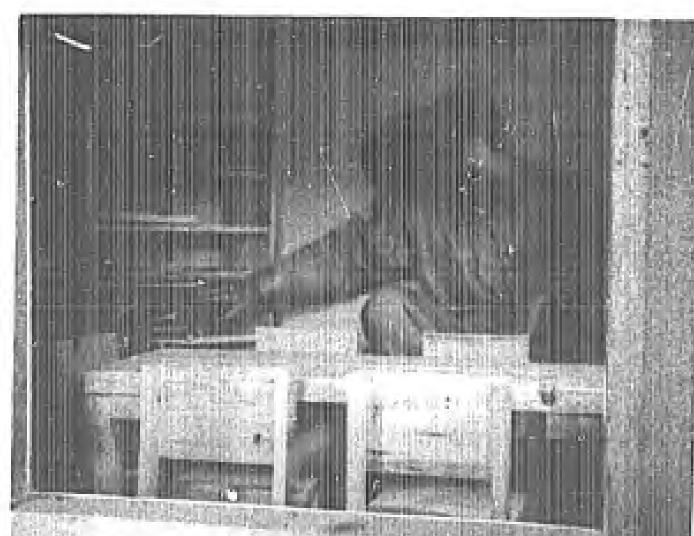
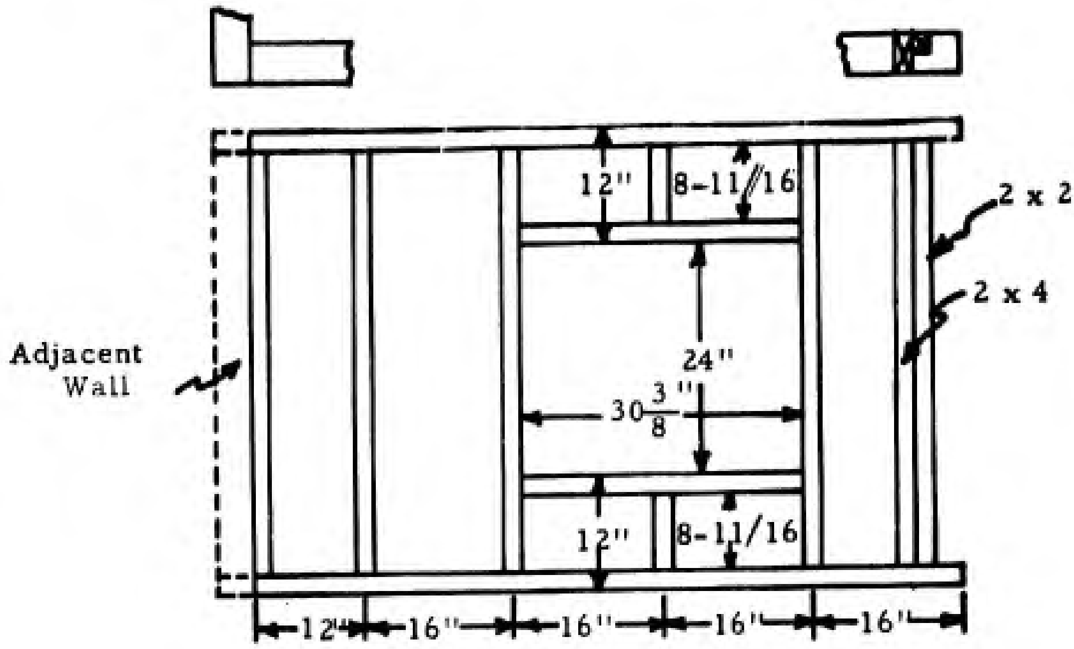
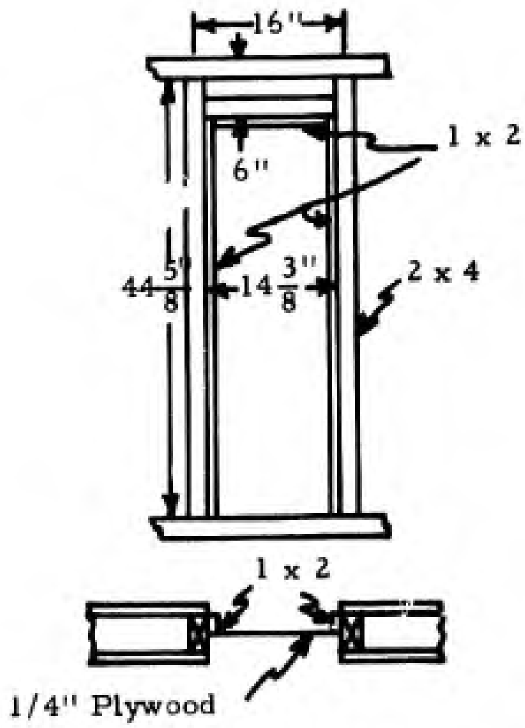


Fig. B-15 INTERIOR VIEW OF 1/2 SCALE ROOM
(FIRE BOAD IN BOOKCASE - CUPBOARD IS INCOMPLETE)

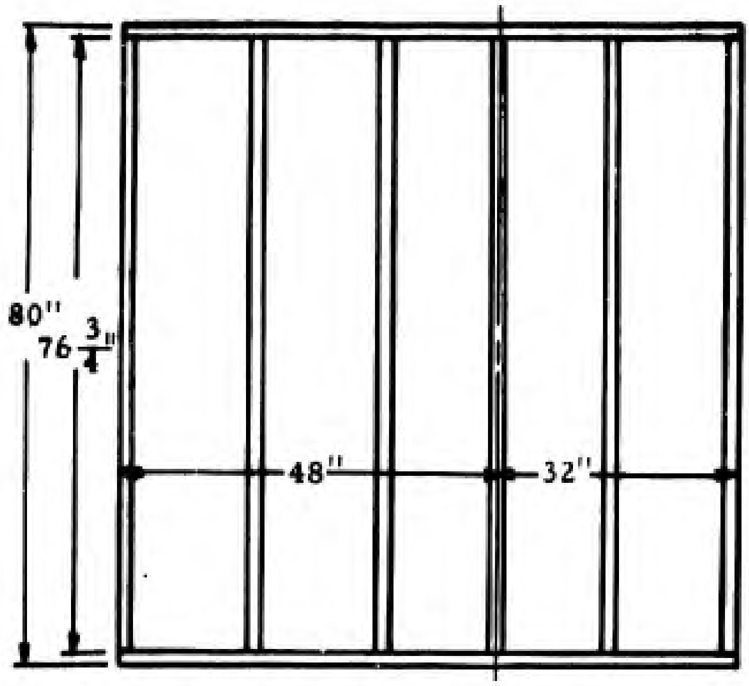


Window Wall

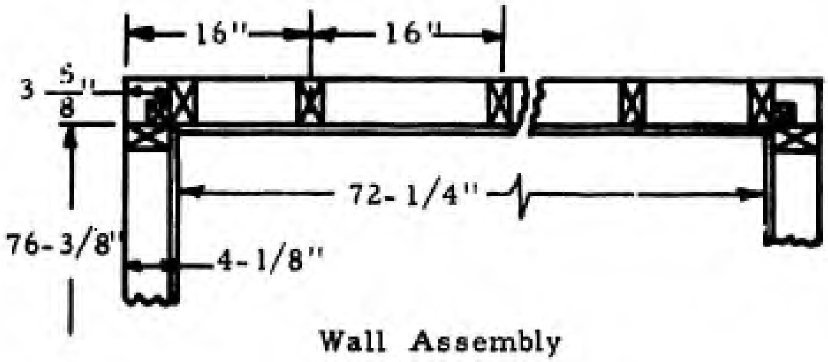


Door Opening

Fig. B-16 HALF SCALE WINDOW AND DOOR WALLS



Ceilings and Floors



Wall Assembly

Fig. B-17 CONSTRUCTION DETAILS FOR HALF-SCALE ROOM

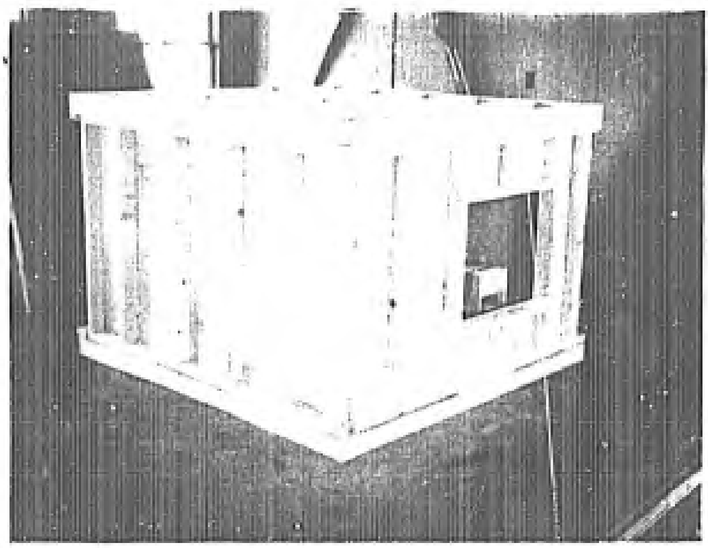


Fig. B-18 ASSEMBLY OF 1/2 SCALE ROOM

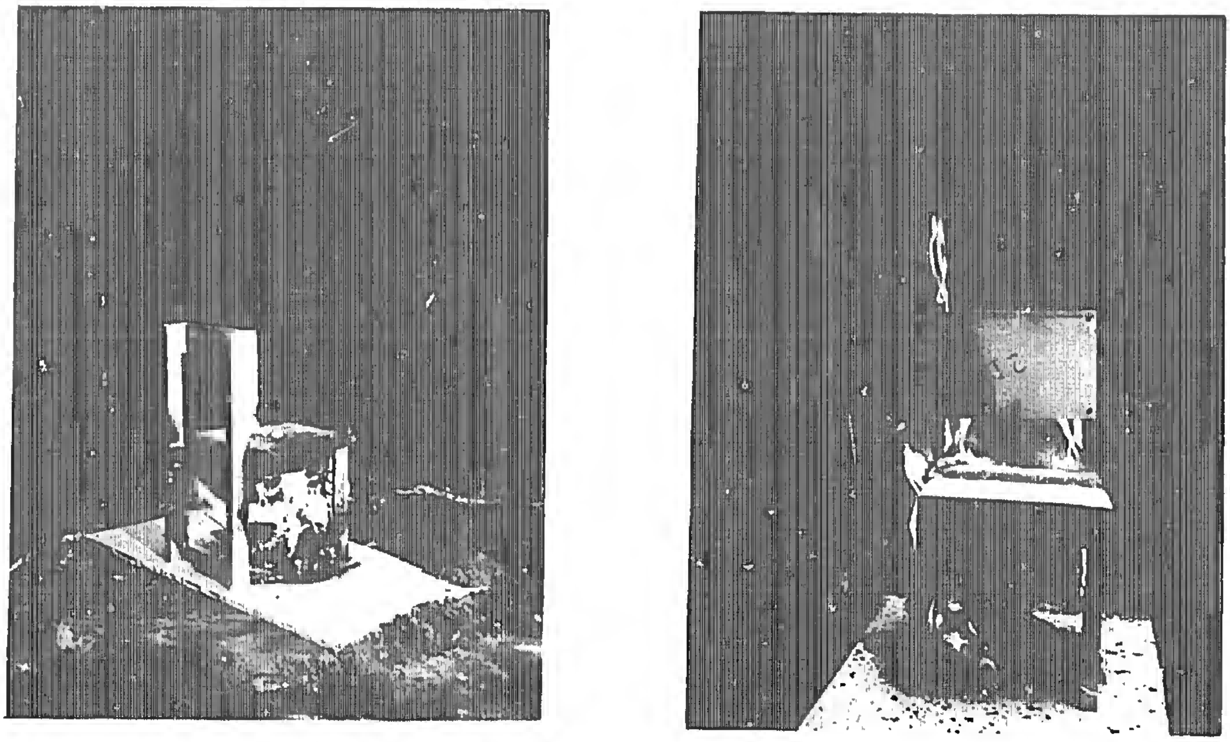


Fig. B-19 BURNING CHARACTERISTICS OF A MODEL CHAIR

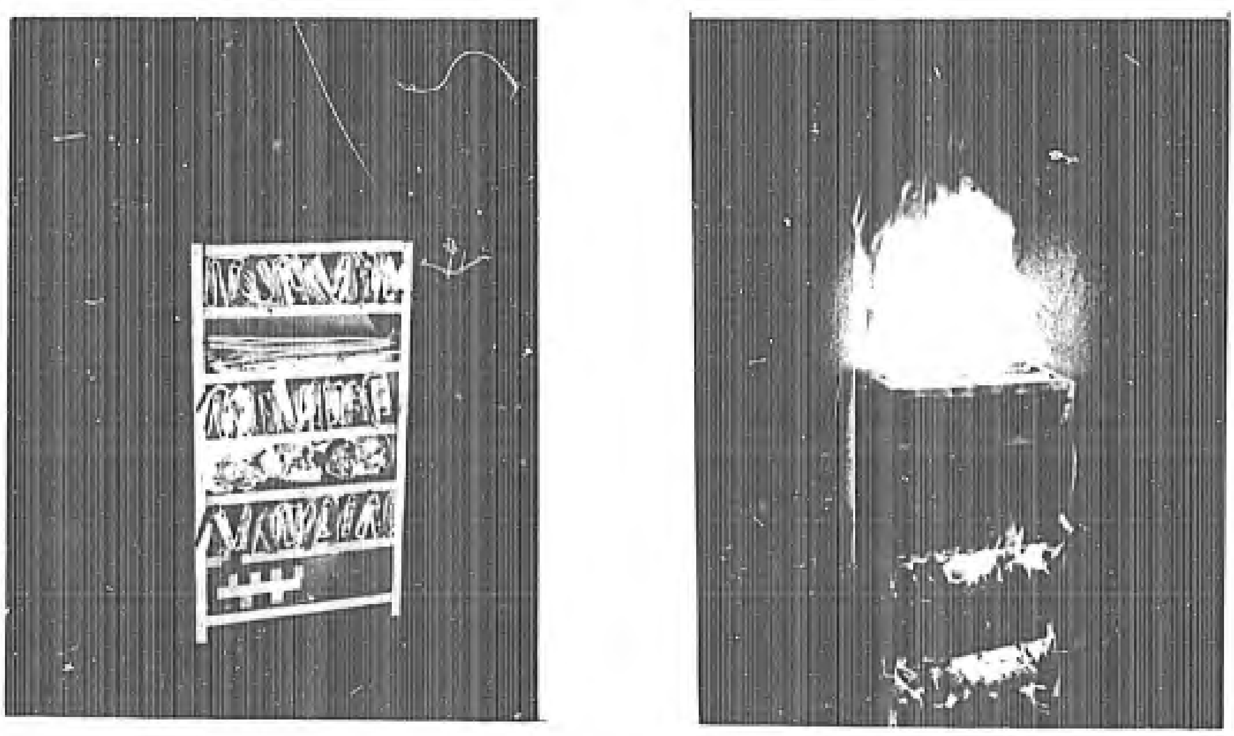


Fig. B-20 BURNING CHARACTERISTICS OF A MODEL BOOKCASE

BURN 1 - (Continued)

2:35 - 50	Ignition.
2:59 - 20	Ceiling thermocouples at 1000°F.
3:00 - 21	Mid-height wall thermocouples at 1000°F.
3:01 - 08	Floor thermocouples at 1000°F.
3:13 - 30	Pieces of drywall fall from ceiling and wall over window.
3:21 - 25	Drywall falling from inside window frame.
3:21 - 30	Window covering removed, flaming out windows follows immediately.
3:24 - 47	Outside top of ceiling burns (paper covering on drywall).
3:26 - 10	Drywall falls from front wall.
3:27 - 30	Drywall falls from ceiling.
3:29 - 00	Drywall falls from ceiling in quantity.
3:33 - 00	Drywall falls from back wall (inside).
3:34 - 00	Drywall falls from outside ceiling layer.
3:37 - 00	Flames appear on outer side walls (paper burns off).
3:41 - 00	Flames appear on outer rear wall, wall cracks.

BURN 2 - 1/4 SCALE, SINGLE ROOM

Difficulties were encountered in ignition of the bookcase due to extreme closeness of shelves. Definite laminar burning behavior of 1/4 scale room fire and questionable behavior of 1/3 scale (burned before this experiment) led to their elimination from later experimental scheduling.

11:31 - 30	Ignition.
11:51 - 10	Fire dying out, JP4 added.
11:57 - 30	Floor is burning in front of bookcase.
12:00 - 10	More JP4 added.
12:01 - 42	Ceiling thermocouples at 1000°F.
12:09 - 30	Midwall thermocouples at 1000°F.
12:09 - 30	Flashover. Flames move across upper room area.
12:09 - 50	Fire dying down.
12:11 - 35	Flames on the table.
12:12 - 00	Fire is burning better.
12:19 - 20	Front chairs collapse.
12:20 - 30	Left leg of table collapses.
12:21	Floor thermocouples at 1000°F.
12:24	Right leg of table collapses.
12:30 - 45	Smoke from drywall under the floor.
12:31 - 00	Bookcase falls over.
12:33 - 37	Drywall falls from ceiling.
12:49 - 00	Exterior ceiling drywall charring.
12:50 - 30	Paper burns from exterior ceiling drywall.

BURN 3 - 1/3 SCALE, SINGLE ROOM

Fire buildup in the bookcase is reasonable although slower than that occuring in 1/2 scale rooms. The lack of butt joints in the interior coverings added to their apparent fire resistance (each wall and ceiling of one piece). As there was some question as to the full turbulence of the flames, this scale was dropped from use in later experiments.

11:01 - 30	Ignition.
11:24 - 30	Couch catches fire.
11:25 - 48	Ceiling thermocouples at 1000°F.
11:28 - 00	Midwall thermocouples at 1000°F.
11:28 - 50	Flashover.
11:29 - 18	Floor thermocouples at 1000°F.
11:36 - 15	Front chairs fall toward window.
11:38 - 00	Table falls.
11:39 - 00	All outside walls are warm.
11:41 - 00	Inside ceiling drywall falls.
11:44 - 30	Bookcase falls.
11:54 - 00	Smoke from drywall on floor.
11:55 - 30	Paper on outside of ceiling drywall catches fire.
11:58 - 00	Outside ceiling falls in.
11:54 - 12:01 - 00	Drywall falls from underside of floor.

BURN 4 - SINGLE ROOM, INTERIOR WALLS AND CEILING OF ONE HALF INCH FIBERBOARD

The fiberboard covering produced an earlier flashover and resulted in faster penetration of walls and ceiling.

2:57 - 10	Ignition
3:03 - 16	Ceiling thermocouples at 1000°F.
3:03 - 46	Flashover, flames move along wall just before flash.
3:05 - 58	Floor thermocouples at 1000°F.
3:14 - 00	Inside ceiling falls.
3:16	Table collapses.
3:17 - 15	Outside paper on ceiling drywall burns.
3:24 - 30	Flames come through front right corner of room.
3:27 - 15	Outer drywall falls from ceiling, large flame shoots out.
3:29 - 40	More drywall falls, again a massive flame appears.
3:30 - 00	Fire very intense.
3:32 - 00	Ceiling rafters dropping, very little ceiling left.
3:34 - 50	Right side drywall starting to fall (outside).

BURN 4A - SINGLE ROOM, INTERIOR WALLS AND CEILING OF DRYWALL COVERED WITH 2" UNBONDED FIBERGLASS, STUD SPACES FILLED WITH UNBONDED FIBERGLASS.

Although non-combustible, the insulating character of this lining resulted in a decreased flashover time comparable to that achieved with the fiberboard. Its inclusion in the stud spaces increased their resistance to spread.

1:11 - 15	Ignition.
1:19 - 33	Ceiling thermocouples at 1000°F.
1:19 - 43	Midwall thermocouples at 1000°F.
1:20 - 10	Flashover.
1:20 - 33	Floor thermocouples at 1000°F.
1:24 - 30	Front chairs fall.
1:26 - 30	Table and rest of chairs fall.
1:28 - 00	Outside wallboard cool (roof and ceiling).
1:29 - 45	Fiberglass insulation falling (ceiling and walls).
1:31 - 00	Dense smoke coming off.
1:31 - 30	Outside roof drywall warming, walls cool.
1:32 - 40	Floor burned through to joists.
1:37 - 40	Drywall from ceiling starts falling.

BURN 5: TWO ROOMS SIDE BY SIDE, NO SEPARATING BARRIER

Although no barrier separated the two rooms, a local flashover of the ignition room preceeded that of the entire space by several minutes. The distinct definition of two flashovers was enhanced by the fact that each room had its own window with a substantial distance of wall separating them.

3:12 - 15	Ignition in left room.
3:25 - 57	Center ceiling thermocouples at 1000°F.
3:26 - 15	Couch has ignited.
3:26 - 31	Flashover in left room, dense smoke in right.
3:28 - 21	Average midwall thermocouples at 1000°F.
3:28 - 39	Center floor thermocouples at 1000°F.
3:30 - 20	Flashover in right side, flame through both windows.
3:30 - 39	Flames receding on right side.
3:31 - 11	Right side flames building up.
3:31 - 30	Left side, chairs fall.
3:31 - 45	Left side, table falls.
3:33 - 30	Right side, chairs fall.
3:37 - 40	Right side, table falls.
3:38 - 00	Inside drywall on left ceiling falling.
3:42 - 45	Inside drywall on right ceiling falling.

BURN 5 (Continued)

3:47 - 00	Majority of drywall has fallen.
3:51 - 00	Paper on outside of left room catches fire.
3:51 - 45	Fire on outside drywall spreads to right side.
3:52 - 15	Exterior ceiling wallboard on left room falls.
3:52 - 30	Exterior ceiling wallboard on right room falls.
4:00 - 00	Inside wallboard on rear wall falls, left side.
4:05 - 15	Paper on out side left wall catches fire.
4:06 - 00	Paper on outside rear charring slightly.

BURN 6 - FOUR - 1/4 SCALE ROOMS, NO SEPARATING BARRIERS

The room array consisted of a large compartment twice the length and width of a single room. The furniture arrangement in each quarter of the space was that of a single room. A single window, equal in width to four standard windows was placed on one wall. Although evidencing the problems typical of 1/4 scale, the local flashover occurrence and spread toward the window, a final full involvement can be noted.

9:55 - 20	Ignition in left rear bookcase.
10:02 - 00	Rear left couch starts burning.
10:09 - 32	Ceiling thermocouples at center of room at 1000^{o}F.
10:10 - 00	Papers on top of bookcase ignite.
10:10 - 30	Rear right side of bookcase is burning.
10:11 - 50	Flash on left rear side, dark smoke from right, flames moving forward.

BURN 6 - (Continued)

10:12 - 02	Rear and left midwall thermocouples at 1000°F.
10:12 - 50	Floor thermocouples at center of compartment at 1000°F.
10:13 - 30	Fire dies down.
10:14 - 30	Fire picks up and moves gradually to right.
10:15 - 20	Fire is completely across right side.
10:21 - 00	Chairs on left fall.
10:21 - 30	Chairs on right fall.
10:22 - 10	Left table falls.
10:23 -	Right table falls.
10:37 - 20	Front inside ceiling starts falling.
10:37 - 30	Left side bookcase falls.
10:39 - 00	Big part of right inside wallboard falls.
10:42 - 20	Right side bookcase falls.
10:47 - 50	Outside ceiling starts charring.
10:48 - 10	Outside ceiling starts burning (paper).
10:50 - 10	Smoke appearing from under floor.
10:53 - 00	Outside ceiling falls and window separation breaks apart and falls.

BURN 7 - FOUR - 1/3 SCALE ROOMS, NO SEPARATING BARRIERS

A 1/3 scale version of Burn 6, the burning behavior of this model appeared fully turbulent. The local flashover behavior was noted.

9:58 - 30	Ignition in left rear bookcase.
10:06 - 15	Floor burning in left rear.
10:12 - 50	Left rear couch ignites.
10:14 - 55	One left rear chair ignites.
10:16 - 55	Paper on right rear bookcase ignites.
10:17 - 00	Left rear table catches fire.
10:17 - 06	Ceiling thermocouples at center of compartment at 1000°F.
10:17 - 15	Left and rear mid-wall thermocouples at 1000°F.
10:17 - 25	Flashover on left rear, flames move to window.
10:18 - 30	Right front bookcase catches fire.
10:20 - 00	Fire in rear of left side appears to have gone out, but front is burning.
10:21 - 00	Right front catches fire gradually.
10:23 - 15	Left front table and chair falls.
10:27 - 45	Right front table collapses.
10:29 - 30	Left front bookcase falls forward.
10:31 - 50	Right front bookcase falls forward.
10:32 - 48	Right mid-wall thermocouples at 1000°F.
10:34 - 05	Ceiling drywall on left front starts falling.

BURN 7 - (Continued)

10:35 - 15	Ceiling drywall on right front starts falling.
10:43 - 15	Front joist between windows collapses.
10:45 - 12	Center floor thermocouples at 1000°F.
10:45 - 20	Outside ceiling drywall paper starts burning.
10:47 - 00	Ceiling drywall starts dropping in rear.
10:47 - 20	Front roof on left side collapses.
10:49 - 00	Front roof on right side collapses.
10:54 - 15	Ceiling joists falling.
11:08 - 30	Drywall on all inside walls are cracked but very little has fallen.

BURN 8 - TWO ROOMS SIDE BY SIDE, SEPARATING WALL HAS OPEN DOORWAY

The restricted opening between the two rooms delays the second flashover by 5-1/2 minutes, approximately 1-1/2 minutes longer than the no partition case (Burn 5).

10:26 - 10	Ignition of left room.
10:35 - 46	Ceiling thermocouples in left room at 1000°F.
10:38 - 22	Floor thermocouples in left room at 1000°F.
10:38 - 34	Thermocouples at mid-height of doorway at 1000°F.
10:38 - 35	Flashover of left room, dense smoke comes from right room.
10:38 - 40	Ceiling thermocouples in right room at 1000°F.
10:38 - 43	All thermocouples on walls mid-height of left room at 1000°F.
10:40 - 25	Bookcase in right room ignites.
10:41 - 55	All thermocouples on walls mid-height of right room at 1000°F.
10:42 - 45	False flashover, right room.
10:43 - 20	Table and chairs in left room collapse.
10:43 - 34	Floor thermocouples in right room at 1000°F.
10:44 - 00	Flashover, right room.
10:49 - 00	Chairs on right side fall.
10:50 - 10	Ceiling inside wallboard on left side falls.
10:50 - 50	Right front table falls.
10:52 - 20	More ceiling wallboard on left side drops.
10:55 - 15	Ceiling wallboard on right side falls.
11:02 - 00	Dividing wall starts falling.
11:16 - 40	Roof wallboard paper catches fire.
11:20 - 00	Roof collapses on left side.

BURN 9 - TWO ROOMS SIDE BY SIDE, SEPARATING WALL HAS CLOSED DOORWAY (FRAMED 1/4" PLYWOOD DOOR)

The added barrier of a closed door increased the time from flashover to flashover to 10 minutes. It is of note that over 50 per cent of this time elapsed after flames penetrated the door.

3:02 - 43	Ignition in left room.
3:14 - 45	Ceiling thermocouples, left room at 1000°F.
3:15 - 27	Mid-wall thermocouples, left room at 1000°F.
3:15 - 35	False flashover in left room dying back.
3:16 - 03	Floor thermocouples, left room at 1000°F.
3:17 - 55	Flashover of left room.
3:19 - 21	Thermocouple on surface of door at mid-height reaches 1000°F, left room.
3:22 - 15	Flames appear through door.
3:22 - 27	Ceiling thermocouples in right room at 1000°F.
3:22 - 39	Right room, thermocouple on surface of door at mid-height reaches 1000°F.
3:24 - 00	Right room, large interior flames.
3:25 - 00	Flames die back on right.
3:25 - 51	Thermocouples midway up walls on right room at 1000°F.
3:26 - 04	Table and chairs in flames, right room.
3:26 - 09	Thermocouples on floor of right room at 1000°F.
3:27 - 52	Flashover, right room.
3:51 - 00	Left room, drywall to right of door is down.
3:56 - 47	Flames through roof.
3:57 - 47	Outer ceiling drywall falls, flames stop coming from left window, very little out of right window, most of flames through roof.

BURN 10 - TWO ROOMS SIDE BY SIDE, SEPARATED BY SLIDING BARRIER WHICH WAS REMOVED UPON FLASHOVER OF FIRST ROOM

The purpose of Burn 10 was to compare the spread in a large compartment (Burn 5) with that of two compartments one-half the size which did not permit spread until flashover occurred. This assumed mode of fire spread in large compartments (a series of smaller compartments with artificial barriers) has been quite useful for calculation purposes.

10:52 - 10	Ignition, left room.
11:03 - 00	Floor starts burning in front of bookcase.
11:03 - 22	Ceiling thermocouples at 1000°F (left room).
11:06 - 55	Mid-wall thermocouples at 1000°F (left).
11:07 - 00	Floor thermocouples at 1000°F (left).
11:07 - 10	Flashover, left room.
11:07 - 20	Sliding panel pulled from room, very dense smoke (right room).
11:10 - 10	Flashover, right room.
11:11 - 30	Table in left room falls.
11:11 - 58	Mid-wall thermocouples at 1000°F (right room).
11:13 - 04	Floor thermocouples at 1000°F (right)
11:15 - 45	Chair in right room falls.
11:18 - 50	Table falls (right)
11:20 - 30	Ceiling drywall falls in left room.
11:25 - 00	Ceiling drywall falls in right room.
11:34 - 15	Drywall falls from left wall near window.
11:39 - 00	Edge of left side roof ignites.
11:40 - 40	More drywall falls from left wall.
11:42 - 30	Drywall falls from right wall.

BURN 11 - TWO ROOMS SIDE BY SIDE, SEPARATED BY A WALL

The wall separating the two rooms was covered, on each side, by a continuous piece of drywall. All edges were restrained and the drywall panel on the cooler side remained in place with only minor cracks long after the studding was consumed. The times for the penetration and subsequent flashover of the second room are unrealistic. The behavior of the second room burnout can be related to that of a blast damaged structure as the one wall was completely open during the peak fire.

1:04 - 35	Ignition, left room.
1:17 - 11	Ceiling thermocouples at 1000°F (left room).
1:18 - 55	Flashover, left room.
1:19 - 23	Mid-wall thermocouples at 1000°F (left room).
1:19 - 35	Floor thermocouples at 1000°F (left room).
1:26 - 30	Table in left room falls.
1:27 - 00	Bookcase falls in left room.
1:33 - 50	Ceiling drywall starts falling, left room.
1:53 - 30	Drywall above window falling, left room.
2:00 - 00	Drywall breaks away from studs on left room side of separating partition.
2:00 - 30	Drywall in right room is charring.
2:02 - 20	Roof falls in left room.
2:04 - 10	Drywall cracking on right room side of room separator.

BURN 11 (Continued)

2:05 - 10	Fire breaks through partition.
2:06 - 55	Drywall falls from left room.
2:09 - 00	More drywall falls, left room.
2:11 - 40	Drywall paper covering ignites bookcase, right room.
2:20 - 00	Left room is almost burned out.
2:33 - 59	Ceiling thermocouples at 1000°F, right room.
2:34 - 45	Separating wall finally falls.
2:35 - 20	Left wall of left room falls.
2:37 - 00	Bookcase developing gradually in right room.
2:41 - 20	False flashover of right room.
2:42 - 20	Table starts to burn.
2:43 - 41	Mid-wall thermocouples at 1000°F, right room.
2:43 - 45	Flashover of right room.
2:43 - 47	Floor thermocouples at 1000°F, right room.

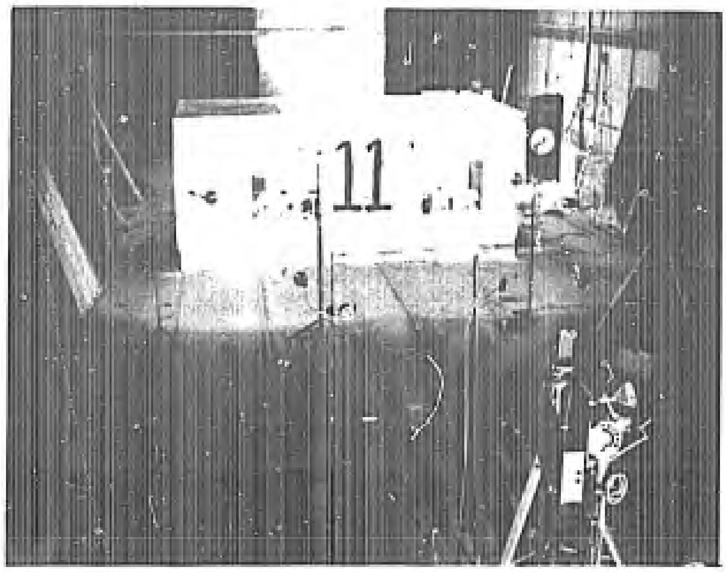


FIG. B-21 TWO ADJACENT (1/2 scale) ROOMS SEPARATED BY A PARTITION COVERED ON BOTH SIDES WITH PLASTERBOARD

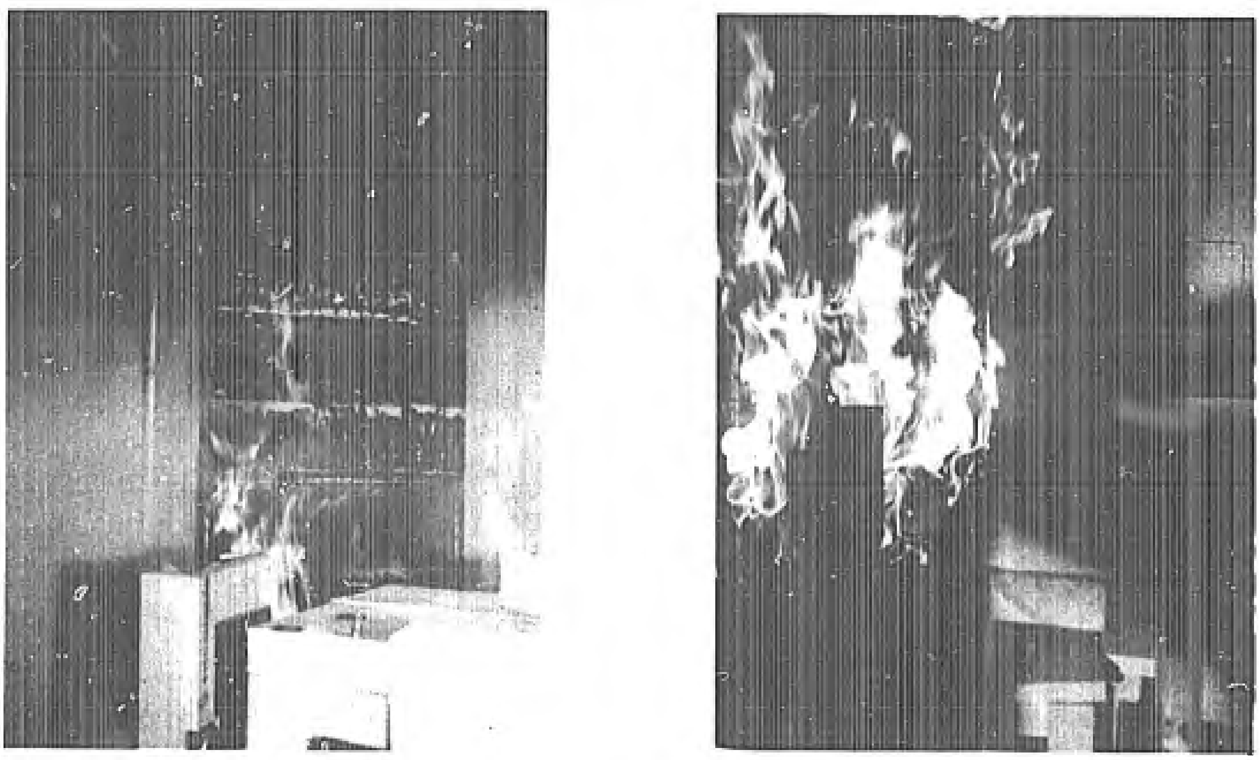


FIG. B-22 FIRE BUILDUP IN THE LEFT ROOM

FIG. B-23 FLASHOVER OF THE LEFT ROOM
(14 minutes after start of fire)

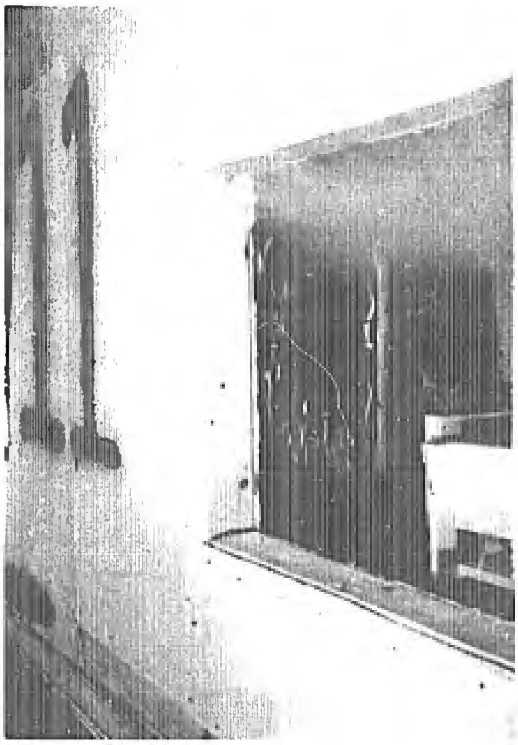


FIG. B-24 PAPER COVER ON THE PLASTERBOARD ON THE RIGHT SIDE BEGINS TO BURN
(56 minutes after start of fire)

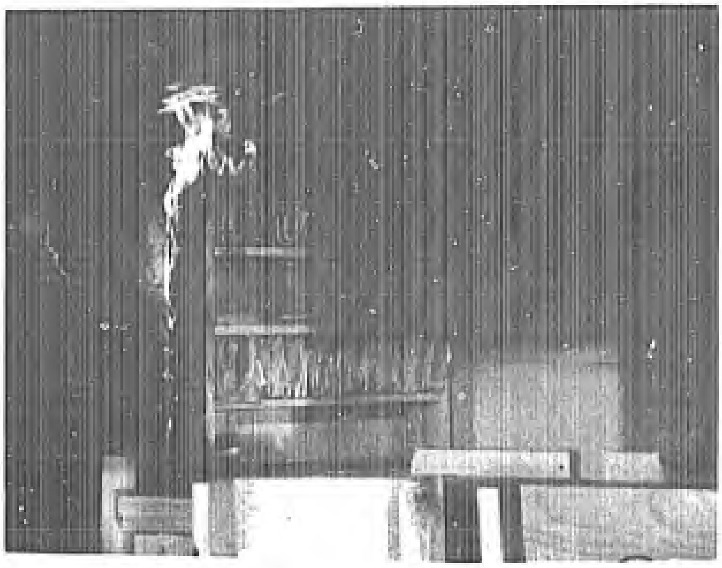


Fig. B-25 IGNITION OF BOOKCASE BY BURNING PLASTERBOARD PAPER

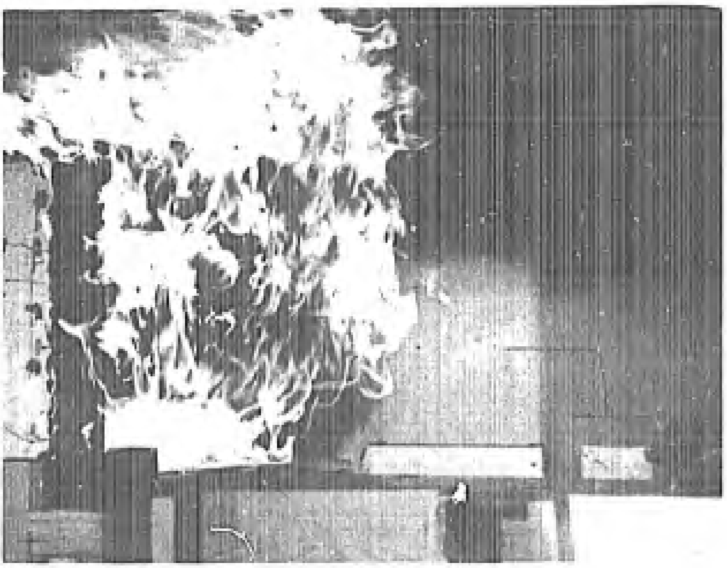


Fig. B-26 FIRE BUILDUP IN THE RIGHT ROOM

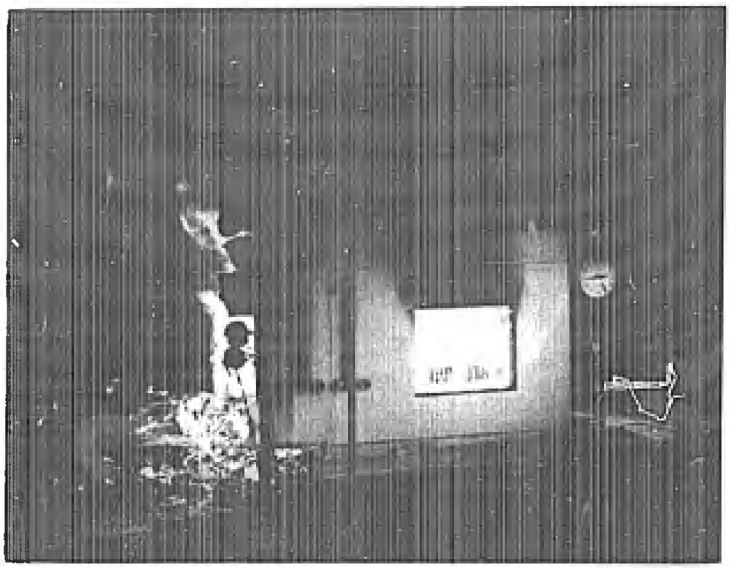


FIG. B-27 FLASHOVER OF THE RIGHT ROOM
(1 hr. and 25 min. after flashover of the left room)

BURN 12 - TWO ROOMS STACKED VERTICALLY, SEPARATED BY FINISHED FLOOR-CEILING CONSTRUCTION (1/2 IN. DRYWALL CEILING, 3/4 IN. PLYWOOD FLOOR). 1ST STORY WINDOW ON FRONT, 2ND STORY WINDOW ON SIDE, IGNITION ON 1ST STORY.

The none-alignment of the windows in this burn eliminated the possible fire spread by this path. It also served to make behavior of the 2nd story room more visible.

2:00 - 00	Ignition on first story.
2:10 - 20	Floor near bookcase catches fire, first story.
2:10 - 24	First story ceiling thermocouples at 1000°F.
2:10 - 55	False flashover on first story.
2:11 - 06	Mid-wall thermocouples at 1000°F, first story.
2:13 - 00	Flashover, first story.
2:13 - 48	Floor thermocouples at 1000°F, first story.
2:19 - 33	Bookcase on first story falls.
2:24 - 35	Ceiling drywall starts falling.
2:37 - 35	Flames break into second story.
2:39 - 10	Flashover, second story.
2:38 - 48	Ceiling thermocouples at 1000°F, second story.
2:39 - 12	Mid-wall thermocouples at 1000°F, second story.
2:39 - 42	Floor thermocouples at 1000°F, second story.
2:42 - 00	Second floor and furniture fall into first story room.

BURN 12A - SAME AS BURN 12 WITH WINDOWS ALIGNED

No significant contribution was added by flames from the 1st story radiating into the 2nd story room.

12:56 - 58	Ignition in first story.
1:10 - 12	Ceiling thermocouples at 1000°F, first story.
1:14 - 34	Mid-wall thermocouples at 1000°F, first story.
1:14 - 49	Flashover, first story.
1:15 - 10	Floor thermocouples at 1000°F, first story.
1:23 - 50	Table collapses on first story.
1:24 - 00	Bookcase falls, first story.
1:30 - 30	Ceiling drywall starts falling, first story.
1:33 - 50	Some ceiling joists fall, first story.
1:36 - 58	Ceiling thermocouples at 1000°F, second story.
1:37 - 58	Floor thermocouples at 1000°F, second story.
1:39 - 04	Mid-wall thermocouples at 1000°F, second story.
1:42 - 15	Flashover, second story.
1:46 - 00	Second floor and furniture fall into first story room.
1:52 - 45	Drywall on ceiling of second story starts falling.

BURN 13 - SAME AS BURN 12, IGNITION ON 2ND STORY

The mode of fire spread downward by the dropping of burning debris is clearly observable. Section V of the text should be consulted regarding the behavior of multi-layer flooring.

11:06 - 06	Ignition on second story.
11:19 - 52	Ceiling thermocouples at 1000°F, second story.
11:20 - 16	Floor thermocouples at 1000°F, second story.
11:20 - 25	Flashover, second story.
11:21 - 04	Mid-wall thermocouples at 1000°F, second story.
11:27 - 17	Bookcase collapses, second story.
11:34 - 30	Ceiling drywall starts falling, second story.
11:45 - 00	Ceiling drywall on first story shows charring of paper covering.
11:52 - 44	Ceiling of drywall on first story falls.
11:53 - 00	Table ignites, first story.
11:54 - 16	Ceiling thermocouples at 1000°F, first story.
11:55 - 52	Mid-wall thermocouples at 1000°F, first story.
11:55 - 30	Flashover, first story.
11:56 - 04	Floor thermocouples at 1000°F, first story.
11:58 - 20	Table and chairs fall, first story.
11:59 - 17	Roof collapses.
12:00 - 15	Bookcase falls, first story.

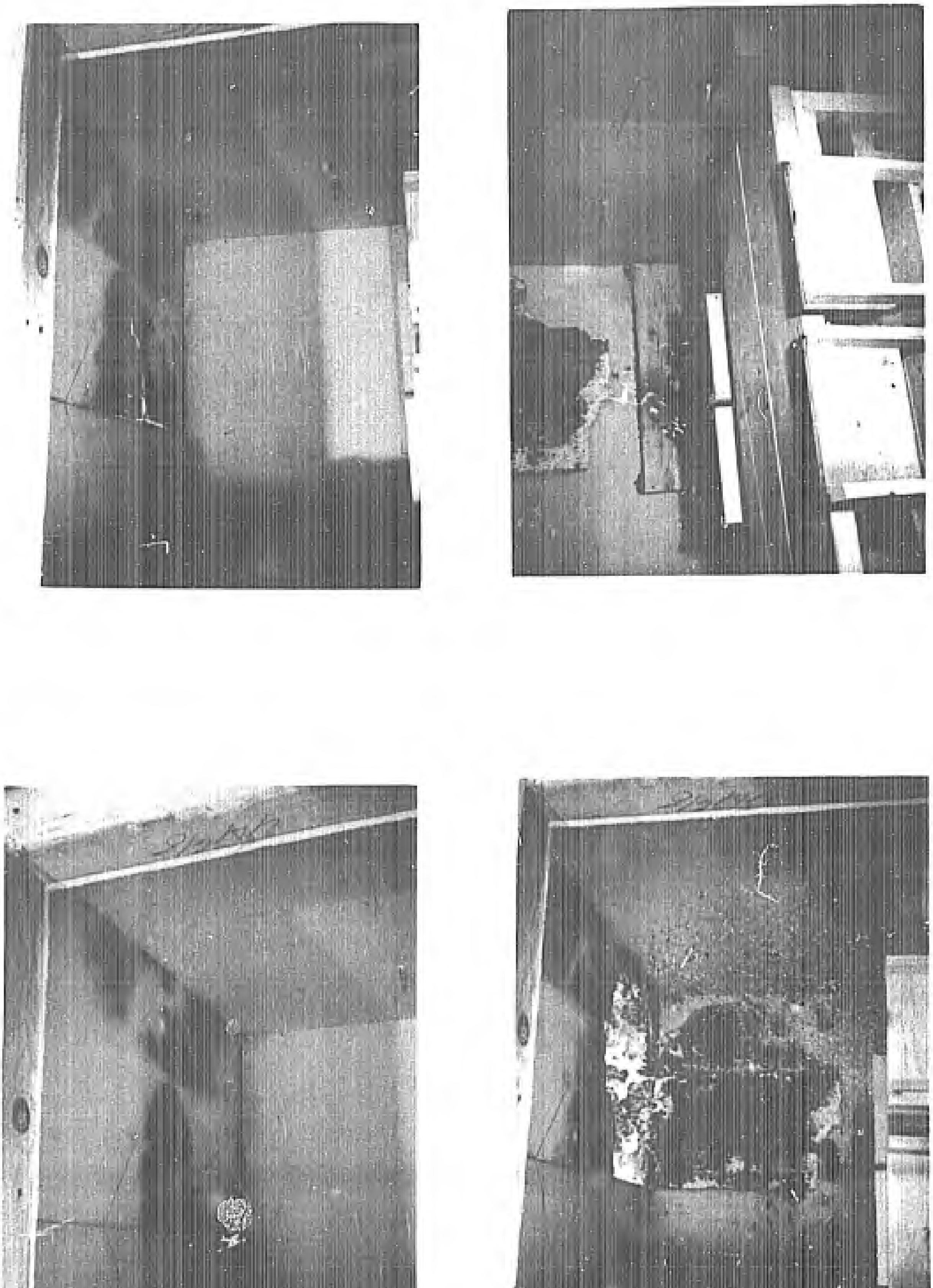


FIG. B-28 DOWNWARD SPREAD OF FIRE

BURN 14 - ARRANGED AS BURN 12, SEPARATING FLOOR HAD NO LOWER PROTECTION. IGNITION ON 1ST STORY

The floor-ceiling assembly resembled that which would be found separating a basement and a first story. The fire spread upward is appropriately faster than that of Burn 12 where such protection existed.

10:49 - 55	Ignition,first story.
10:55 - 13	Ceiling thermocouples at 1000°F, first story.
10:56 - 40	Flashover, first story.
10:57 - 00	Very dense smoke from first story.
10:57 - 19	Floor thermocouples at 1000°F, first story.
10:59 - 25	Mid-wall thermocouples at 1000°F, first story.
11:03 - 15	Front chairs fall, first story.
11:04 - 10	Table and rest of chairs fall, first story.
11:08 - 30	Bookcase falls, first story.
11:09 - 10	Flames penetrate floor to second story.
11:13 - 25	Ceiling thermocouples at 1000°F, second story.
11:13 - 43	Floor thermocouples at 1000°F, second story.
11:15 - 25	Mid-wall thermocouples at 1000°F, second story.
11:16 - 00	Floor collapses into first story.
11:34 - 00	Flames above roof.
11:35 - 00	Roof collapses.

BURN 14A - REPEAT OF BURN 14 WITH NO ROOF OVER 2ND STORY TO INCREASE PERIOD OF ACTIVE FLAMING ABOVE ROOF

As such, the flashover of the second story was not as distinct due to the open roof which permitted the hot gases to escape. The second story ceiling thermocouples, referred to below, were suspended at the appropriate locations as though the ceiling were present.

10:57 - 00	Ignition first story.
11:09 - 06	Ceiling thermocouples at 1000°F, first story.
11:09 - 25	Flashover, first story.
11:11 - 42	Floor thermocouples at 1000°F, first story.
11:12 - 30	Mid-wall thermocouples at 1000°F, first story.
11:19 - 50	Table collapses, first story.
11:23 - 30	Floor charring on second story.
11:26 - 05	Flashover, second story.
11:26 - 15	Floor thermocouples at 1000°F, second story.
11:26 - 18	Ceiling thermocouples at 1000°F, second story.
11:28 - 28	Floor collapses.
11:29 - 24	Mid-wall thermocouples at 1000°F, second story.
11:33 - 30	Drywall drops from left wall, first story.

BURN 15 - SAME AS BURN 14, IGNITED ON 2ND FLOOR

Fire spread downward was faster in this case than in Burn 13 (finished ceiling) as the restraint of the finished ceiling on falling brands was absent.

1:55 - 48	Ignition second story.
2:07 - 44	Ceiling thermocouples at 1000°F, second story.
2:07 - 45	Flashover, second story.
2:08 - 20	Floor thermocouples at 1000°F, second story.
2:08 - 32	Mid-wall thermocouples at 1000°F, second story.
2:14 - 30	Front chairs fall.
2:15 - 00	Smoke coming through door.
2:16 - 00	Table falls.
2:17 - 20	Bookcase falls.
2:18 - 15	Charring of underside of floor.
2:20 - 50	Debris falling from second to first through floor.
2:21 - 00	Couch burning, first story.
2:23 - 20	Ceiling thermocouples at 1000°F, first story.
2:23 - 25	Flashover, first story.
2:23 - 44	Mid-wall thermocouples at 1000°F, first story.
2:25 - 02	Floor thermocouples at 1000°F, first story.
2:26 - 15	Ceiling wallboard falling, second story.
2:28 - 35	Table falls on first story.
2:29 - 30	Bookcase collapses, first story.

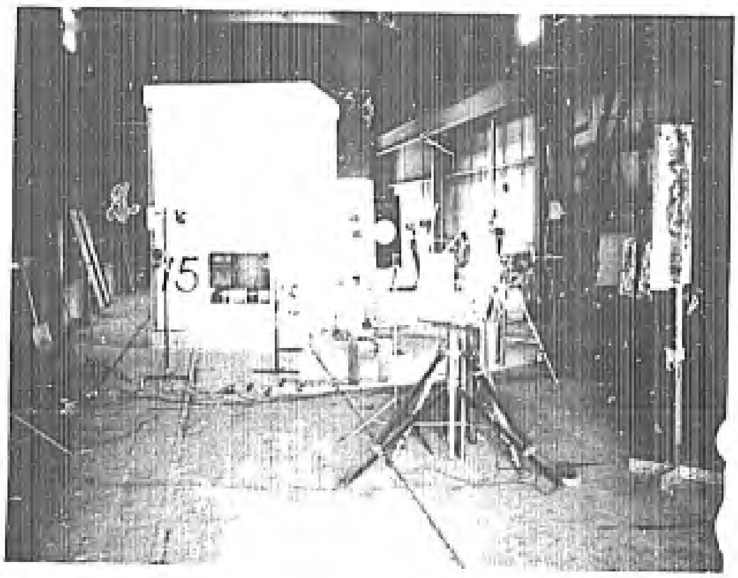


FIG. B-29 TWO STORY ASSEMBLY (1/2 sc.)
IGNITED ON SECOND STORY

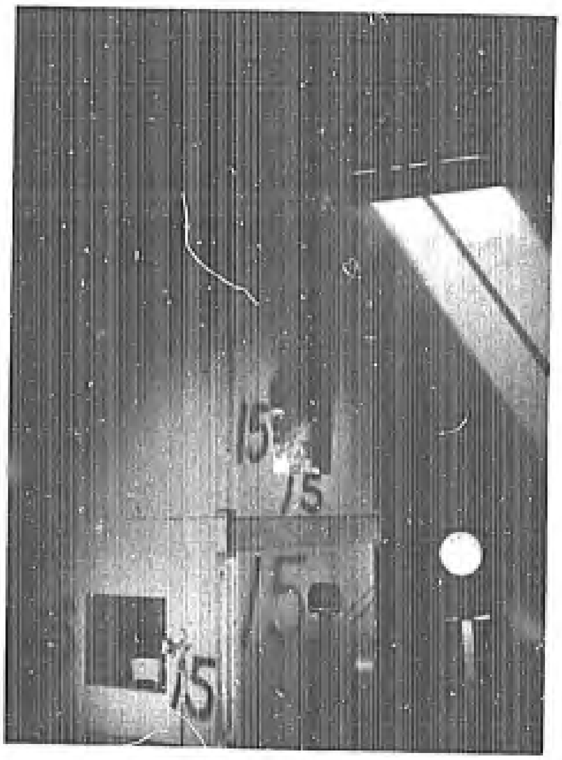


FIG. B-30 FLASHOVER OF THE SECOND STORY
(12 minutes after start of fire)

FIG. B-31 START OF FIRE PENETRATION TO THE FIRST STORY
(11 minutes after flashover of second story)

FIG. B-32 DEBRIS FALLING TO THE FIRST FLOOR

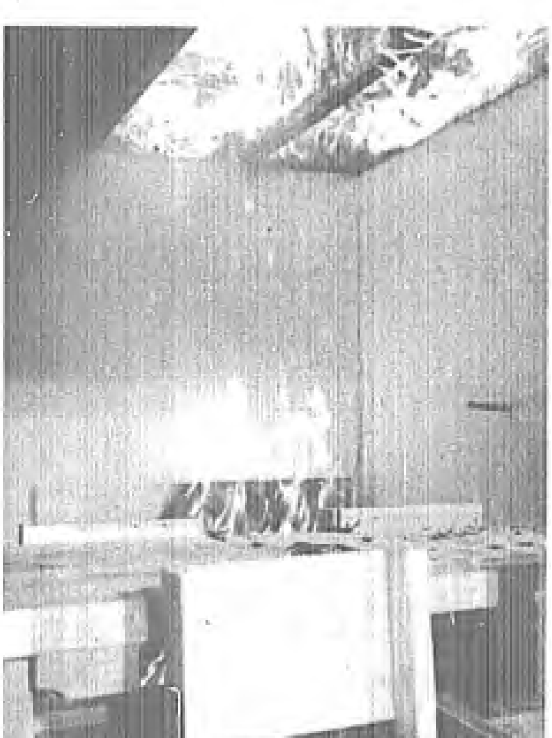


FIG. B-33 FIRST STORY FURNISHING BEGINS TO BURN

Fig. B-34 FLASHOVER OF THE FIRST FLOOR

Fig. B-35 FLOW OF FLAMES AFTER PARTIAL COLLAPSE OF FLOOR

BURN 16 - TWO ROOMS SEPARATED BY A CORRIDOR

The corridor (equivalent to a full scale 5 ft. wide by 12 ft. long) ended at each room in an open doorway. Temperatures given for corridor are those midway down the length.

2:03 - 18	Ignition, room 1 (right).
2:16 - 48	Ceiling thermocouples at 1000°F, room 1.
2:19 - 10	Flashover, room 1.
2:19 - 18	Mid-wall thermocouples at 1000°F, room 1.
2:19 - 18	Doorway thermocouples at 1000°F, room 1.
2:19 - 24	Floor thermocouples at 1000°F, room 1.
2:20 - 06	Ceiling in corridor at 1000°F.
2:21 - 06	Mid-wall in corridor at 1000°F.
2:21 - 36	Doorway to room 2 at 1000°F.
2:22 - 00	Flames entering room 2.
2:24 - 00	Ceiling thermocouples at 1000°F, room 2.
2:26 - 40	Door frame burning, room 2.
2:30 - 50	Flashover, room 2.
2:30 - 54	Mid-wall thermocouples at 1000°F, room 2.
2:31 - 30	Floor thermocouples at 1000°F, room 2.
2:37 - 30	Chairs fall, room 2.
2:38 - 23	Table falls, room 2.

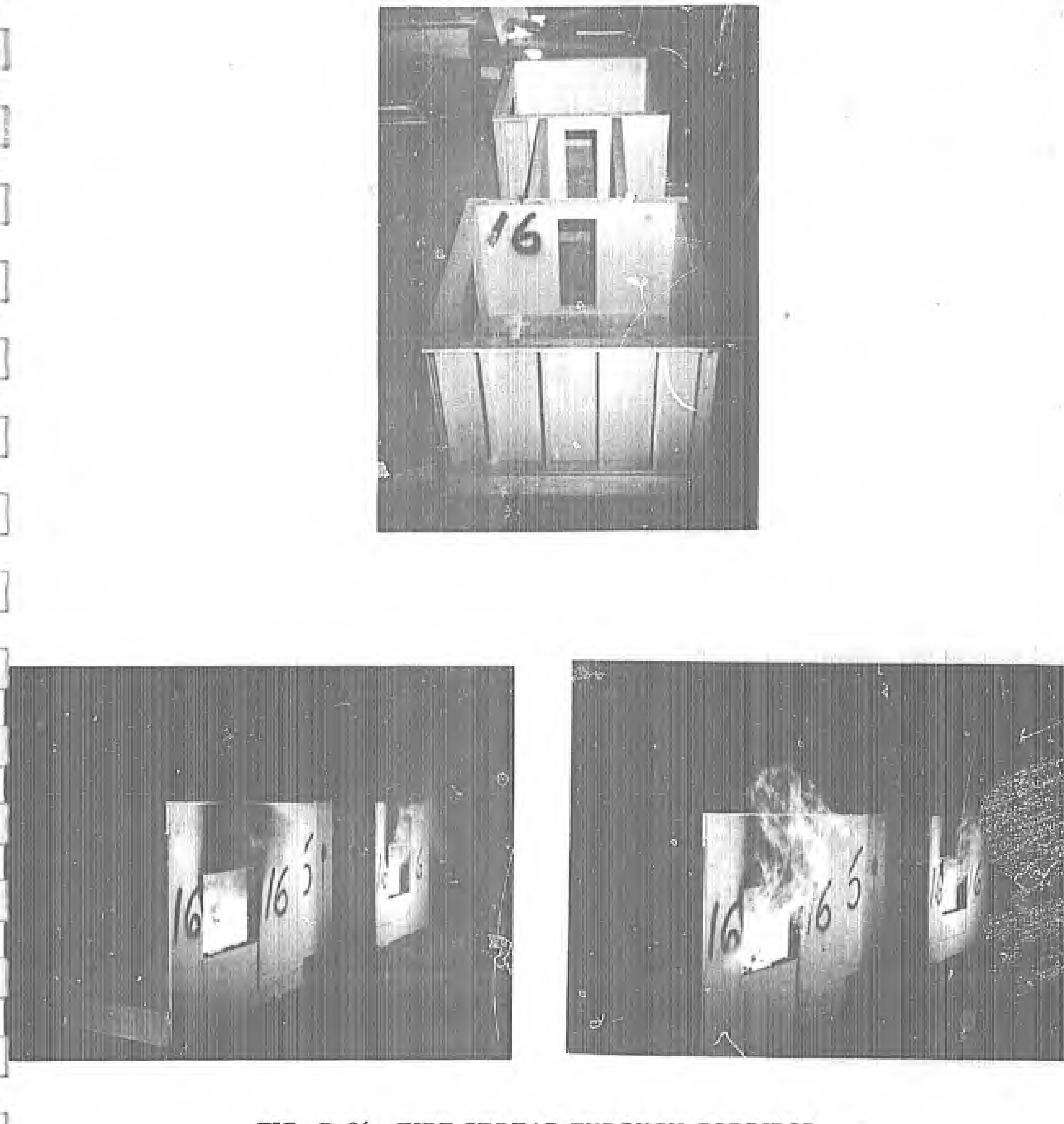


FIG. B-36 FIRE SPREAD THROUGH CORRIDOR

BURN 17 - TWO ROOMS STACKED VERTICALLY. TOTALLY ENCLOSED STAIRWELL ALONG ONE SIDE SEPARATED FROM EACH ROOM BY 1/4 IN. PLYWOOD DOOR. IGNITION ON FIRST STORY

The doors to the stairwell were offset so that flames from the first story did not directly impinge on second story door. The tightness of the stairwell was sufficient to retard fire spread by this path to the extent that the second story was first penetrated through the finished floor-ceiling construction.

2:57 - 00	Ignition, first story.
3:07 - 00	Ceiling thermocouples at 1000°F, first story.
3:10 - 20	Couch ignition, first story.
3:11 - 02	Flashover, first story.
3:12 - 24	Floor thermocouples at 1000°F, first story.
3:13 - 03	Mid-wall thermocouples at 1000°F, first story.
3:16 - 05	Burn through near top of door, first story.
3:18 - 18	Stairwell at 1000°F at first story level.
3:20 - 34	Bookcase falls, first story.
3:25 - 30	Ceiling drywall starts falling.
3:35 - 00	Burn through of floor.
3:36 - 06	Ceiling thermocouples at 1000°F, second story.
3:36 - 42	Floor thermocouples at 1000°F, second story.
3:37 - 00	Flashover, second story.
3:38 - 42	Stairwell at 1000°F at second story level
3:39 - 32	Mid-wall at 1000°F, second story.
3:40 - 15	Floor collapses.
3:44 - 33	Drywall falls from back wall, first story.

BURN 18 - REPEAT OF BURN 17, WINDOW ADDED TO STAIRWELL AT SECOND STORY LEVEL.

The rather unexpected behavior of Burn 17 was attributed to the gas tightness of the stairwell. Thus Burn 18 was made with a window at the second level of the stairwell. The window was equal in height to a room window and one-half the width of a room window. Since the prime information to be gathered was mode of fire spread, the roof and three walls of the second story room were omitted to increase the visibility of the door and floor.

11:24 - 21	Ignition, first story.
11:38 - 55	Floor in front of bookcase burns.
11:39 - 03	Ceiling thermocouples at 1000°F, first story.
11:39 - 22	Flames crawl along ceiling.
11:39 - 41	Mid-wall thermocouples at 1000°F, first story.
11:39 - 52	Flashover, first story.
11:42 - 09	Floor thermocouples at 1000°F, first story.
11:46 - 04	Stairwell thermocouples at 1000°F, even with top of first story.
11:47 - 21	Doorway thermocouples at 1000°F, first story, corridor side.
11:48 - 30	Door collapses at first story, flashover of stairwell.
11:49 - 45	Thermocouple above stairwell window at 1000°F.
11:49 - 51	Doorway thermocouples at 1000°F, second story, corridor side.
11:50 - 27	Top of stairwell at 1000°F.
11:52 - 05	Ceiling drywall dropping, first story.
11:53 - 18	Flames come through door on second story.
11:58 - 33	Floor thermocouples at 1000°F, second story.

BURN 29* - TWO ROOMS STACKED VERTICALLY, CONNECTED BY INTERNAL OPEN STAIRWELL. IGNITION ON FIRST STORY

This situation is commonly found in two story, single family residences and in small mercantile occupancies. No isolation of the stairwell opening from the compartments is made. The behavior of the model can be related to the behavior of that portion of a real situation near the stairwell in the case of large compartments. For the experiment, the area of the stairwell opening equalled that of a room window.

10:17 - 30	Ignition on first story.
10:29 - 33	Floor catches fire.
10:31 - 54	Ceiling thermocouples at 1000°F, first story.
10:32 - 42	Mid-wall thermocouples at 1000°F, first story.
10:33 - 12	Thermocouples in center of floor opening at 1000°F.
10:33 - 25	Simultaneous flashover of first and second stories, fire in second story then recedes somewhat.
10:33 - 36	Ceiling thermocouples at 1000°F, second story.
10:33 - 42	Floor thermocouples at 1000°F, first story.
10:33 - 48	Mid-wall thermocouples at 1000°F, second story.
10:34 - 04	Dense black smoke from second story.
10:35 - 00	Flames and very black smoke coming from second story.
10:35 - 17	Floor thermocouples at 1000°F, second story.

*Burns 19-28 were scheduled as 1/4 scale and, as such, were omitted. Original numbering system as shown in proposal has been retained where possible.

BURN 29 - (Continued)

10:42 - 07	Ceiling wallboard from first and second stories start falling.
10:44 - 40	Second story floor falls.
10:49 - 20	Drywall falling, first story right rear.
10:51 - 40	Drywall to left of windows on both stories pulling away from wall.
10:54 - 20	Outside drywall on second (left of window) drops.
10:55 - 10	Paper covering outer roof drywall catches fire.
10:58 - 20	Roof collapses.

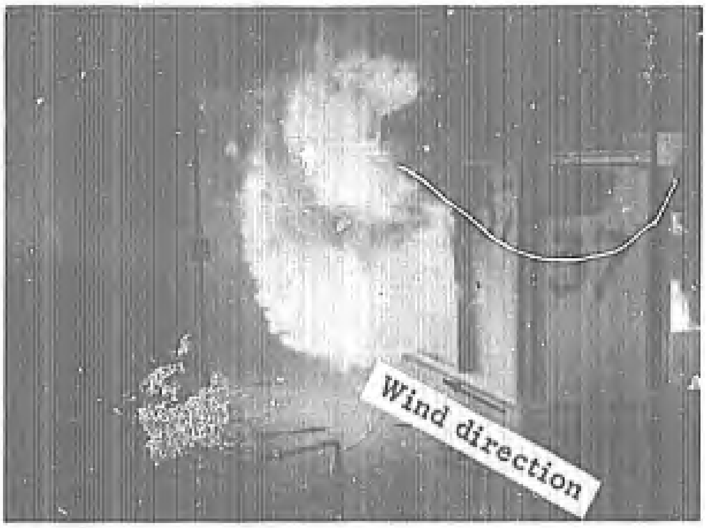
BURN 30 - SAME AS BURN 29, IGNITION ON SECOND STORY

The collapse of the bookcase on the second story prematurely dumped a significant amount of burning fuel into the first story and thus shortened the fire buildup time.

1:07 - 02	Ignition on second story.
1:19 - 14	Ceiling thermocouples at 1000°F, second story.
1:23 - 28	Flashover, second story.
1:23 - 40	Mid-wall thermocouples at 1000°F, second story.
1:23 - 44	Floor thermocouples at 1000°F, second story.
1:24 - 14	Thermocouple in center of floor opening at 1000°F.
1:25 - 50	Bookcase of second story falls dumping contents through opening into first story.
1:26 - 20	Thermocouples on ceiling of first story at 1000°F.
1:26 - 32	Thermocouples on floor of first story at 1000°F.
1:26 - 40	Mid-wall thermocouples at 1000°F, first story.
1:27 - 20	Flashover, first story.
1:27 - 50	Fire recedes, second story.
1:29 - 05	Flames reappear through second story window.
1:34 - 00	Ceiling drywall starts falling in second story.
1:35 - 25	Ceiling drywall starts falling in first story.
1:52 - 15	Roof covering collapses.

BURNS 31-40 - WIND EXPERIMENTS

This series of experiments was conducted on both one and two room structures. In order to reduce the total structure weight for burning rate measurements, most studding and all exterior covering was omitted. Ignitions were started in all rooms and winds of varying magnitude imposed only after flashover. As such the experiments are of interest only during the burning of the room contents and were halted upon significant wall or ceiling cracking which occurred at times slightly earlier than that for completely supported structures.



Single story, wind velocity 38 ft/sec

Two story, wind velocity 54 ft/sec in first story

FIG. B-37 TYPICAL WIND EXPERIMENTS

REFERENCES

1. Hird, D. and C. F. Fischl, "Fire Hazard of Internal Linings", National Building Studies, Special Report 22, London, 1954.

2. Bruce, H. D., "Experimental Dwelling-Room Fires", U. S. Department of Agriculture, Forest Service, No. D1941, June, 1953.

3. "Fire Research - 1960", Department of Scientific and Industrial Research and Fire Offices' Committee, Joint Fire Research Organization, London, 1961, p. 24.

4. Davey, N. and L. A. Ashton, "Investigations on Building Fires - Part V. Fire Tests on Structural Elements", National Building Studies Research Paper No. 12, London, 1953.

5. Webster, C. J. and L. A. Ashton, "Investigations on Building Fires - Part IV. Fire Resistance of Timber Doors", National Building Studies, Technical Paper No. 6, London, 1951.

6. Thomas, P. H., "Studies of Fires in Buildings Using Models", Research, February-March, 1959.

7. Thomas, P. H., "The Size of Flames from Natural Fires", Ninth Symposium (International) on Combustion, 1962, pp. 844 - 859.

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APPENDIX C

FIRE SPREAD FROM INTERIOR KINDLING FUELS

1. INTRODUCTION

The major cause of fire from a nuclear attack has been shown to be the ignition of kindling fuels by the thermal pulse of the weapon. This is particularly true with megaton weapons for which the area subject to thermal effects far exceeds that of significant blast overpressures. Although attention has been given to the critical ignition energy of various upholstery materials, most recently by Martin[1], little has been accomplished in assessing the behavior of interior furnishings concerning the time between their ignition and the flashover of the compartment in which they are contained. Since the heating effects from a burning compartment beome pronounced after the flashover, the accurate knowledge of this time is important for the prediction of fire spread within and between structures.

The studies of Hird and Fischl[2] were directed at determining the effect of wall and ceiling covering materials on the flashover time for a uniform ignition procedure involving a fiberboard chair and a thin veneered cupboard. In this manner, any variation in results due to fire origin was eliminated. This technique was followed in our own model-room studies where effects of room size and barrier fire resistances were being determined. Several experimental fires by Bruce[3] similarly used a single ignition procedure consisting of a small crib under a dining room chair which was in turn placed at a table. These fires evidenced a variation in buildup time due to variability of the chair fire buildup; however, the time elapsed between active burning of the chair (corresponding roughly to ignition of the table) until room flashover was quite consistent.

The study of interior kindling fuel was originally directed toward the determination of what furniture piece or group of pieces constitutes a major item of kindling fuel. Upon burning the first couch, it was immediately evident that the fire buildup in upholstered furniture was not that which might be anticipated from examination of the burning behavior of individual samples of the upholstery fabric or padding materials. In most cases, the fire would concentrate at joints where local reinforcement of fire on adjacent surfaces could take place. Surface spread of flames would occur only when radiant reinforcement of the flames at such a joint became significant. Usually there was little external fire activity until shortly before the entire item becam involved. Because of this, it was decided to examine the furniture items by placing them in a full scale room for burning. In this manner, the buildup of hot gases and smoke could also be noted giving a further indication of the progress toward flashover.

II. EXPERIMENTAL ROOM

The room constructed was 12 foot square with an 8 foot ceiling height. The interior surfaces of the walls and ceiling were 1/2 in. drywall, which was replaced when necessary in the course of the experimental series. Several burns were conducted with fresh drywall sheets for each fire; although the presence of the paper surface on the gypsum drywall sheets enhanced the flashover, its effect was quite negligible. Hence, no further replacement of the drywall was made except in positions where appreciable deterioration of the walls or ceiling was evident. The wall sections adjacent to the furniture items were most susceptible to deterioration and were replaced most frequently. A single window opening 48-in. high by 62-in. wide was built into one wall with the lower sill 2 ft. above the floor and one side 17-in. from the nearest corner. This window was left entirely open to provide a realistic situation since in areas subject to critical ignition energy levels, overpressures will be sufficient to break out the glass.

III. IGNITION PROCEDURE AND GENERAL FIRE BEHAVIOR

Although complete simulation of the thermal pulse from a nuclear weapon could not be achieved, an ignition technique was established to approximate the extent of burning that would exist over a major portion of an upholstered furniture item after an exposure to the thermal pulse. This consisted of wiping the exposed surfaces of the furniture item with a cloth dampened with JP-4 fuel. An equally successful alternative was to place cloth or paper damp with JP-4 fuel over the desired ignition area. In a number of cases, the floor immediately in front of the item was also covered with igniting cloths to simulate the simultaneous ignition of a rug (i. e., assuming thermal pulse exceeds the critical ignition energy of both rug and furniture covering). The result of this was a fire which burned actively over the ignited area for 15-30 seconds and then died down, leaving only those areas susceptible to sustained burning still aflame. These, in the case of the chairs and couches, were the joints between arms and backs, cushions and backs, lower cushion edge and front, etc. Even at these joints, depending on the item, the flaming varied from continuously active to little or no visible flame. In most cases, the flaming was negligible until very shortly before flashover, with the buildup coming from the interior of the item. Thus, the area of ignition was not too critical, as long as portions of the joints were involved. Most of the buildup time involved the penetration of the fire to the interior spring spaces after which the fire picked up quickly by rapidly filling these interior spaces. The exceptions to this behavior were items padded with foam rubber. These burned in the joints for only a short period, until the covering was consumed in these areas and the rubber ignited. After this time, the flames spread rapidly over all foam-padded areas, resulting in a slightly quicker room flashover than might have been obtained had the furniture contained other padding materials.

The buildup time for beds was generally shorter than that for chairs and couches. This was primarily due to the relatively rapid spread of flames around the perimeter of the bed (in sheets and bedding) followed by reinforcement at the head and footboards. Also, easy penetration of most mattresses and box springs through the lightly padded edges contributed to the rapid buildup. Exceptions were found, however, particularly for those mattresses having rather heavy cotton padding and few springs, so that the interior space was not very large.

For both living room and bedroom ignitions, the presence of a flaming rug occasionally enhanced the fire buildup. This would occur when the furniture frame was sufficiently high above the floor to allow exposure of the rug for some distance under the item. Upon ignition of this exposed rug area the flames would reach the under side of the furniture item and ignite the lower frame cover. This material was usually a light cotton which spread the fire across the lower surface of the entire furniture item and, in turn, ignited the burlap spring straps. Certain of the more combustible rugs further enhanced the fire by reinforcing the flames on the under side of the furniture, with both furniture item and rug continuing to burn actively well past the initial ignition period.

IV. RESULTS

Figures C-1 and C-2 and Tables C-1 and C-2 summarize all results obtained for flashover times. These include the specific experiments performed for the present program plus a number of results obtained in the course of experimental extinguishment studies for the Office of Civil Defense. As can be seen in Fig. C-1, the expected flashover time for living rooms is about 18 minutes. The use of 10 minutes is suggested for bedrooms.

A detailed account of each experiment, including room layouts (Figs. C-3 and C-4), is given in subsequent pages.

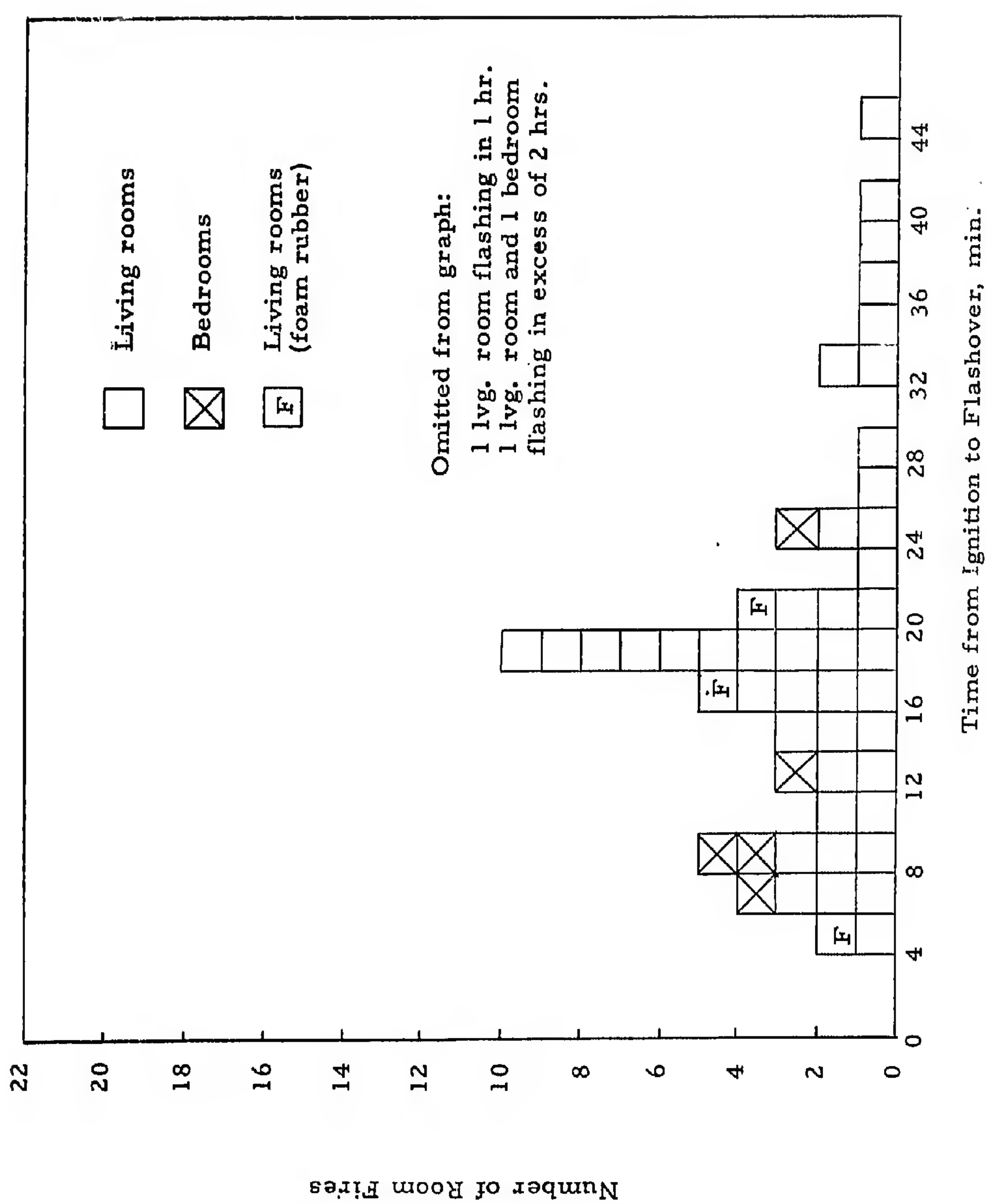


Fig. C-1 FREQUENCY OF FLASHOVER OCCURENCE

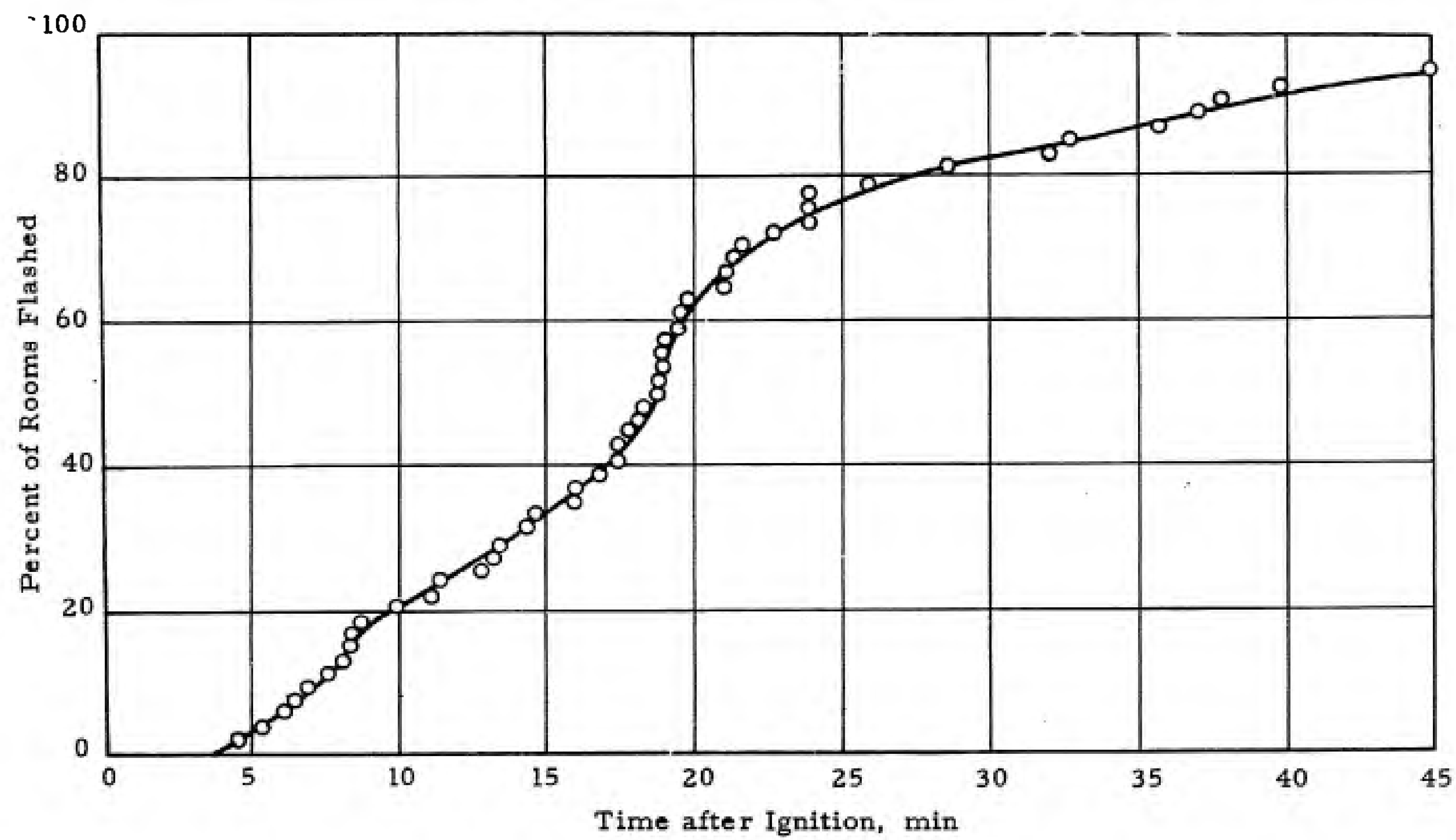


Fig. C-2 PERCENT OF ROOM FLASHOVERS AS A FUNCTION OF TIME AFTER IGNITION

Table C-1

SUMMARY OF IGNITION TO FLASHOVER EXPERIMENTS

No.	Time of Flashover	Time at Ignition	$\Delta\tau$ min-sec.	Portion Ignited*
2	11:42.40	11:23.51	18.49	1/3
3	2:43.45	2:24.12	19.33	1/3
4	4:32.08	4:16.18	15.50	1/2
5	2:28.18	2:13.56	14.22	1
6	4:47.43	4:02.35	45.08	**
7	11:39.20	11:03.30	35.50	1/3
8	2:18.00	1:45.05	32.55	2/3
9	4:34.50	3:56.50	38.00	***
10	2:08.00	1:42(avg)	26.00	+
11	11:12.15	10:53.10	19.05	1/3
12	3:58.00	3:33.54	24.06	++
13	11:10.40	11:02.26	8.14	1
14	3:11.54	2:50.43	21.11	1/3
15	10:46.59	10:29.29	17.30	1
16	2:05.57	1:28.48	37.10	1/3
17	4:23.58	4:09.17	14.41	1/3
18	1:29.51	1:10.09	19.42	1/3
19	4:18.43	3:46.29	32.14	+++
20	10:32.42	10:13.47	18.55	1/3

* Unless otherwise noted, the ignited item is a couch and the ignited area includes the arm-seat-back joint.
** Outer surface of one side of chair ignited.
*** Chair ignited.
\+ 2 of 3 chairs ignited.
++ 1/3 couch plus 1 of 2 chairs ignited.
+++ 1 of 4 chairs ignited (chair No. 2, Fig. C-3)

Table C-2

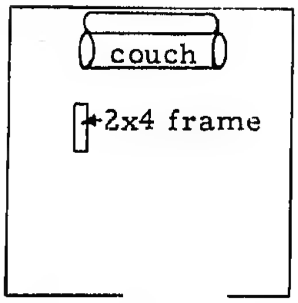
SUMMARY OF OCD EXTINGUISHMENT STUDIES

No.	Ignition to Flashover Time Min-Sec.	Ignited Item(s)	Wind
106	13^{15}	One side of bed	0
110	19^{45}	Chair	0
117	6^{30}	2/3 of couch	0
118	24^{00}	2/3 of couch	0
119	19^{00}	Chair and 1/3 of couch	0
120	22^{45}	2 chairs	0
121	13^{20}	2 chairs	0
127	40^{00}	Chair	0
E7	8^{39}	Couch	N. E. 15-20 mph
E8	16^{08}	Couch	N. E. 15-20 mph
E9	6^{10}	Couch	N. E. 5-10 mph
E10	8^{27}	Couch	N. E. 5-10 mph
E11	21^{19}	Couch, chair, rug	N. E. 5-10 mph
E12	6^{50}	Couch, chair, rug	N. E. 5-10 mph
E13	16^{50}	Foam rubber couch, chair, rug	N. E. 5-10 mph
E15	12^{55}	Couch	N. 5-10 mph
E16	18^{15}	Couch	N. E. 5-10 mph

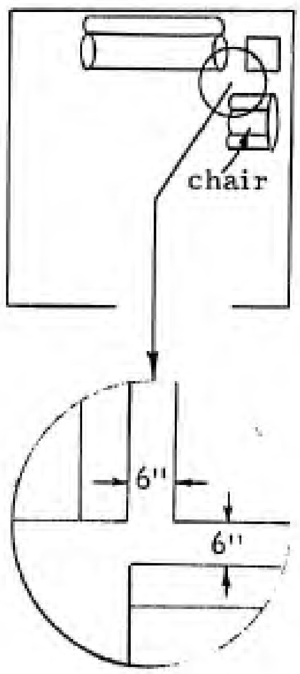
*Experiments 106-127 were conducted within the laboratory and as such had no wind effects. Experiments E7-E33 were conducted in an outside structure. The major wind effect was to dilute the smoke within the room thus slightly improving visibility.

Table C-2 (Continued)

No.	Ignition to Flashover Time Min-Sec.	Ignited Item(s)	Wind	
E17	11^{30}	Couch	N. E.	5-10 mph
E18	18^{58}	Couch	S. W.	4-6 mph
E19	28^{41}	Couch	S. W.	2-4 mph
E20	9^{58}	Bed	S.	2-4 mph
E21	11^{05}	Couch	S.	2-4 mph
E23	18^{25}	Couch	N. E.	2-4 mph
E24	7^{40}	Bed	N. E.	2-4 mph
E25	8^{15}	Bed (Hidabed in L. R.)	E.	4-8 mph
E26A	21^{44}	Foam rubber couch	E.	4-8 mph
E26B	21^{02}	Couch	E.	4-8 mph
E27	2 hours +	Couch	S. W.	2-4 mph
E28	5^{20}	Couch	S.	10-15 mph
E29	2 hours +	Bed (open springs)	S.	10-15 mph
E30	17^{50}	Couch	E.	4-8 mph
E31	4^{35}	Foam rubber couch	S. E.	4-8 mph
E32	24^{05}	Bed	S.	10-15 mph
E33	17^{20}	Couch	S. W.	10-15 mph

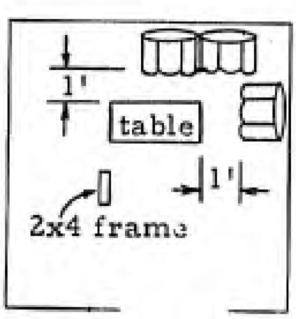


Couch burns nos. 2-5, non-combustible floor (2 x 4 frame consists of 2-upright 2 x 4's 40" high and 2 ft. apart with 3-2 x 4 horizontal members at 6", 24" and 40" above floor)



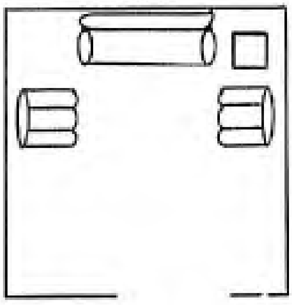
Couch burns nos. 6-9, 11, 14, 15, non-combustible floor. Nos. 16, 17, combustible floor (plywood) weekday newspaper on table (couch burn no. 9 - left one half of window blocked with drywall)
Couch burns nos. 18, 20 sectional sofas, no table, combustible floor

16" x 16" x 16" table
(3/4 ply)

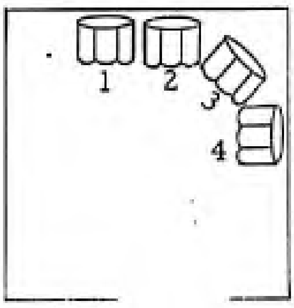


Couch burn no. 10, non-combustible floor, 3/4" plywood table 16" x 16" x 48", left-one half of window closed.

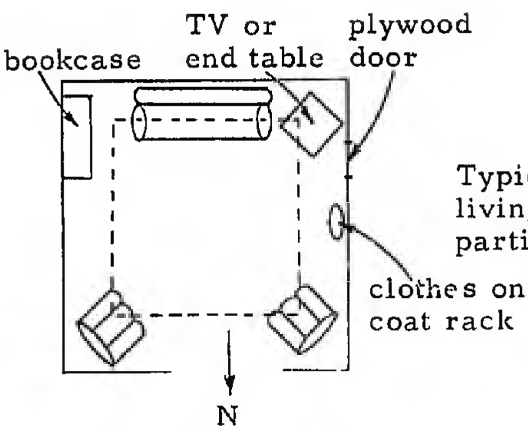
Fig. C-3 ROOM LAYOUTS



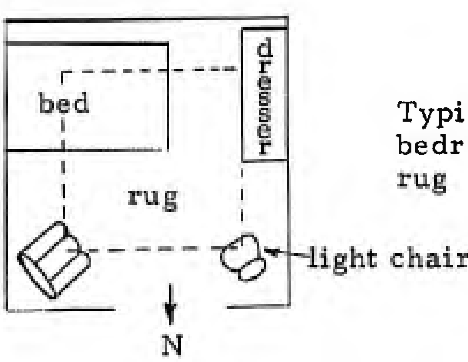
Couch burns nos. 12, 13, non-combustible floor, layout as no. 6 with additional chair, 1 lb. newspaper near right end of couch, 4 lb. newspaper on table.



Couch burn no. 19, combustible floor, 6'' between chairs 1 and 2, chairs 2, 3 and 4 touch at front corners.



Typical extinguishment study living room, plywood floor partially rug covered



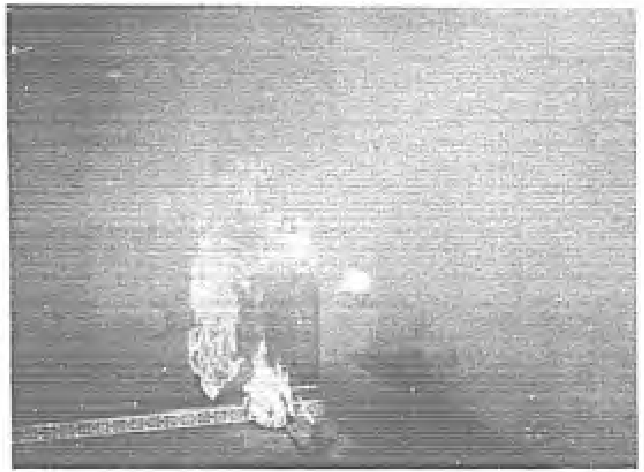
Typical extinguishment study bedroom, plywood floor with rug

Fig. C-4 ROOM LAYOUTS

V. SYNOPSIS OF FLASHOVER EXPERIMENTS

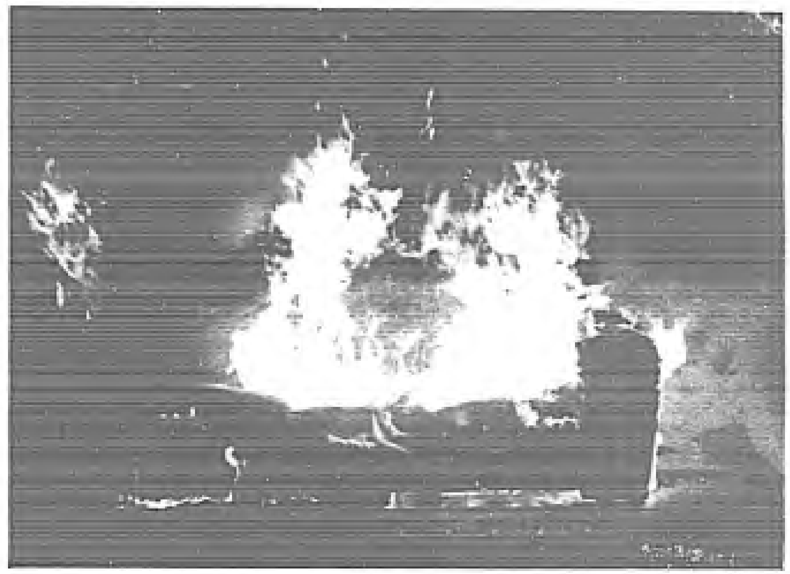
COUCH NO. 2

Fabric:	Cotton and wool blend
Padding:	Cotton batting backed with hemp
11:23.^{51}	Ignition. Right 1/3 of couch covered with paper, dampened with JP-4 and ignited.
11:24.^{02}	End of ignition.
	Flames continue in corner of seat-arm-back.
11:25 - 11:30	Gradual spread of charred area over right 1/3 of back rest.
11:32	Visible flames die out, smoke increasing.
11:35.^{12}	Flames from right arm of couch on both sides of arm.
	Gradual spread to cover right 1/3 of backrest-seat joint.
11:37	Flames visible under right 1/3 of couch
11:40.^{30}	Flame from left side of couch, apparently up the back side, reach 6-7 feet above ground.
	General build up from here until...
11:42.^{40}	Flashover.



Ignition

End of Ignition

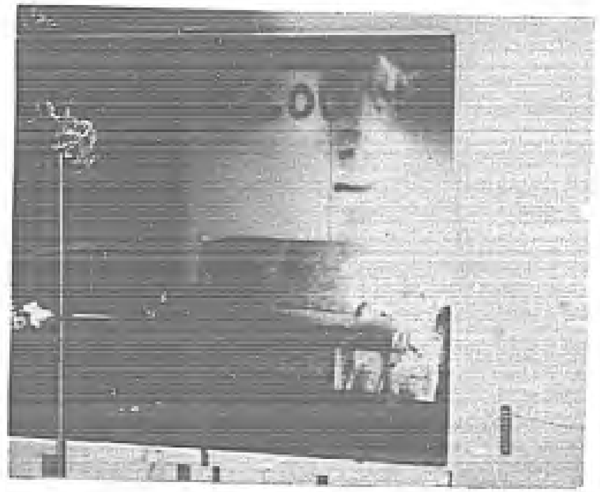


Near Flashover

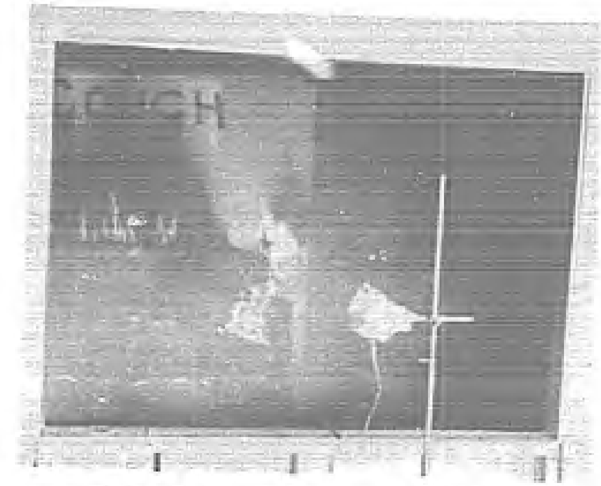
Fig. C-5 BURNING BEHAVIOR OF UPHOLSTERED FURNITURE

COUCH No. 3 (138 lbs)

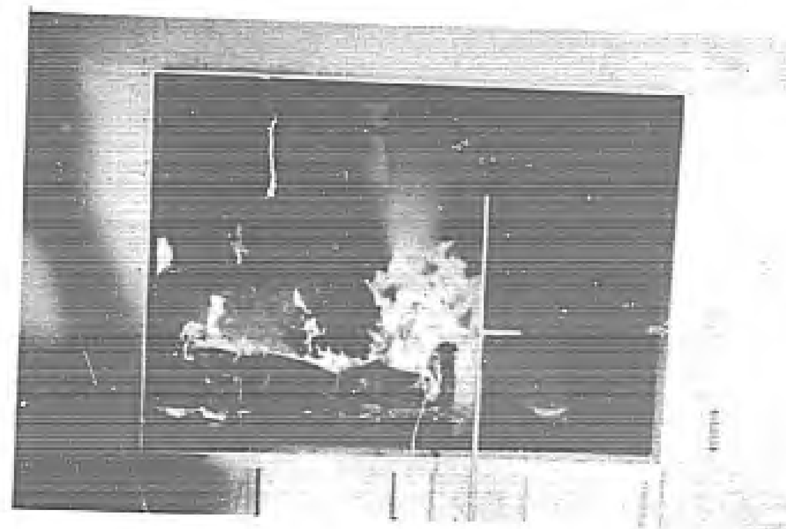
Fabric:	Cotton and rayon blend
Padding:	Cotton batting
2:24.^{12}	Ignition on right 1/3 of couch.
2:24.^{30}	End of ignition.
	Flaming sustained in right rear corner (back-seat-arm junction)
2:25.^{53}	Flames dying down, fire is working between cushion and arm (probably also cushion and back).
2:32.^{05}	Thick, black smoke from right side of couch.
2:34.^{56}	Heavy smoke in room.
2:36.^{50}	Occasional flame visible under couch.
2:37.^{40}	Continual flame visible under couch.
2:39.^{00}	Flames visible up rear of couch at right end.
2:39.^{15}	Flames up rear of couch 6 or 7 feet above floor.
2:39.^{23}	Flames from both ends of couch.
2:43.^{45}	Flashover.



Ignition



Flashover Minus 5 Minutes



Near Flashover

FIG. C-6 BURNING BEHAVIOR OF UPHOLSTERED FURNITURE

COUCH NO. 4 (160 lbs)

Fabric:	Rayon and wool pile on cotton backing
Padding:	Cotton batting backed with hemp
4:16.18	Ignition of right 1/2 of couch.
4:16.51	End of ignition.
4:21.43	Right arm of couch burning.
4:23.50	Right back of couch burning.
	Flames momentarily flare to 6 ft. above floor.
	Flames also visible under right end of couch.
4:24.05	All of back of couch burning.
	Flame peak traveled across rear some 4 feet high.
4:24.26	Very little flames present.
4:29.30	Flames now visible under right 1/2 of couch.
4:30.24	Right side of couch burning very well.
4:31.36	Left side of couch buildup.
4:32.08	Flashover.

COUCH NO. 5 (125 lbs)

Fabric:	Cotton and wool pile on cotton backing
Padding:	Cotton batting backed with cotton
2:13.56	Ignition of entire couch.
2:14.22	End of ignition. Burning sustained in both corners, (arm, seat, back).
2:15.35	Flames visible under right hand end of couch.
2:16.34	Dense smoke in room, no flames visible.
2:27.04	Flames coming from couch, (still dense smoke present).
2:28.18	Flashover.

COUCH NO. 6 (167 lbs)

CHAIR NO. 6 (73 lbs)

Couch:	Cotton and wool pile on cotton backing.
Chair:	Cotton and rayon pile on cotton backing.
3:46^{47}	Ignition on left 1/3 of couch.
3:47.^{40}	End of ignition.
4:02.^{35}	Couch apparently out. Chair ignited on one side.
4:04^{28}	End of chair ignition.
4:06.^{00}	Small amount of flames visible from behind chair above back.
4:10^{30}	Flames from back of chair in great quantity.
4:12.^{15}	Flames visible on right side of chair (ignition region) and build up over next few minutes.
4:17^{02}	Chair flames die down.
4:26.^{13}	Chair actively flaming again.
4:27.^{50}	Flames building up over back of chair.
4:31.^{15}	Entire chair aflame except left arm and side.
4:37.^{55}	End table-paper ignites.
4:39.^{48}	Right arm of couch catches fire
4:47.^{43}	Flashover.

COUCH NO. 7 (130 lbs)

CHAIR NO. 7 (60 lbs)

Couch fabric:	Cotton and acetate blend
Couch padding:	Cotton batting backed with hemp
Chair fabric:	Cotton and rayon blend
11:03.[30]	Ignition on left 1/3 of couch.
11:04.[48]	End of ignition. Left 1/3 of couch charred. Smoke filling top of room, no visible flames.
11:22.[20]	Very small flames on left side of center cushion of couch.
11:33.[08]	Thick smoke in room, right cushion burning on right side.
11:39.[20]	Room clears of smoke. Flames build up over entire couch and are shooting out from rear at ends. Flashover.

COUCH NO. 8 (143 lbs)

CHAIR NO. 8 (47 lbs)

Couch fabric:	Cotton, rayon and wool blend
Couch padding:	Cotton batting, hair
Chair fabric:	Wool pile on cotton backing
Chair padding:	Cotton batting
$1:41.^{40}$	Ignition of couch (left 2/3).
$1:42.^{00}$	End of ignition, 2/3 of couch appears scorched.
$1:45.^{05}$	Couch re-ignited. The first ignition was weak and did not result in any sustained burning.
$1:46.^{00}$	Ignition over.
$1:55.^{06}$	Flames from couch building up
$1:55.^{20}$ - $2:05.^{00}$	Left 1/3 of couch burning
$2:05.^{09}$	Flames coming from rear of couch ignite table.
$2:10.^{00}$	All of couch seat burning.
$2:18.^{00}$	Flashover.

COUCH NO. 9 (235 lbs)

CHAIR NO. 9 (53 lbs)

Couch fabric:	Cotton and wool pile on cotton backing
Couch padding:	Cotton batting, hair
Chair fabric:	Cotton
Chair padding:	Cotton batting backed with hemp
$3:46.^{45}$	Ignition of left 2/3 of couch.
$347.^{30}$	End of ignition. (Not much of couch burned).
$3:47.^{30}$ - $3:53.^{30}$	No flaming at all, not much evidence of burning.
$3:56.^{50}$	Chair ignited.
$3:58.^{30}$	End of ignition on chair.
$3:58.^{45}$	Dense smoke in room.
$4:13.^{05}$	Flames coming from chair.
$4:15.^{33}$	Flames from both ends of couch.
$4:29.^{16}$	Chair burning very well. Still dense smoke in room. (Present since $3:58.^{45}$).
$4:33.^{14}$	Couch starting to burn pretty well.
$4:34.^{50}$	Flashover, chair was cause of flashover, couch might have smouldered for hours without re-ignition from chair.

CHAIRS NO. 10 (from left to right 80, 98, 68 lbs)

Fabrics:	Cotton and wool blends
Paddings:	Cotton padding, hair
1:41.[25]	Ignition of left chair.
1:42.[30]	Ignition of center chair.
1:43.[56]	Smoke filling room. Very little flame visible on center chair, none on left.
2:03.[43]	Left and center chairs flaming. Thick smoke in room.
2:08.[00]	Flashover.

COUCH NO. 11 (176 lbs)

CHAIR NO. 11 (71 lbs)

Couch fabric:	Wool pile on cotton backing
Chair fabric:	Rayon pile on cotton backing
Paddings:	Cotton batting backed with hemp
10:53.[10]	Ignition of left 1/3 of couch.
10:55.[50]	End of ignition. Thick smoke filling room.
10:58.[50]	Room filled with smoke. Only flames visible are very small ones from bottom of couch at left side.
10:58.[59]	No flame visible because of thick smoke.
10:59.[45]	Flames at bottom of couch (right side). Flames not visible 7 seconds later.
11:01.[20]	Flames across the front bottom of couch.
11:02.[18]	Flames on right arm of couch. Thick smoke still present.
11:02.[47]	Very little flame visible.
11:06.[30]	Flames from center cushion of couch.
11:08.[35]	Large flames from center cushion.
11:08.[58]	Back of couch burning. Left cushion of couch burning.
11:11.[38]	Back of couch burning very well. Right cushion burning
11:12.[15]	Flashover

COUCH NO. 12 (125 lbs)

CHAIRS No. 12 (45 lbs left, 75 lbs right)

Couch and left chair fabric:
Wool pile on cotton backing

Couch and left chair padding:
Cotton batting backed with hemp

Right chair fabric:
Cotton and rayon pile on cotton backing

Right chair padding:
Cotton batting backed with hemp and cardboard

3:33.^{54}	Ignition of right 1/3 of couch, right chair and papers on end table.
3:36.^{03}	Right cushion of couch burning, end table burning, right chair cushion burning. Right 1/3 of couch charred. Smoke filling room.
3:41.^{55}	Room filled with smoke. Flames as before.
3:55.^{35}	Flames on left arm of couch. Room still filled with smoke.
3:56.^{15}	Flames from left rear of couch.
3:57.^{15}	Flames from entire rear of couch.
3:58.^{00}	Flashover.

COUCH NO. 13 (117 lbs)

CHAIRS No. 13 (69 lbs left, 79 lbs right)

Couch:	Wool pile, cotton backing, over cotton batting and hemp stuffing
Chair: (left)	Wool pile on cotton backing over cotton batting and hair stuffing
Chair: (right)	Cotton and rayon fabric over cotton batting and hair stuffing
11:02.^{26}	Ignition of entire couch.
11:03.^{25}	End of couch ignition, smoke filling room.
11:03.^{57}	Room filled with thick smoke. Very little flames on couch.
11:05.^{50}	Table burning.
11:06.^{35}	Arm on right chair ignites.
11:07.^{19}	Flames on couch building up. Smoke still present.
11:07.^{25}	Seat on left chair ignites.
11:08.^{12}	Couch burning very well.
11:10.^{40}	Flashover.

COUCH NO. 14 (153 lbs)

CHAIR NO. 14 (37 lbs)

Fabrics:	Cotton.
Couch padding:	Cotton batting, hair.
Chair padding:	Cotton batting.
$2:50.^{43}$	Ignition of left 1/3 of couch.
$2:53.^{25}$	End of ignition. Left 1/3 of couch charred.
$3:04.^{40}$	Flames on left side of couch.
	Smoke filling the room.
$3:08.^{52}$	End table burning.
	Smoke present but not too thick.
	Flames from back of couch and left cushion.
$3:11.^{08}$	Center and right cushions of couch burning.
$3:11.^{44}$	All of couch burning very actively.
$3:11.^{54}$	Flashover.

COUCH NO. 15 (115 lbs)

CHAIR No. 15 (73 lbs)

Couch fabric:	Rayon and acetate pile on cottong backing.
Couch padding:	Cotton batting, hair backed with hemp.
Chair fabric:	Cotton and rayon blend.
Chair padding:	Cotton batting, hair
10:29.[29]	Ignition of entire couch.
10:30.[43]	End of ignition. Smoke filling room Flames on seat of couch. All cushions of couch charred.
10:34.[48]	Room pretty well filled with smoke. Some flames from seat of couch.
10:35.[19]	Flames from behind left side of couch.
10:39.[20]	Flames from behind right side of couch. Flames from center cushion of couch.
10:44.[04]	Couch burning very well.
10:46.[59]	Flashover.

COUCH NO. 16 (162 lbs)

CHAIR NO. 16 (72 lbs)

Couch fabric:	Wool and rayon pile on cotton backing.
Couch padding:	Cotton batting, moss.
Chair fabric:	Wool pile on cotton backing.
Chair padding:	Cotton batting backed with hemp.
1:28.48	Ignition of left 1/3 of couch.
1:29.23	End of ignition. Left 1/3 of couch charred. Small flames from left cushion of couch.
1:32.04 - 1:56.02	Couch smoldering, smoke filling room.
1:56.02	Flames on left couch cushion. Only top of room now filled with smoke.
2:01.05	Flames from behind right side of couch. Not much smoke in room. Bottom left side of couch burning on the interior.
2:04.06	Left side of couch burning very well.
2:04.49	Center cushion of couch starts burning.
2:05.50	Back rest of chair and right side of couch burning. Bottom of couch burning on the interior.
2:05.57	Flashover.

COUCH NO. 17 (140 lbs)

CHAIR NO. 17 (47 lbs)

(Combustible Floor)

Couch fabric:	Cotton.
Couch padding:	Excelsior.
Chair fabric:	Cotton and rayon blend.
Chair padding:	Cotton batting.
4:09.17	Ignition of left 1/3 of couch.
4:10.01	End of ignition. Flames from left side of couch. Left 1/3 of couch charred. Smoke filling room.
4:16.35	Small flame on center cushion only. Top half of room filled with smoke.
4:17.20	Left half of couch charred. Small flames on center cushion.
4:20.43	Flame on center cushion growing. Smoke still at top of room.
4:23.35	Flames from behind couch.
4:23.58	Flashover.

SECTIONAL COUCH NO. 18 (320 lbs)

CHAIR NO. 18 (32 lbs)

(Combustible Floor)

Couch fabric:	Cotton and rayon fabric.
Chair fabric:	Cotton fabric over cotton underfabric.
Paddings:	Cotton batting, hair backed with hemp
1:10.09	Ignition on left 1/3 of couch.
1:11.54	End of ignition. Left 1/3 of couch charred. Flames from left couch cushion. Smoke in top half of room.
1:22.28	Small flames from left couch cushion. Smoke still in top half of room.
1:25.58	Flames on left side of couch building up. Smoke near bottom of room. Top of room has cleared quite a bit.
1:29.06	Center cushion of couch burning. Room fairly clear of smoke.
1:29.51	Flashover.

CHAIRS NO. 19

(From left to right - 60, 52, 75, 25 lbs)

(Combustible Floor)

Materials:	No. 1	(From left) Cotton mattlisse over cotton batting and hair
	No. 2	Cotton sailcloth over cotton waste and linters
	No. 3	Vinyl polymer over cotton batting
	No. 4	Cotton tapestry over cotton batting, covered with thin vinyl slip cover.
3:46.29		Ignition of Chair 2 and one corner of Chair 3.
3:47.27		End of ignition. Chairs 2 and 3 burning.
3:49.46		Cushion of Chair 2 burning very well.
3:52.16		Chair 2 burning only slightly. Small flame on Chair 3. Heavy smoke in room.
4:06.32		Chair 2 burning fairly well although fairly well consumed, smoke still heavy.
4:07.38		Right leg of Chair 1 catching fire. Chair 2 burning fairly well. Not much smoke in room.
4:10.11		Chair 3 catching fire. Not much left of Chair 2. Chair 1 burning in the bottom.
4:13.38		Chair 1 actively flaming. Chair 2 pretty well destroyed. Chair 3 hardly burning.
4:18.38		Chair 1 pretty well destroyed. Flames from behind Chair 3.
4:18.43		Flashover.

COUCH NO. 20 (125 lbs)

CHAIR NO. 20 (85 lbs)

(Combustible Floor)

Couch:	Cotton over cotton batting and sisal - very open weave
Chair:	Cotton, wool and rayon over cotton batting
10:13.47	Ignition of left 1/3 of couch.
10:15.24	End of ignition. Left 1/3 of couch charred.
	Couch burning on left side.
10:17.56	Not much flame on left side of couch.
	Smoke filling top half of room.
10:21.12	Flames from behind left side of couch.
	Heavy smoke on top half of room. No flames on cushions of couch.
10:23.57	Not much smoke in room
	Flames behind left 2/3 of couch.
	Left cushion burning slightly.
10:27.45	Left cushion and back rest burning pretty well.
	Flames still present from behind couch.
	Center cushion starting to burn.
10:32.01	Left 1/3 of couch flaming actively.
10:32.24	Flames cover center of couch.
10:32.42	Flashover.

REFERENCES

1. Martin, S. "On Predicting the Ignition Susceptibility of Typical Kindling Fuels by the Thermal Radiation from Nuclear Detonations", USNRDL-TR-367 AFSWP-1135, 21 April 1959.

2. Hird, D. and C. F. Fischl, "Fire Hazard of Internal Linings", National Building Studies, Special Report 22, London, 1954.

3. Bruce, H. D., "Experimental Dwelling-Room Fires", U. S. Dept. of Agriculture, Forest Service, No. D1941, June 1953.

APPENDIX D

FIRE SPREAD FROM EXTERIOR KINDLING FUELS

I. INTRODUCTION

The purpose of this series of experiments was to determine whether exterior kindling fuels, ignited by the thermal pulse from a nuclear burst, have the ability to ignite portions of structures such as wooden stairways, railings, or combustible siding. The distribution of these "transient" exterior fuels was indicated by Sauer et al[1] in 1953. At that time they stated "...the ratio of primary fires to primary ignition --- remains a critical gap in mass fire development research." To the best of our knowledge, the present study is the first attempt to fill this gap.

The structural items for study consisted of: (1) wall sections sheathed diagonally with 1 x 8 lumber and covered with either asphalt shingles, stained red cedar siding or painted red cedar siding, (2) four-step stairways constructed of 2 in. lumber, and (3) railings having both 2 in. and 1 in. lumber. Details of construction are shown in Figs. D-1, D-2 and D-3. In each case, the structural item was assembled, allowed to dry for several weeks, painted with house paint, porch and deck enamel, or stained and then placed outside to weather for several months (June, July and August). All items were then returned to inside storage for a further drying period of two months, after which the experiments were conducted. Moisture content ranged from 9 - 11 percent with few exceptions. No significant effect of moisture content was noted, even in those cases where it was as low as 6.5 percent or as high as 14 percent.

The kindling materials were loose paper (windblown into a pile), excelsior, or cribs in association with sufficient paper to cause their ignition.

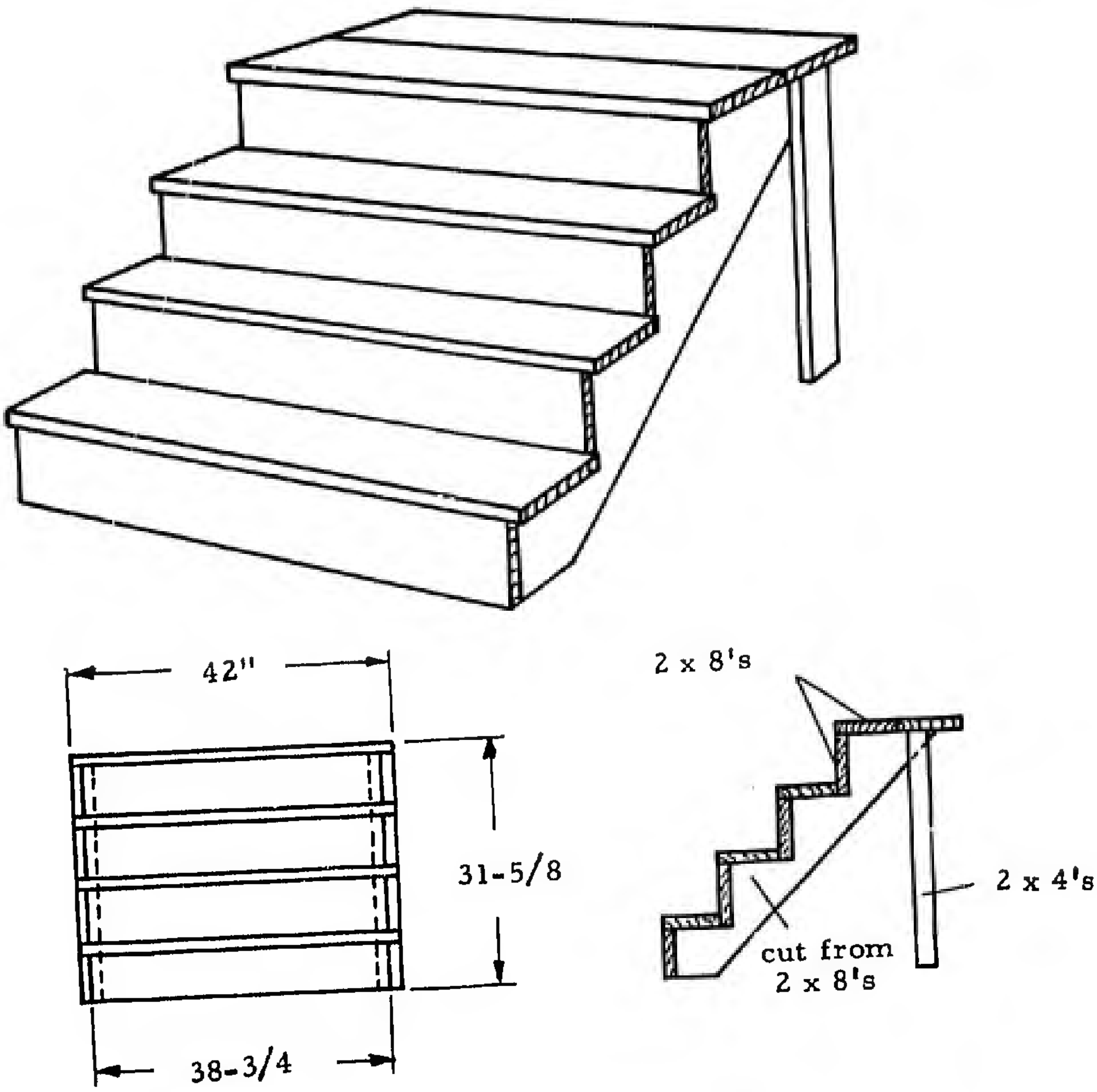


Fig. D-1 CONSTRUCTION DETAILS OF STAIRS

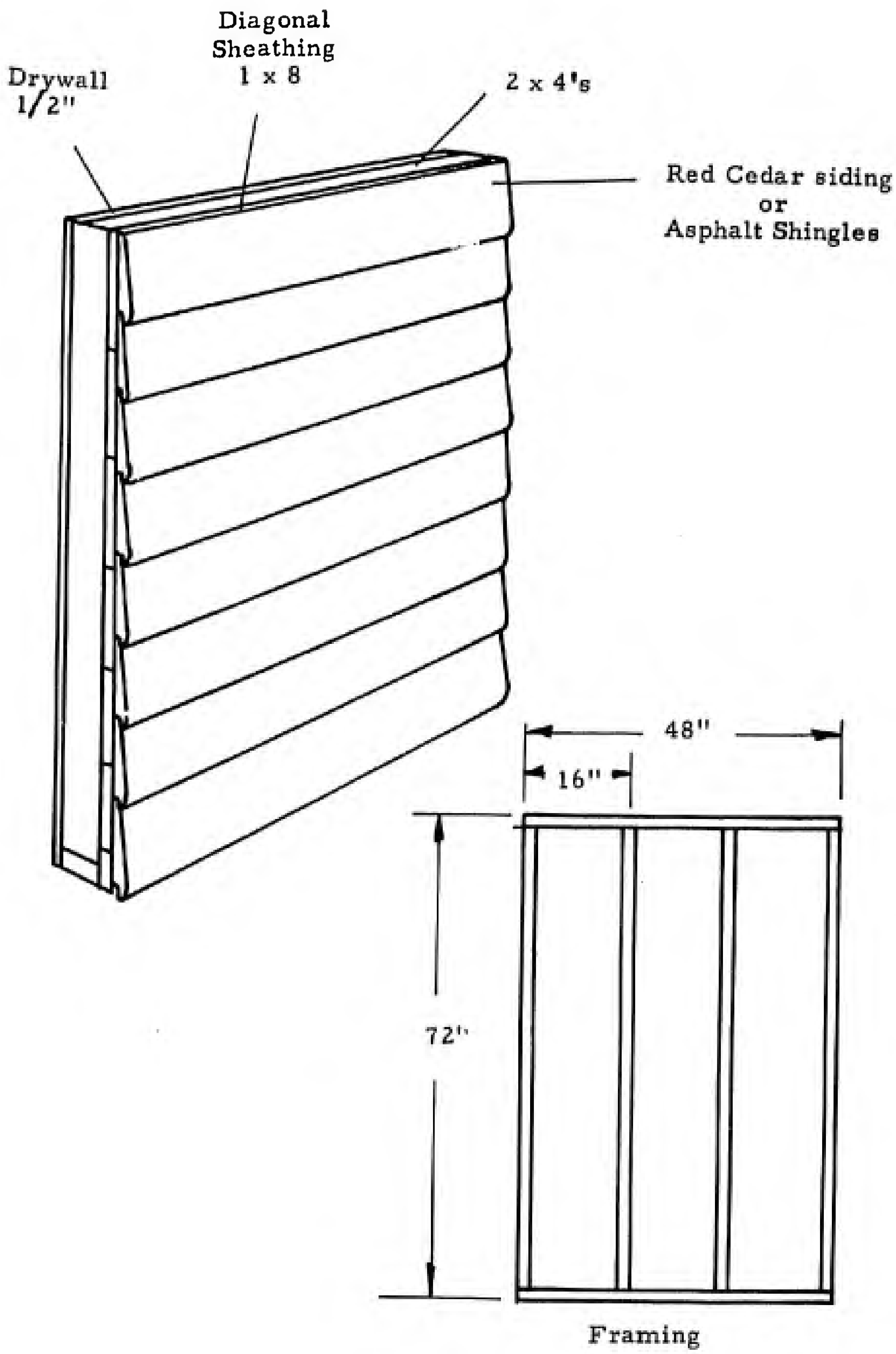


Fig. D-2 CONSTRUCTION DETAILS OF SIDING PANELS

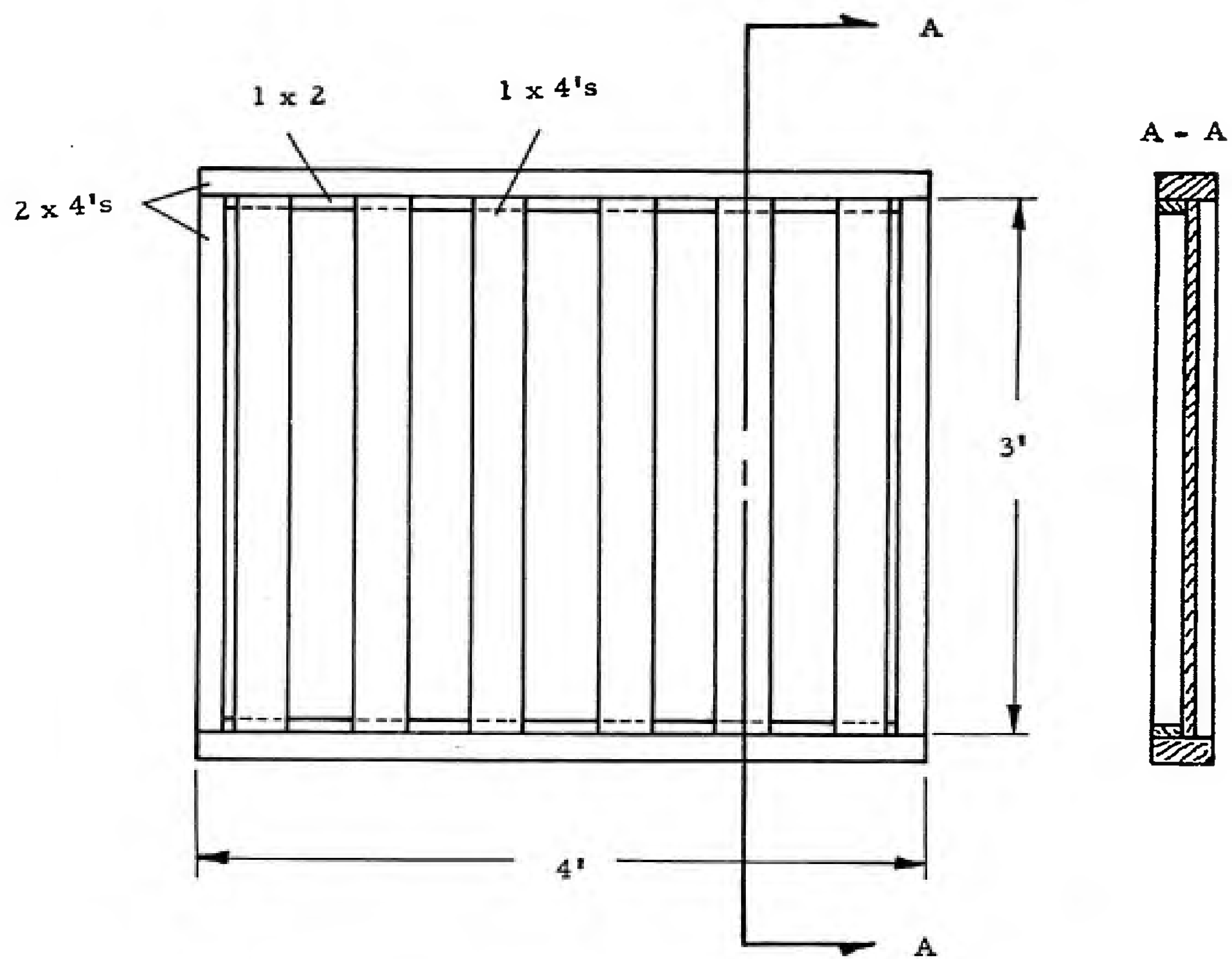


Fig. D-3 CONSTRUCTION DETAILS OF RAILING

Each structural situation is treated separately in the following sections.

II. WALL SECTIONS - WOOD SIDING

In these experiments, the wall panel under test was inserted as a section of a larger, non-combustible wall in order to eliminate any edge effects such as penetration of the fire between the siding and sheathing at the ends. The kindling material was placed against the base of the wall and ignited with the aid of a small amount of kerosene to cause sustained ignition over the entire kindling surface. Only under two situations was sustained burning of the wall panels accomplished. One situation was that where the wall sections had very loose siding (approximately 1/2 in. air gaps between siding boards and sheathing). This situation, in real practice, will normally be encountered in conjunction with rotting boards which have a good chance of sustaining ignition without the presence of the kindling fuel. The other was where coals left by the larger cribs (4 lb) were in intimate contact with the lower boards causing extended radiation reinforcement and penetration of the siding at this points. Thus, sustained burning occurred only when conditions permitted the mutual reinforcement of adjacent burning surfaces. This result held true for both painted and stained wall sections. As exterior siding rarely reaches the ground, radiant reinforcement of the wall section by the kindling fuel will not continue past the peak burning period of the kindling. In other words, items such as loose papers, grass and excelsior in conjunction with small amounts of wood are not capable of sustaining the combustion of walls covered with sound wood siding. Only when mixed with quantities of longer burning materials such as old tires, boxes etc., as might be found in rubbish piles, will they contribute to the over-all fire hazard. This does not contradict the results of the "house in the middle" tests in Nevada in 1953.[2] The Nevada house, tested with exterior kindling fuel, had weathered siding as well as a large accumulation of trash and a lattice-type lower wall.

For the case of well-preserved, well-maintained siding, one may estimate the trash pile required to guarantee sustained burning of such a wall by examining those cases where intimate contact between the wall and the coals of the igniting crib was maintained. The first of these is shown in Fig. D-4 where the ignition crib consisted of about 4 lb of 1 x 2 lumber. The radiometer record indicates that the peak fire was well over before penetration of the siding occurred (thermocouples were inside the wall). In all, some 25 minutes elapsed before sustained burning of the wall was established. Figure D-5 for a similar crib weight of 2 x 2 lumber shows a more sustained peak burning period (radiometer record) which is reflected in the fact that about 15 minutes were required to establish sustained burning of the wall section itself directly behind the crib. This time is representative of the minimum required, since a similar panel placed as a barrier to a fully developed room fire would require 10 minutes to penetrate the siding. Certainly the exterior situation is not nearly so severe. This is supported by the observation that the radiant intensity of the flames above windows may be represented by an emissivity of about 0.5, while the opening itself has an emissivity of close to 1.0.

Thus, in order to sustain ignition of a sound wood-sided wall, one of the two following conditions must be met:

1. The siding must drop below the level of the exterior kindling and the total duration of burning of the kindling must exceed 15 minutes.

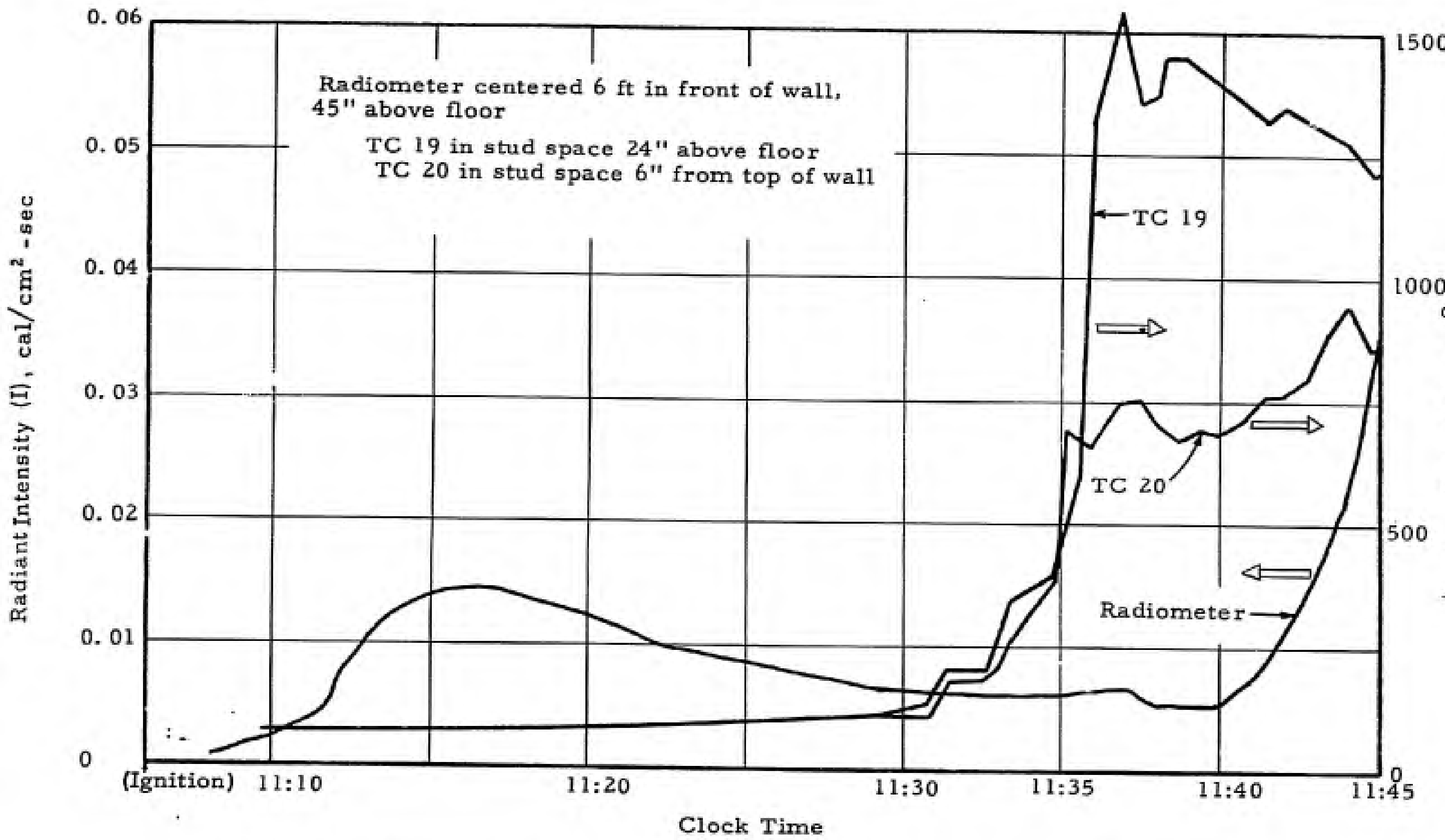


Fig. D-4 IGNITION OF A PAINTED EXTERIOR WALL BY A 4-LB CRIB OF 1 X 2 LUMBER (WALL 6)

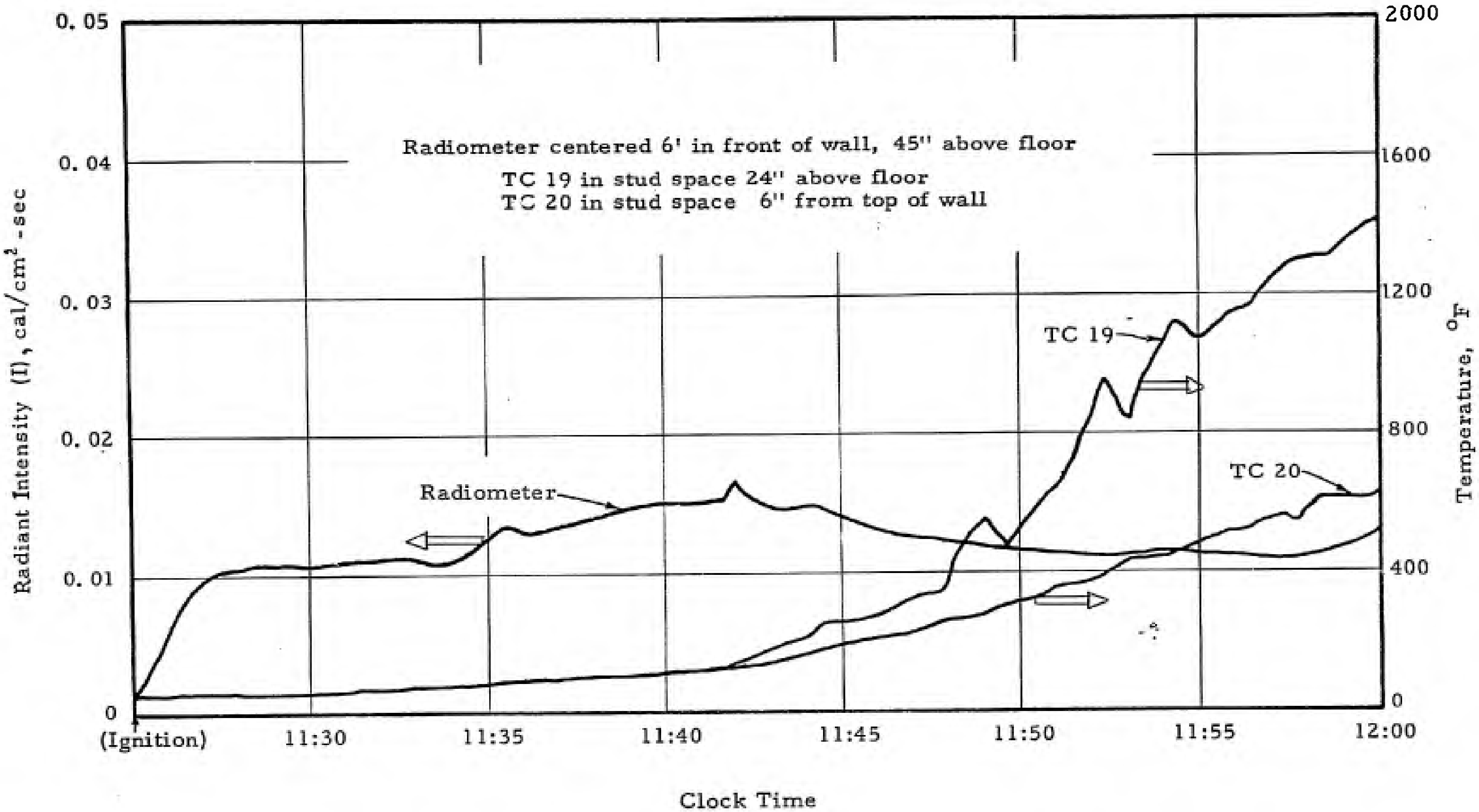


Fig. D-5 IGNITION OF A PAINTED EXTERIOR WALL BY A 4 LB CRIB OF 2 X 2 LUMBER (WALL 7)

2. The flames from the kindling must envelope a portion of the siding and the peak burning period of the kindling must exceed 15 minutes. This in all probability is most closely represented by the large trash piles rated as "10 ignition points" by Sauer[1]

III WALL SECTIONS - ASPHALT SHINGLE SIDING

These wall sections were inserted in a larger wall in the same manner as were the wood sided panels described before. In some of these cases, the wall was protected from direct contact with the kindling fuel by a small section of plasterboard placed between them. This was done since even relatively small amounts of kindling in direct contact with the wall produced sustained burning of the wall due to the fact that tar from the shingles ran onto the kindling and sustained its burning period. Even with the plaster-board in place, kindling fuels capable of producing flames high enough to irradiate the shingles caused sustained burning in about five minutes. Since the thermal pulse of a nuclear weapon would cause additional melting and run down of the tar, sustained burning in an attack situation would occur sooner (sustained burning occurs upon exposure of the of the shingle felt), and with less kindling fuel (5 sheets newspaper were sufficient without the pulse), since some of the dripping tar would burn in the kindling pile.

An additional effect of the asphalt shingled section was that it burned readily over the entire surface, radiating strongly to its surroundings. The difference in this respect between asphalt and wood sided sections is shown in Fig. D-6. Wood siding panels were burned in this manner (i.e. active over the entire surface) only by reinforcing the fire with other burning walls. Upon removal of the reinforcing wall, the fire died out completely as penetration had as yet not been achieved.

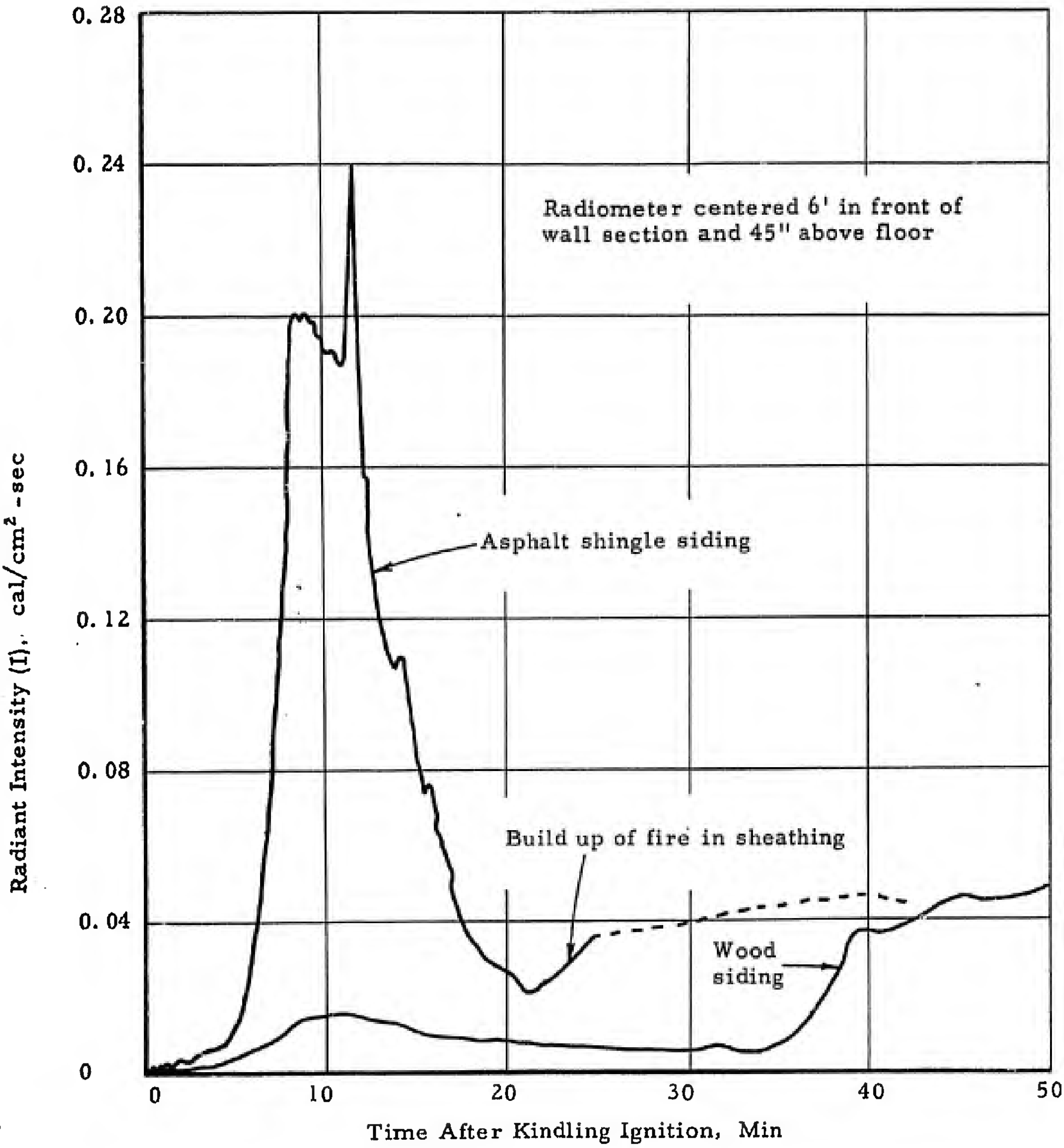


Fig. D-6 A COMPARISON OF RADIATION FROM A WOOD-SIDED WALL SECTION AND AN ASPHALT SHINGLED WALL SECTION

IV. WALL-RAIL COMBINATIONS

This experimental grouping consisted of a wood-sided wall placed as before with the addition of a railing section attached at 90° near one end of the wall section. The kindling fuel was placed at the base of the wall-rail juncture much as it might tend to accumulate in real situations. Two results of these experiments were:

1. The railing risers, if ignited, would not sustain combustion unless reinforcing radiation were supplied.
2. The wall-rail joint did not seem to be any more susceptible to sustained burning than was the plain wall. Apparently the gaps produced at the juncture were too small to permit adequate air to reach this potential reinforcing position.

V. STAIRWAYS

In each of the stairway experiments, the stairs were placed against a noncombustible wall. In the majority of the cases, they were placed so that a person ascending them moved parallel to the plane of the wall. In this position a full view of the underside of the stairway was possible. The kindling fuel was placed under the stairs as it might occur in reality due to being windblown, in the case of paper, or stored, in the case of cribbing, simulating a trash or rubbish collection. The results may be summarized as follows:

1. Stairs of well maintained, sound lumber are not ignited by reasonable amounts of windblown paper, although they show less resistance to this type of kindling than do the wall sections due to the corners and joints which reinforce the flames more readily.

2. Loose boards on stairs and open joints between boards are very susceptible to ignition. This case in real practice will correspond to poorly maintained stairs which may well be rotted and as such, susceptible to direct ignition by the thermal pulse.
3. Any rubbish or trash storage which combines kindling fuels with thicker more sustained burning materials will probably cause sustained burning of stairwells. The only compensating effect here is that the stairs do offer more shielding from the weapon to such items than do the walls.

VI SYNOPSIS OF EXPERIMENTS ON EXTERIOR KINDLING FUELS

WALL NUMBER 1 - PAINTED

Kindling Fuel: 18 pcs 1 x 1 - 6 in. (1 lb) crib (with sufficient paper and JP 4 to cause sustained crib ignition).

Results: No wind - no permanent ignition of wall. Flames exist as long as crib remains in position but die out immediately if crib is removed. At end of crib fire, wall flames die out permanently.

Summary of Film Record:

1:32^{11}	Ignition of crib at base of wall with a small amount of paper and JP 4.
1:32^{32}	JP and paper exhausted, crib barely burning.
1:33^{42}	Flames building up in crib.
1:34^{42}	Flames reach 1/3 of wall height.
1:36^{42}	Flames reach 1/2 of wall height..
1:39^{56}	Small flames at base of wall. Wall charred in the middle from bottom to 2/3 of height of wall.
1:57^{23}	Flames die out.
1:59^{51}	End of test. Damage to wall as above.

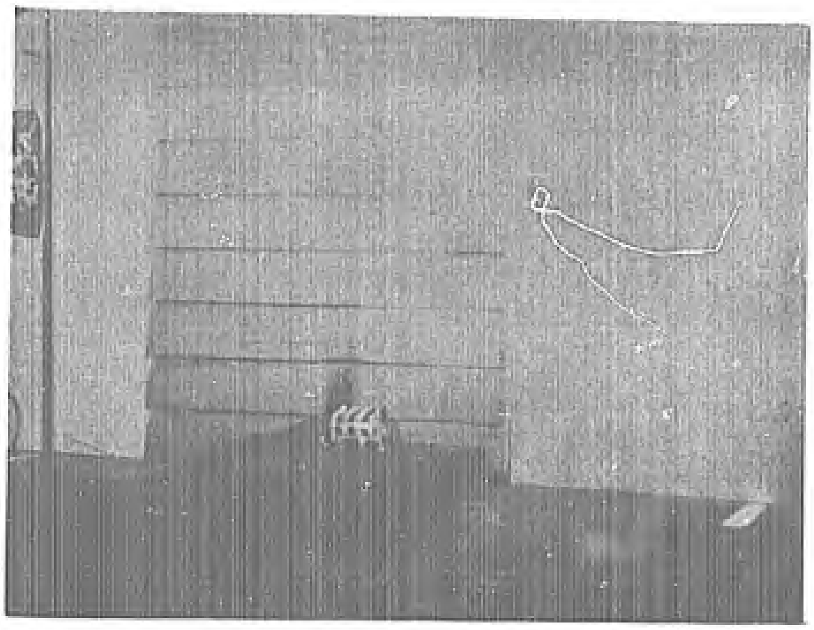


Fig. D-7 POSITION OF THE CRIB FIRE USED TO DETERMINE IGNITION PROBABILITY OF VARIOUS PANELS

WALL NUMBER 2 - PAINTED

Kindling Fuel:	18 pcs 1 x 1 - 6 in. (1 lb) crib.
Results:	Similar to wall No. 1, in this case 1 mph gusts of wind applied to wall about 15 percent of time during first 15 minutes, continuously for remainder of experiment.

Summary of Film Record:

11:03^{38}	Ignition of crib at base of wall.
11:04^{25}	JP 4 and paper exhausted.
11:04^{56}	Flames building up from crib.
11:05^{31}	Flames on wall up to 1/4 of height of wall.
11:07^{18}	Flames reach up 1/3 of wall height.
11:09^{53}	Flames dying down.
11:11^{23}	Very little flame present. Wall charred in the middle from bottom to about 1/2 of the wall height.
11:25^{13}	End of experiments, flames out, damage to wall same as before.

WALL NUMBER 3 - PAINTED

Kindling Fuel:	18 pcs 1 x 1 - 6 in. (1 lb) crib.
Results:	As before, no sustained burning - a 1 to 3 mph gusty wind (average velocity 1.5 mph) was directed at wall at an angle of 60° to the perpendicular.

Summary of Film Record:

$12{:}51^{30}$	Ignition of crib at base of wall.
$12{:}52^{16}$	JP 4 and paper exhausted, very little flame visible.
$12{:}53^{03}$	Small flames reached to 1/5 of wall height.
$12{:}54^{34}$	Flames up to 1/3 of wall height.
$12{:}59^{53}$	Not much flame present. Wall charred at middle from bottom up to 1/3 of wall height.
$1{:}01^{55}$	No flames present, damage as before.
$1{:}08^{04}$	No flames. End of experiment.

WALL NUMBER 4 - PAINTED

Kindling Fuel: 18 pcs 1 x 1 - 6 in. (1 lb) crib.

Results: No sustained burning. Wind steady 4 - 5 mph at 60° to perpendicular to wall face for first 13.5 minutes. On 50 percent of time for next 7.5 minutes, continuous after that time. The only way in which this size crib could sustain burning of the wall was with no wind until crib exhausted and then a very strong (4 - 5 mph continuous) from this point on.

Summary of Film Record:

$1{:}25^{24}$	Ignition of crib at base of wall.
$1{:}26^{10}$	Not much flame in crib.
$1{:}27^{39}$	Crib fire building up.
$1{:}28^{31}$	Flames up to 1/3 of wall height.
$1{:}33^{13}$	Not much flame present. Amount of char not distinguishable (Not more than 1/3 up the wall.) This is due to rapid fluctuation of flame which did not permit significant continuous charring of any one location.
$1{:}55^{00}$	No further damage, end of experiment.

WALL NUMBER 5 - PAINTED

Kindling Fuel:	Four pounds excelsior.
Results:	No sustained burning. Butted joint near top of wall burned for some time with aid of wind but finally ceased.

Summary of Film Record:

$4:00^{36}$	Excelsior ignited (pile covers entire bottom of wall, covering all of 2 bottom boards and part of third)
$4:01^{15}$	Flames from excelsior reaching above top of wall
$4:03^{36}$	End of ignition period. Middle of wall charred from bottom to top. At bottom of wall char is almost as wide as wall, and is quite deep. At top of wall char is 1/2 the width of wall. Draft reignites butted joint near top of wall.
$4:03^{36}$-$4:30^{00}$	Small flame continues at butted joint near top of wall, gradually burning hole in sheathing at this point.
$4:30^{00}$	Upon burn through of sheathing, flame dies out.
4:35	End of experiment. Damage to wall as before.

WALL NUMBER 6 - PAINTED

Kindling Fuel: 18 pcs 1 x 2 - 12 in. (4 lb) crib.

Results: Fire burned through wall behind crib and then spread up interior of panel. Wind 0.1 - 0.5 mph, average 0.25 - 0.3 mph.

Summary of Film Record:

$11{:}06^{00}$	Ignition of crib.
$11{:}21^{32}$	Paint burned completely off lower 1/5 of wall above crib. Char extends up to 1/2 of wall height. Not much flame present.
$11{:}35^{51}$	Smoke coming from sides of wall. Char as before. Very small flames at mid-height. Hole burned through center of bottom of wall (width = 1/2 width of wall; 1/5 wall height). This is directly behind starting crib.
$11{:}36^{28}$	Heavy smoke from top half of wall. Damage about same as before. Flames at mid-height of wall.
$11{:}40^{58}$	Flames on wall growing.
$11{:}41^{54}$	Flames at 2/3 of wall height. Thick smoke in front of wall.
$11{:}44^{05}$	Flames at top of wall. Char extends to top of wall (in middle section). Smoke still present.
$11{:}44^{10}$	Smoke cleared quite a bit. Flames from 1/3 of wall height to top of wall.
$11{:}44^{32}$	Thick smoke present again. Flames only reach up to 2/3 level. Holes in wall from bottom to half way up.
$11{:}46^{55}$	Flames reach to top of wall. Smoke still present. Holes from bottom to 2/3 level. Wall charred at center from bottom to top.

WALL NUMBER 6 - PAINTED (Continued)

$11{:}49^{41}$	Flames from 2/3 of wall height to top. Center 1/2 of wall burned away from bottom to 2/3 level.
$11{:}53^{10}$	Center of wall burned away from top to bottom. (one stud space)
$11{:}59^{21}$	Right side of wall burning 1/2 way up. Left side hardly touched (very little char present).
$11{:}59^{30}$	Right side of wall burning very well from mid-height to top. Left side hardly touched (some smoke from left side at 3/4 of wall height).
12:00	End of experiment. It can be noted here that each study space tends to burn as a separate and distinct unit.

WALL NUMBER 7 - PAINTED

Kindling Fuel: 18 pcs 2 x 2 - 6 in. (4 lb) crib

Results: Similar to wall No. 6 - the heavier crib material produced less flame height but resulted in a slightly longer burning crib. Thus less scorching of the face of the wall took place; however, the end result of penetration near the crib was the same.

Summary of Film Record:

$11:25^{30}$	Ignition of crib at base of wall.
$11:26^{30}$	Flames from crib reach halfway up wall. Center of wall charred from bottom to mid-height.
$11:28^{30}$	Bottom two boards of wall burning. Char reaches from bottom to middle of seventh board.
$11:42^{45}$	Partial collapse of crib.
$11:47^{23}$	Only flames present are near remains of crib. Paint burned off bottom three boards. Film record ends here, remainder of results from visual, thermocouple, and radiometer records (see Fig. D-5).

WALL NUMBER 8 - PAINTED

Kindling Fuel: Two pounds "windblown" newspaper including one small magazine (Woman's Day).

Results: No sustained burning, small area of penetration of siding (probably small crack in wood) near ground died out before penetrating sheathing.

Summary of Film Record:

$2{:}07^{55}$	Ignition of newspapers at bottom of wall.
$2{:}08^{27}$	Flames from newspapers reaching to top of wall.
2:10	Small flames from remains of newspapers. Triangular shaped char on wall from bottom to top. At bottom of wall char is almost as wide as wall.
$2{:}10^{45}$	Flames from remains of newspaper. Paint burned off most of bottom board.
$2{:}11^{20}$	No flame present. Small area burned through near bottom of lowest siding board. This penetration does not extend through sheathing board and is localized near magazine.

WALL NUMBER 9 - PAINTED

Scorched Over Entire Surface Prior to Test

Kindling Fuel: Three pounds windblown newspaper.

Results: Sustained burning when augmented by wind after kindling consumed. This rather large quantity of paper can be considered as near the critical amount although the presence of wind during the entire experiment would have reduced the severity of fire at any one point as shown in experiments No. 1 - 4.

Summary of Film Record:

$2:33^{50}$	Ignition of newspapers at base of wall(pile covers most of lower three boards).
$2:34^{13}$	Flames from newspapers reaching above top of w .
$2:36^{05}$	Small flames from remains of newspapers. Paint burned off much of bottom three boards.
$2:40^{50}$	No flames present. Small area of siding penetrated at bottom, at joint between 3rd and 4th boards, and 5th and 6th boards; still smouldering at these points.
$2:42^{10}$	Wall placed outside. (wind 1-5 mph).
$2:48^{08}$	Very small flames on wall.
$2:54^{05}$	No flames on wall. Heavy smoke coming from.wall.
$2:56^{50}$	No flames and very little smoke.
$3:04^{58}$	Small flames at middle of bottom and third boards.
$3:05 - 3:05^{18}$	Flames as before. Intermittant smoke from wall at various points.

$3:05^{20}$	Thick smoke from wall. Small flames from bottom, third, and fourth boards. (Wind holding at 5 mph.)
$3:05^{24}$	Flames from bottom and fourth boards. Smoke from top half of wall.
$3:07^{34}$	Flames as before. Bottom board nearly all consumed.
$3:12^{22}$	Flames from boards 1-5. Flames are small but larger than before. (Wind 3 - 8 mph.)
$3:17^{29}$	Flames from boards 4 and 5. Hole in center of wall from bottom to top of fourth board.
$3:21^{16}$	Hole up to top of sixth board. Flames on sixth board. Paper on back side of drywall bursts into flame.

WALL NUMBER 10 - STAINED

Kindling Fuel: 18 pcs 1 x 2 - 12 in. (4 lb) crib.

Results: Similar to wall No. 6 - no significant difference in behavior was noted between the stained and painted walls. Since in the nuclear attack situation the wall would be prescorched, any surface finish effect would be further reduced.

Summary of Film Record:

$4{:}30^{10}$	Ignition of crib at base of wall.
$4{:}32^{30}$	Flames from crib reaching halfway up wall.
$4{:}37^{53}$	Crib still burning well. Triangular shaped char on wall (from bottom to middle of seventh board). Char is half the width of wall at the bottom of the wall.
$4{:}39^{02}$	Small flames at middle of second and third boards. Crib still burning.
$4{:}40^{55}$	Small flames from crib. Smoke from bottom of wall.
$4{:}42^{17}$	Flames at center of second board.
$4{:}46^{13}$	No visible flames. Damage as before.
$4{:}50^{00}$	End of film. From logbook (visual) record - crib reinforces lower board and fire continues eventually building up in intensity. If siding not all way to ground there would be no sustained fire.

WALL NUMBER 11 - ASPHALT SHINGLES

Kindling Fuel:	18 pcs 1 x 2 - 12 in. (4 lb) crib.
Result:	Sustained burning. Rapid spread of flames across entire wall section. Much of shingle material drips to floor where it spreads while burning. Upon consumption of shingles, wall behaves much like wood siding and burns at a less active pace.

Summary of Film Record:

$10{:}18^{07}$	Crib ignited.
$10{:}23^{09}$	Flames from crib reaching above top of wall. Burning tar starts to spread across floor.
$10{:}23^{30}$	Flames from crib above top of wall. Flame width about half that of wall.
$10{:}24^{12}$	Right two-thirds of wall covered with flames. Flames reach way above top of wall.
$10{:}24^{56}$	Almost all of wall engulfed in flames.
$10{:}29^{53}$	Most of visible flames on left side of wall. All of shingles burned off of right side of wall.
$10{:}33^{25}$	All shingles burned off wall. Some flames from rubble at base of wall.

WALL NUMBER 12 - ASPHALT SHINGLE, LOWER 6" PROTECTED WITH DRYWALL

Kindling Fuel: 18 pcs 1 x 1 - 6 in. (1 lb) crib.

Results: Sustained burning - lowest unprotected shingle dripped asphalt until felt exposed.

Summary of Film Record:

$1:06^{32}$	Ignition of crib.
$1:09^{57}$	Flames from crib not very high. Never reached to more than 1/4 of wall height.
$1:11^{47}$	Flames as before. Some tar dripping from small area at bottom of wall. Crib removed.
$1:11^{54}$	Small flame on middle shingle of third row. Tar dripping from this area onto floor. Fire intensity increases until extinguished by smothering.

WALL NUMBER 12A: WALL NUMBER 12, LOWER 24" PROTECTED WITH DRYWALL

Kindling Fuel: 5 double sheets of newspaper.

Results: No sustained burning.

Summmary of Film Record:

$1:16^{23}$	2' high drywall placed against wall.
$1:17^{14}$	Newspaper at base of wall ignited.
$1:18^{26}$	End of ignition of newspaper. No visible damage to wall.

WALL NUMBER 12B: WALL NUMBER 12 EXPOSED TO FLAME UNTIL EDGES OF SEVERAL SHINGLES HAVE FELT SHOWING. LOWER 8" PROTECTED BY DRYWALL

Kindling Fuel: 5 double sheets newspaper.

Results: No sustained burning.

Summary of Film Record:

$1{:}35^{16}$ 8" high drywall placed at bottom of wall and under edge of 3rd row of shingles. Newspapers ignited.

$1{:}36^{23}$ End of burning of newspapers. Shingle tar melted slightly but no other damage to wall.

WALL NUMBER 12C: WALL 12B WITH KINDLING MOVED TO LEFT SIDE WHERE WALL WAS AS YET UNDAMAGED

Kindling Fuel: 10 double sheets windblown newspaper.

Results: No sustained burning.

Summary of Film Record:

$1{:}40^{23}$ Windblown newspaper ignited on left side of wall.

$1{:}41^{40}$ End of burning of newspaper. Few rows of shingles above drywall significantly melted. Some tar dripped but not enough to cause sustained fire.

WALL NUMBER 12D: WALL 12 B WITH KINDLING MOVED TO RIGHT SIDE (Undamaged)

Kindling Fuel: 10 double sheets newspaper folded for delivery.

Results: No sustained burning.

Summary of Film Record:

$1{:}50^{31}$	Flat folded newspaper ignited.
$1{:}54^{40}$	End of burning of newspaper. Shingles show melting part way up wall. Some tar dripped.

WALL NUMBER 12E: WALL 12 SPRAYED WITH JP4 AND IGNITED

Results: Flamed actively about 1/2 minute. Vertical wall permitted rapid runoff of melted tar thus exposing shingle felt. It is therefore believed that large yield weapons (pulse duration ~20 sec) plus presence of small amounts of kindling will cause sustained burning of this type wall.

Summary of Film Record:

$2{:}04^{04}$	Wall ignited.
$2{:}04^{30}$	End of ignition. Some small flames on wall yet.
$2{:}04^{40}$	3 shingles burning, one each in 11th, 13th and 14th rows. Wall pretty well blackened (tar melt).
$2{:}12^{43}$	Flame on 2nd shingle of 14th row is gradually growing (near center of wall).
$2{:}19^{41}$	Flames to right (11th row) and left (13th row) of wall increasing.
$2{:}22^{49}$	Top of wall burning very well.

WALL NUMBER 13 - ASPHALT SHINGLE, LOWER 8" COVERED WITH DRYWALL (Placed under 3rd row of shingles so that tar can drip on kindling)

Kindling Fuel: 1 lb. newspaper folded as delivered (flat).

Results: No sustained burning.

Summary of Film Record:

$3{:}28^{08}$	Ignition of flat folded newspaper placed to left of center of wall.
$3{:}30^{28}$	End of burning of newspaper. Some shingles on left side of wall above newspaper are slightly melted. Insufficient tar dripped on kindling to sustain fire.

WALL NUMBER 13A: WALL 13

Kindling Fuel: 1 lb. windblown papers placed below undamaged portion of wall.

Results: No sustained burning.

Summary of Film Record:

$3{:}40^{23}$	Windblown newspapers ignited.
$3{:}41^{40}$	End of burning of newspaper. Several shingles near center of wall slightly melted.

WALL NUMBER 13B: WALL 13, DRYWALL REMOVED FROM BASE OF WALL

Kindling Fuel: 1 lb. windblown newspapers.

Results: Sustained burning just barely achieved at previously damaged point. This further confirms that the combined effect of thermal pulse and kindling would cause sustained burning.

Summary of Film Record:

$3{:}48^{06}$	Windblown newspaper ignited.
$3{:}49^{23}$	End of peak flaming of newspaper. More of shingles show damage.
$3{:}50^{35}$	Small flame on lowest previously damaged shingle. Flame is growing gradually.
$3{:}54^{17}$	Flame now reaches half way up wall but is barely as wide as one shingle.
$3{:}57^{36}$	Flame covers one half of wall and reaches above top of wall.
$4{:}02^{38}$	2/3 of wall burning. End of film.

WALL NUMBER 14 - ASPHALT SHINGLE

Kindling Fuel: 1/2 lb. excelsior.

Results: Sustained burning - one shingle directly behind excelsior ignited.

Summary of Film Record:

$4{:}45^{43}$	Ignition of excelsior at base of wall.
$4{:}46^{55}$	End of active kindling flaming. One shingle directly behind excelsior is burning. Fire extinguishment by smothering.

WALL NUMBER 14A - WALL 14, DAMAGED PORTION COVERED BY PLACING "8" HIGH DRYWALL UNDER EDGE OF 3RD ROW OF SHINGLES

Kindling Fuel: 2 lb. excelsior.

Results: Sustained burning.

Summary of Film Record:

$4{:}51^{30}$	Excelsior ignited.
$4{:}52^{30}$	Excelsior actively burning flames about 1/2 wall height.
$4{:}54^{00}$	Active flames from wall reinforced by kindling fire.
$4{:}55^{00}$	Burning increases, tar running down wall, end of film.

WALL NUMBER 15 - PAINTED, LOOSE BOARDS

Kindling Fuel: 18 pcs 1 x 1 - 6 in. (1 lb.) crib.

Results: Sustained burning:

Summary of Film Record:

9:57^{23}	Ignition of crib at base of wall.
9:59^{12}	Flames reach about 1/4 way up wall (1st 3 boards). Small area of wall behind flames is charred.
10:05^{39}	Not much flame present. Smoke from behind right side of wall. Lower right wall area is charred.
10:14^{11}	Very little external flaming, fire building up inside wall. End of film.

WALL NUMBER 16 - PAINTED WALL FACING ASPHALT SHINGLED WALL 4 FT. AWAY

Kindling Fuel: 18 pcs 1 x 2 in. (4 lb.) crib at base of painted wall, asphalt shingled wall ignited with JP4.

Results: Rapid flame spread over face of painted wall when reinforced with facing fire, removal of reinforcement causes painted wall to stop active flaming except at several lap joints where fire was well established.

Summary of Film Record:

$1{:}32^{13}$	Ignition of JP 4 on right wall (asphalt shingle). and crib at base of left wall (painted).
$1{:}32^{54}$	Additional JP4 squirted on right wall. Crib barely burning.
$1{:}33^{14}$	JP4 added. Right wall flares up and dies back. Crib fire picking up.
$1{:}34^{37}$	More JP4 added to right wall. Same results as before.
$1{:}34^{58}$	More JP4 added.
$1{:}35^{17}$-$1{:}35^{41}$	Many squirts of JP4 on right wall. Crib flame to 1/3 wall height.
$1{:}36^{12}$	Right wall engulfed in flames. Flames creeping up left wall (at half way point).
$1{:}36^{44}$	Flames on left wall above top of wall. Flames not very wide. Flames on right wall cover whole wall and reach well above the top.
$1{:}37^{08}$	Width of flames on left wall increasing. Right wall as before.

$1:37^{25}$ Left wall completely covered with flames. Flames on both walls reach well above the top of the walls.

$1:38^{13}$ Paint flaming only on bottom half of left wall. Top half pretty well charred. Right wall as before.

$1:39^{05}$ Thin flames on left wall. Crib burning very well. Right wall as before.

$1:41^{38}$ Right wall and crib removed, flames die on left wall.

WALL NUMBER 17 - PAINTED WALL FACING ASPHALT SHINGLED WALL 4 FT. AWAY

Kindling Fuel: Painted wall touched with burning brand at intervals, asphalt shingled wall ignited with JP4.

Results: Once critical ignition level reached burning brand touches off painted wall (energy level too unstable to get accurate measurement). Upon removal of asphalt shingled wall, painted wall dies out.

Summary of Film Record:

$2:33^{40}$ Ignition of JP4 on bottom of right wall (asphalt shingled).

$2:33^{59}$ Left wall (painted) touched with flaming brand, does not burn. Some flames at base of right wall.

$2:34^{21}$ More JP4 put on right wall. Flames die quickly.

$2:34^{52}$ Left wall touched with burning stick - does not burn. Flames at base of right wall.

$2:35^{18}$ More JP4 on right wall. Results same as before.

$2:35^{44}$ More JP4 added. Flames die but not as much as before.

$2{:}35^{55}$	Much more JP4 added. Huge flame at first but quickly dies. Bottom 1/3 of right wall burning continuously.
$2{:}36^{18}$	Much more JP4 added. Very huge flame on right wall that dies quickly but right wall is burning very well.
$2{:}36^{52}$	Left wall touched with burning stick. Much smoke produced and then wall ignites. Right wall engulfed in flames.
$2{:}37^{00}$	Flames on left wall in center of top 2/3 of wall. Flames reach above top of wall. Right wall as before.
$2{:}37^{28}$	All of left wall burning.
$2{:}38^{00}$	Right wall removed, flaming dies rapidly on left wall.
$2{:}38^{09}$	Left wall smoking but no flames - wall is completely charred on the surface.

WALL NUMBER 18 - PAINTED WALL, LOOSE BOARDS

Kindling Fuel: 3 lbs. windblown newspaper.

Results: Sustained burning.

Summary of Film Record:

$1{:}12^{55}$	End of ignition of paper at base of wall. Middle of wall charred from top to bottom. Smoke coming from top of left side of wall.
$1{:}14^{13}$	Some flames from ashes of paper. Paint completely burned from bottom board, flames at 2nd middle and top lap joints.
$1{:}15^{03}$	Smoke from behind wall.
$1{:}15^{41}$	Small flame from top of wall.
$1{:}17^{37}$	Top board burning actively.
$1{:}17^{52}$	Flames increasing, end of film.

WALL NUMBER 19 - STAINED, LOOSE BOARDS

Kindling Fuel: 3 lbs. windblown newspaper.

Results: Sustained burning.

Summary of Film Record:

$1{:}38^{12}$	Ignition of paper at base of wall.
$1{:}38^{20}$	Flames from paper reaching above top of wall.
$1{:}41^{38}$	Very small flames from ashes of paper. Almost all of wall is charred.
$1{:}42^{18}$	Two very small flames present, one near top and one near bottom of wall.
$1{:}50^{58}$	Flames barely visible at all.
$1{:}59^{57}$	Small flame growing in center of middle board.
$2{:}01^{37}$	Flame weakens. Smoke from top half of wall.
$2{:}07^{13}$	Flames growing in lower right hand corner of wall. Smoke from left side of wall.
$2{:}09^{09}$	Flames growing in center of middle board. Small flames in lower, right corner. Much smoke from rest of wall.
$2{:}12^{05}$	Flames scattered over lower half of wall. No smoke present.
$2{:}12^{39}$	Lower half of wall burning very well. Flames reach to top of wall.
$2{:}14^{53}$	Small flames scattered over bottom half. Large flames at middle and right side of center board. Flames reaching above top of wall.

$2{:}16^{59}$	Right side of top half of wall burning well. Flames growing at lower left corner of wall.
$2{:}19^{41}$	Large flame on right side of wall. Smaller flame at left side. End of film.

WALL - RAIL 20 - RAILING PLACED AT 90° TO PAINTED WALL NEAR ONE END

Kindling Fuel:	3 lbs. windblown newspaper.
Results:	No sustained burning of railing or wall-rail juncture.

Summary of Film Record:

$9{:}58^{20}$	Paper burning. Flames reach above top of wall.
$10{:}00^{09}$	Right half of wall charred. Most of rail charred. Not much flame from ashes of paper.
$10{:}06^{56}$	No active flames present. Damage as before.
$10{:}09^{18}$	Very small flame at middle of 2nd board from top, defect in board at this point permitted reinforcement.

Fig. D-8 POSITION OF NEWSPAPER USED IN EXTERNAL KINDLING FUEL EXPERIMENTS

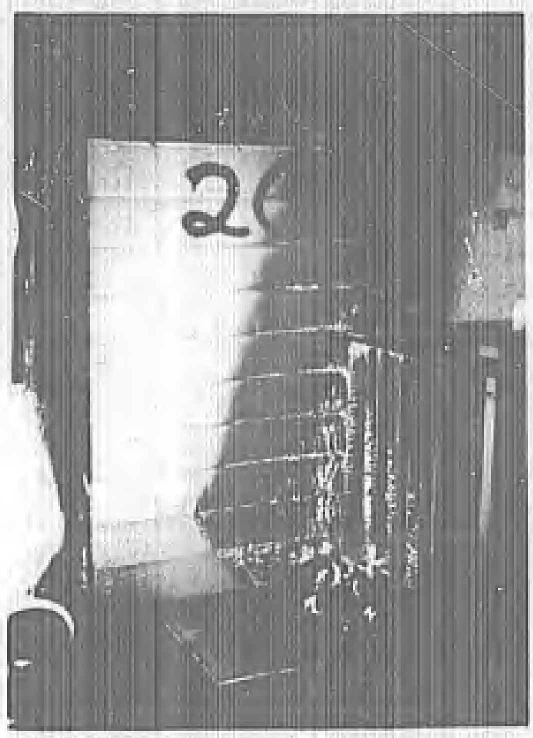


Fig. D-9 WALL-RAIL 20, 2 MINUTES AFTER IGNITION

WALL - RAIL 21: RAILING PLACED AT 90° TO PAINTED WALL NEAR ONE END

Kindling Fuel: 18 pcs 1 x 1 - 6 in. (1 lb.) crib.

Results: Smouldering area on wall directly behind crib and at wall-rail juncture 2 ft. above crib. Wind from selected direction might have augmented this sufficiently to cause sustained burning.

Summary of Film Record:

$3{:}11^{05}$	Ignition of crib at base of wall.
$3{:}13^{54}$	Flames from crib reaching to top of railing. Wall charred a little on right side from bottom to mid-height.
$3{:}21^{47}$	Very little flames present. Right side of wall charred up to 3/4 of wall height. No significant damage to railing.
$3{:}35^{03}$	No flames present. Removal of railing at this time shows smouldering area behind it where siding bevel produced small gap.

WALL - RAIL 22 - ASPHALT SHINGLED WALL 4 FT. FROM AND FACING PAINTED WALL WITH RAILING JOINING THEM NEAR ONE END

Kindling Fuel: Asphalt shingle wall ignited with 18 pcs 1 x 2 - 12" (4 lb.) crib placed at far end from railing.

Results: Radiation from asphalt shingled wall augments flame spread across rail and painted wall (see Fig. D-10 for radiation level at painted wall vs. time).

Summary of Film Record:

$1:58^{38}$	Crib ignited.
$2:01^{59}$	Flames spreading up right (asphalt shingled) wall.
$2:19^{30}$	Middle 1/3-1/2 of right wall actively flaming.
$2:20^{31}$	1st railing support ignited.
$2:21^{54}$	2nd railing support ignited.
$2:21^{57}$	3rd railing support ignited.
$2:22^{10}$	4th railing support ignited.
$2:22^{35}$	5th railing support ignited.
$2:22^{55}$	6th railing support ignited, left wall (painted) smoking actively.
$2:24^{14}$	Left wall ignited.
$2:24^{31}$	Left wall fully aflame. Upon removal of right wall and rail, flames die out.

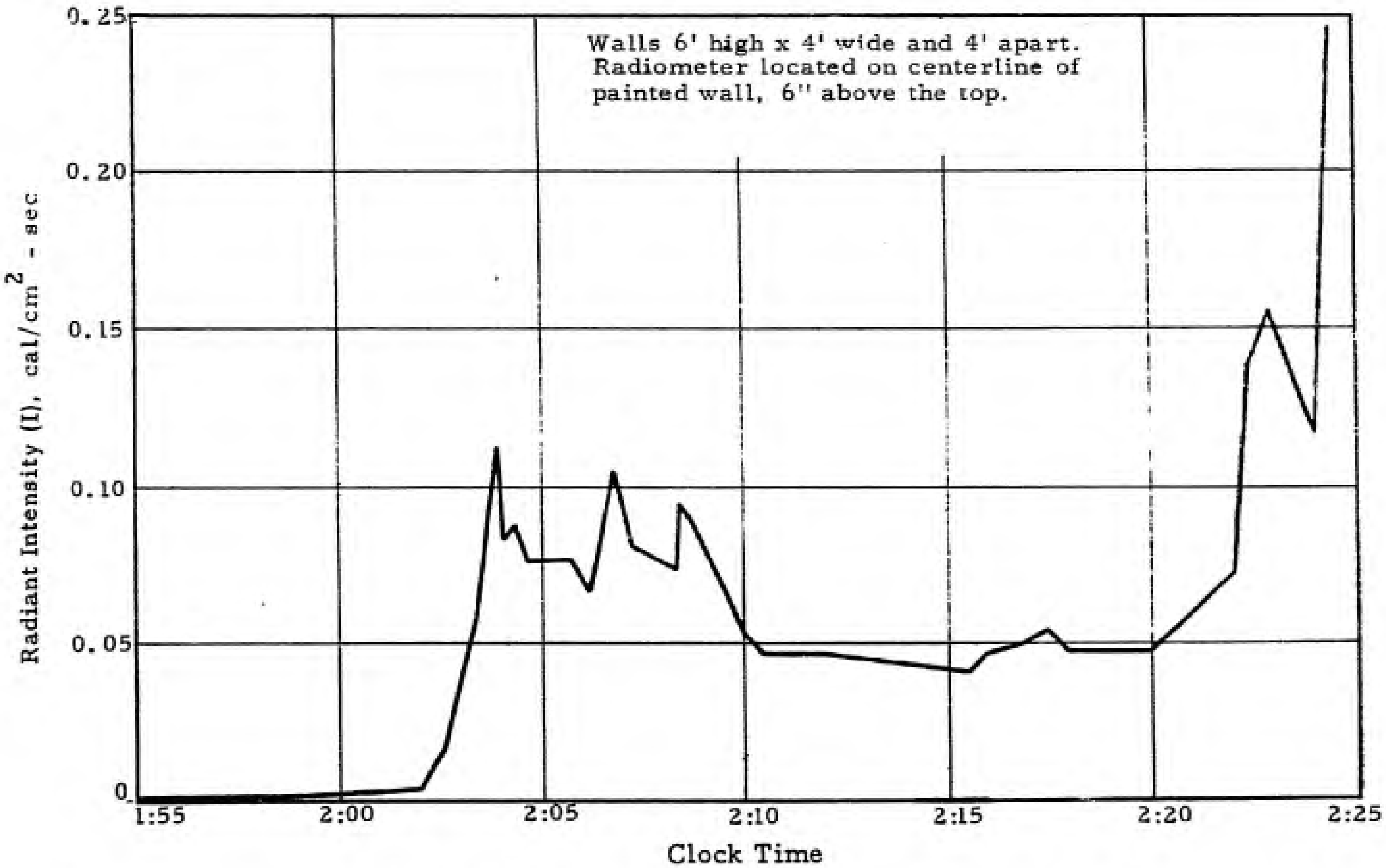


Fig. D-10 RADIATION LEVEL FROM WALL-RAIL 22. FIRE EXPERIMENT

STAIR NUMBER 23 - DIRECTION OF ASCENT PERPENDICULAR TO WALL

Kindling Fuel: 18 pcs 1 x 2 - 12 in. (4 lb.) crib.

Results: Sustained burning.

Summary of Film Record:

$2{:}47^{22}$	Ignition.
$2{:}47^{50}$	Crib barely burning.
$2{:}51^{10}$	Crib becoming active, smoke visible between 2nd tread and 3rd riser, smoke builds up.
$2{:}52^{00}$	Flames appear from under stair near 3rd tread.
$2{:}52^{35}$	Entire underside of stair actively flaming.
$2{:}53^{40}$	2 x 4 support in flames on side facing inward.
$2{:}54^{05}$	Flames reaching about 1 ft. above top landing.
$2{:}55^{05}$	Flaming above landing ceases.
$3{:}03^{25}$	Active flaming ceases - crib collapses.
$3{:}05^{00}$	Small flames visible between boards on landing.
$3{:}13^{00}$	Small flames continue near landing.
$3{:}16^{35}$	Supports have pulled loose, stairway falls, flames building up.
$3{:}21^{00}$	Board step and landing actively burning, test ended.

STAIR NUMBER 24 - DIRECTION OF ASCENT PARALLEL TO WALL

Kindling Fuel: 18 pcs 1 x 2 - 12 in. (4 lb.) crib.

Results Sustained Burning.

Summary of Film Record:

$4{:}08^{20}$	Ignition.
$4{:}08^{22}$	Flames touch underside of 2nd tread, flames then die down.
$4{:}09^{30}$	Flames have built up until underside of 1st tread above crib is bathed in flame, tips of flame touch underside of 2nd tread.
$4{:}10^{50}$	3/4 of 3rd tread now flaming, tips of flame touching bottom of landing.
$4{:}12^{00}$	Flames cover all of underside of 2nd, 3rd and landing.
$4{:}13^{30}$	Building in intensity, supports now involved, paper on drywall base starts to burn.
$4{:}14^{00}$	Dies down.
$4{:}15^{30}$	Builds up again.
$4{:}16^{00}$	Dies back.
4:16-4:19	Approximately 1/2 of underside actively flaming.
$4{:}19^{00-45}$	All of 1st stair (underside) flaming.
4:19-4:21	All of 2nd stair (underside) flaming.
$4{:}21^{00}$	Flames receeding.
$4{:}23^{00}$	Flames on 1/2 of 1st, 1/2 of 2nd, 1/4 of 3rd.
$4{:}25^{25}$	Crib settles.
$4{:}27^{00}$	Flames appearing along step - wall junction.

$4{:}29^{00}$	Flames appearing near landing-support juncture.
4:30-4:37	Active flames near crip, flickers of flames near all joints.
$4{:}37^{00}$	Part of landing and 2 x 4 support near wall fall to ground, entire stair gradually sags, flames now active on top side of stairs, end of test.

STAIR NUMBER 25, "PARALLEL"

Kindling Fuel: 3 lbs. windblown newspaper (+2 lbs added later).

Results: No sustained burning due to first ignition.

Summary of Film Record:

$1{:}15^{45}$	Ignition of paper.
$1{:}16^{00}$	Active burning over entire pile.
$1{:}18^{00}$	Papers all consumed, paint burned, wood charred.
1:18-1:35	Several joints smouldered, no flame.
$1{:}36^{00}$	2 lbs. windblown paper added under stairs.
$1{:}36^{15}$	Ignition of paper.
$1{:}36^{30}$	Active burning of entire pile.
$1{:}37^{10}$	Paper all consumed.
$1{:}37^{10}$-$1{:}40^{00}$	Joints continue to smoulder.
$1{:}40^{00}$	Stair removed to outside of lab where wind fanned joint on landing into flames.

STAIR NUMBER 26 - "PARALLEL"

Kindling Fuel: 18 pcs 1 x 1 - 6 in. (1 lb.) crib.

Results: Marginal - sustained burning achieved by adding 5 mph wind near end of experiment. Smouldering joints may or may not have continued.

Summary of Film Record:

$1{:}54^{25}$	Ignition of crib.
$1{:}54^{37}$	End of burning of JP4.
$1{:}54^{43}$	Small flames at base of crib.
$1{:}55^{10}$	Flames building up, touch bottom of 1st, and 2nd treads.
$1{:}56^{00}$	1/3 of 1st and 1/2 of 2nd tread covered with flame.
$1{:}57^{20}$	1/2 of 1st, all of 2nd and 3rd treads and 1/2 of landing covered with flame.
$1{:}58^{15}$	Flames have died back to 1/3 of 1st, 2nd and 3rd treads (apparently build up was burnoff of paint).
$1{:}59^{00}$	Flames spread along underside of 2nd tread and up the rail igniting paint at far side of landing.
$2{:}01^{00}$	Joint between planks on landing burning.
$2{:}02^{45}$	Active flaming stops at crib.
$2{:}03^{15}$	Crib collapses.
$2{:}06^{15}$	Flaming stops at landing.
$2{:}06^{15}$-$2{:}13^{30}$	Smouldering continues in joints.
$2{:}13^{30}$	Blower turned on (5 mph). Landing is flaming near supports and top plank joint on each side, some flames at 1st tread and riser joint directly over crib.
$2{:}28^{00}$	One support falls - end of test.

STAIR NUMBER 27 - "PARALLEL", LOOSENED TREADS TO SIMULATE DISREPAIR

Kindling Fuel: 3 lb. windblown newspaper.

Results: Small gust of wind sufficient to rekindle open smouldering joints after kindling consumed.

Summary of Film Record:

$3:34^{36}$	Ignition of paper.
$3:34^{55}$	Entire pile burning actively.
$3:36^{15}$	End of active burning of paper, underside of stairway still flaming.
$3:37^{30}$	End of all active flaming.
$3:38^{30}$	Blower on 5 sec causing active flaming of plank joint on landing as well as the loosened tread-riser joints. Continues to burn gradually building up intensity until -
$4:12^{45}$	Entire stairway collapses.

REFERENCES

1. Sauer, F.M., Craig C. Chandler and Keith Arnold. "Primary Ignitions Following Atomic Attack on Urban Targets-Transient Exterior Fuels", Interim Technical Report AFSWP-413, June 30, 1953.

2. Glasstone, S., "The Effects of Nuclear Weapons", Revised Edition, U.S. Dept. of Defense, April 1962.

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APPENDIX E

FULL-SCALE BUILDING FIRES

I. INTRODUCTION

The objective of the full-scale building fires was to extend and verify laboratory experiments. Full-scale experiments were conducted on five buildings, located in Chicago (Ellis Parkway), Gary, Indiana, Plato Center, Ill., Lake Forest, Ill., and Homewood, Ill. The Ellis Parkway (Chicago) and Gary dwelling burns were completely free-burning fires, with no attempts to extinguish or control the fire at any time. The Ellis Parkway burn constitutes the primary experiment and is treated in considerable detail. Because of the size of the building and type of construction, the Gary burn had limited application and is treated in less detail. The other three burns were free-burning fires combined with extinguishment studies. The information reported on the burns at Plato Center, Lake Forest and Homewood, Illinois includes only that part related to the objectives of this work.

II. ELLIS PARKWAY BURN

A. General

A three-story apartment building, located on Ellis Parkway in Chicago, was used to study the fire spread within structures. The building was made available to IIT Research Institute by the Department of Urban Renewal of the City of Chicago. The experiment was conducted with the cooperation of the Chicago Fire Department.

The Ellis Parkway burn was designed to provide a well-documented, detailed time record of the many events which mark the progress of fire through a moderately large structure, without interference of fire-fighting operations. The obtained data is used to determine the fire penetration and collapse time of various structural members, and in particular, the external radiation from flames.

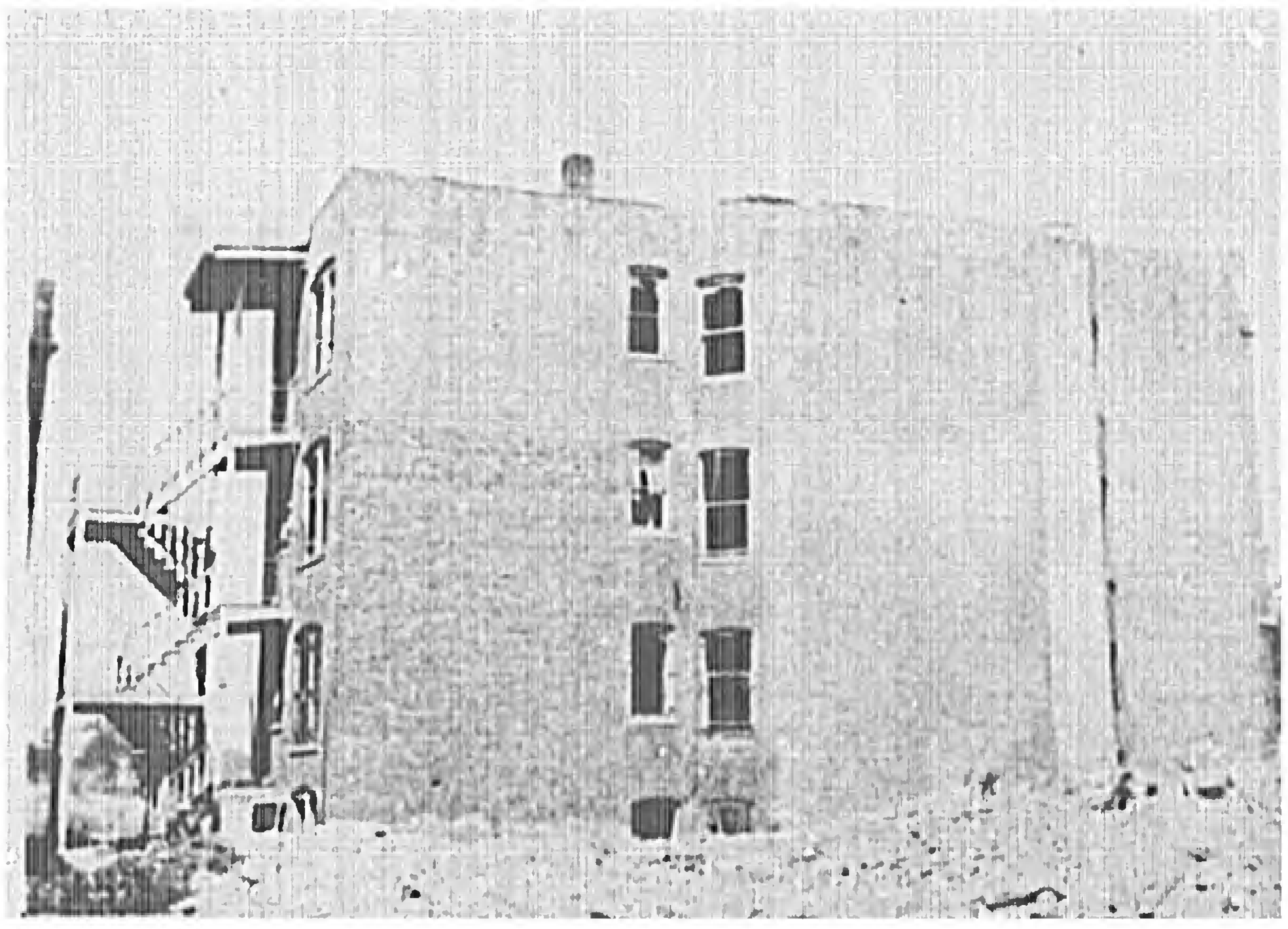
B. Description of the Building

A typical pre-World War I residential structure in the Chicago area, the building was approximately 25 feet wide by 67 feet long, by 40 feet high (three (3) stories), with full basement and blind attic space to allow for the gentle pitch of a "flat" roof. The first, second and third story walls were 16, 12, and 12 inches thick, brick masonry, supported on a concrete foundation. The basement floor was concrete on earth. Other floors were constructed of one-inch tongue and groove red oak, on a 1" x 6" sub-floor, supported by 2" x 10" joists spaced 16 inches center-to-center. The third story ceiling joists and roof rafters were 2" x 8", 16" center-to-center. The roof deck was 1" x 6" tongue and grooved sheathing covered by a 4 or 5-ply felt and gravel roof covering.

All interior partitions (approximately 150 linear feet on each floor) had 2" x 4" studdings 16 inches center-to-center, sheathed on both sides with 1/2-inch thick lime plaster on wood lath. Ceilings and furred exterior walls also were sheathed with wood lath and plaster. Window sash and frames, door frames, baseboards and other interior trims were soft wood. All doors were 1-1/2 inch thick, wood-panelled type.

Photographs of the building are shown in Fig. E-1. A schematic representation and floor layout of the building are given in Fig. E-2 and Fig. E-3, respectively.

All window glass was removed, as would be the case for a building located within a blast region of 1 psi overpressure. To assure realistic fire behavior, all ceiling, wall and floor damage was repaired.



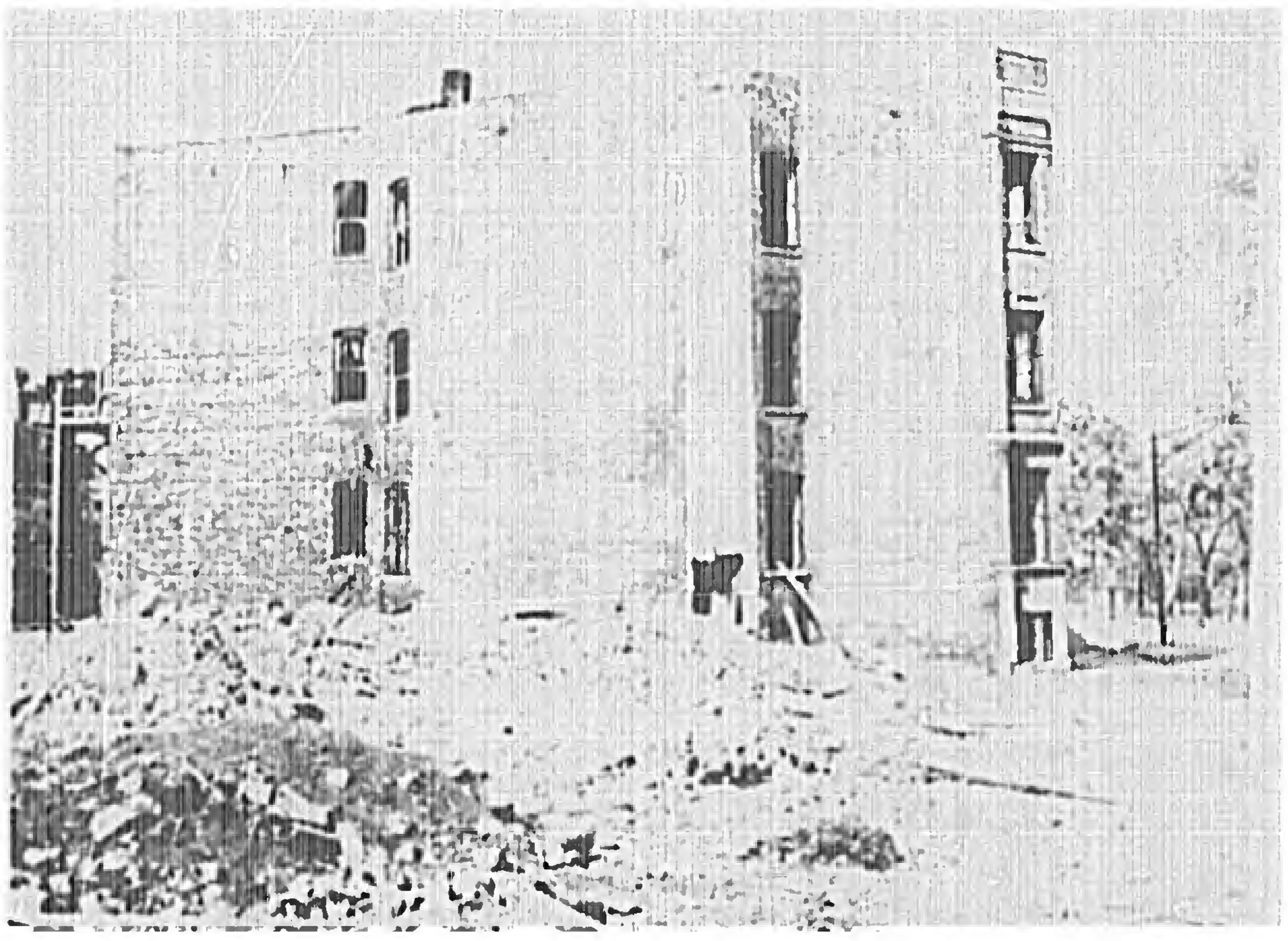


Fig. E-1 PHOTOGRAPHS OF THE EXPERIMENTAL BUILDING

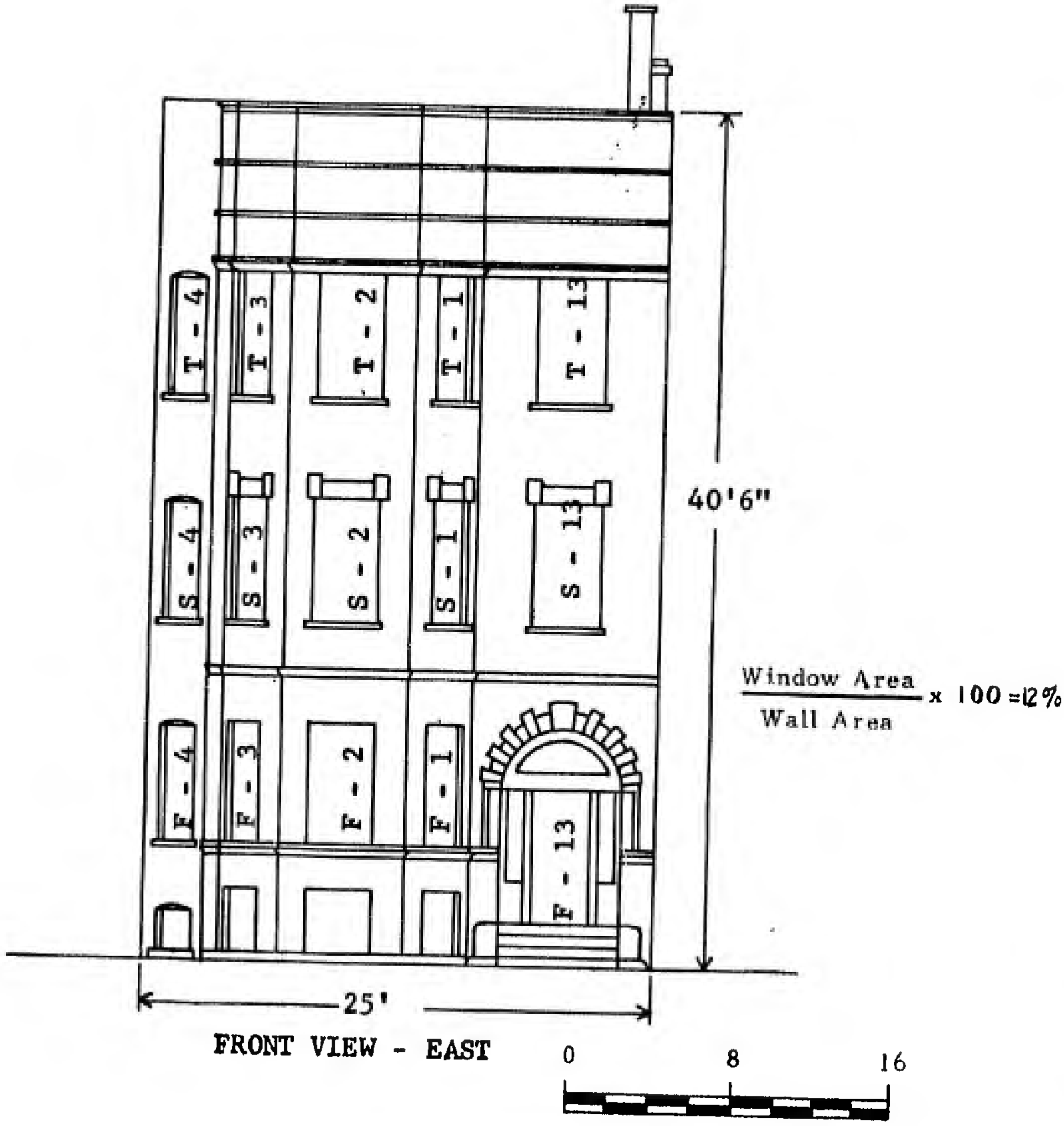


Fig. E-2a. ELEVATION VIEW OF ELLIS PARKWAY BUILDING

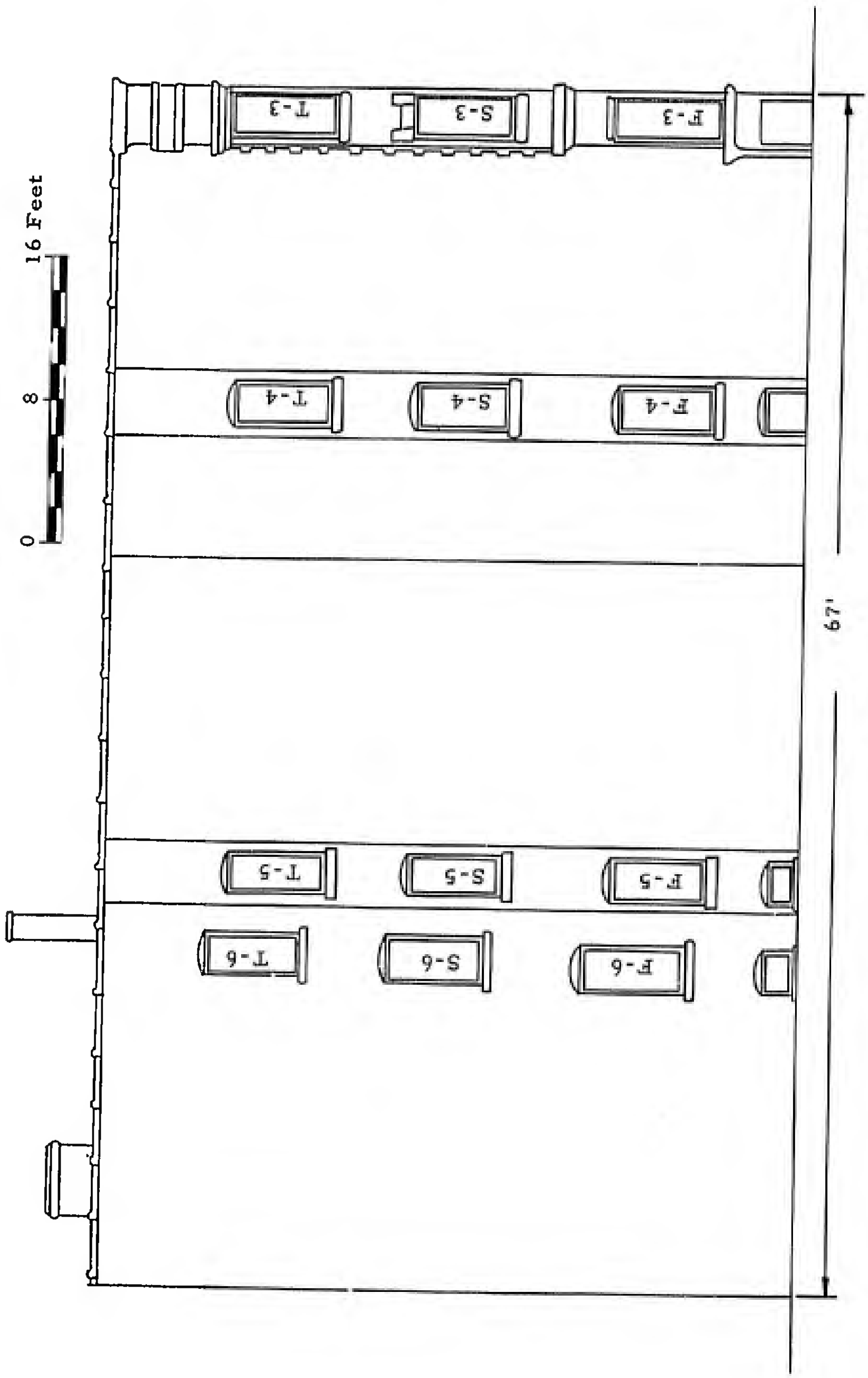
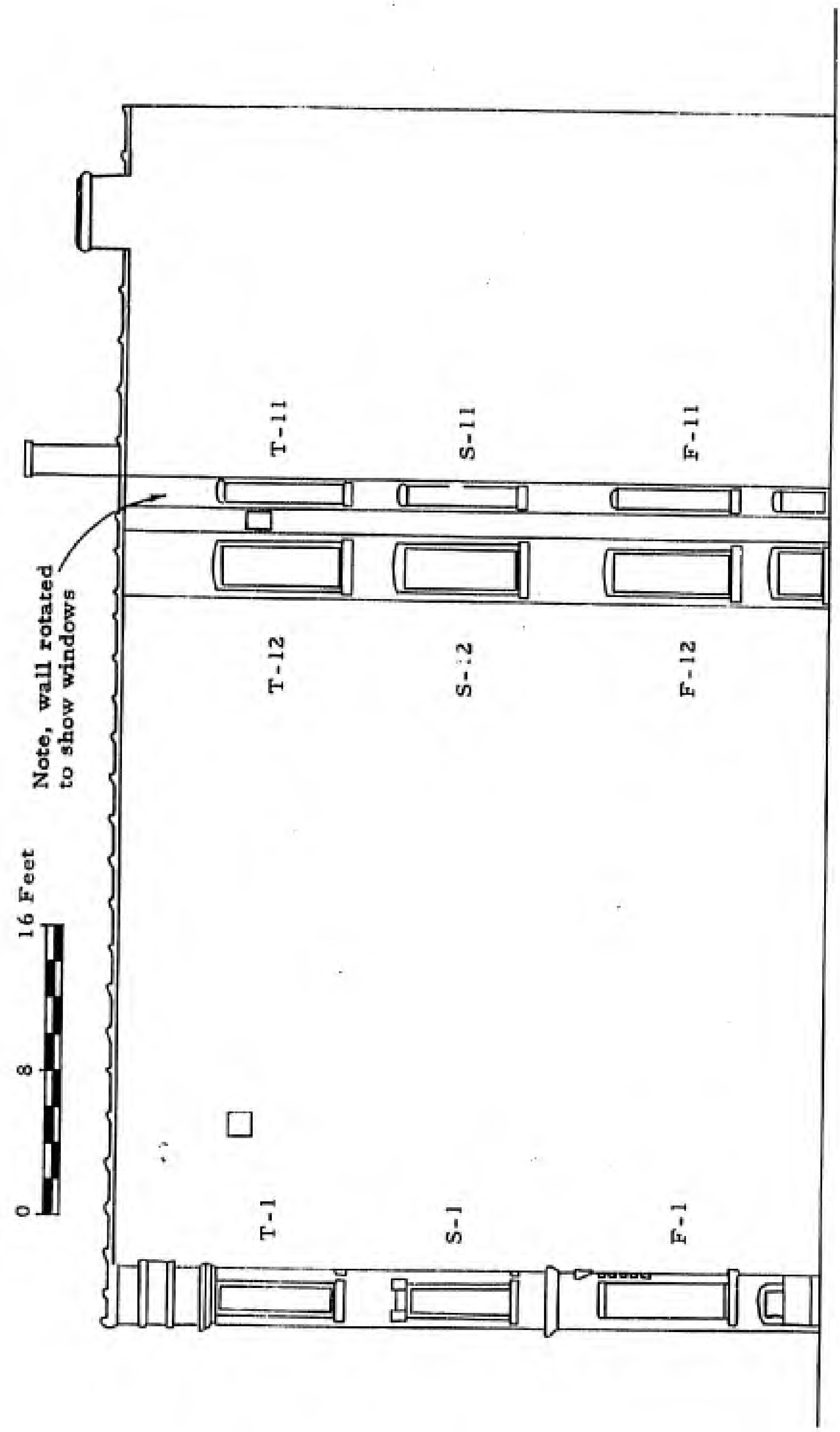


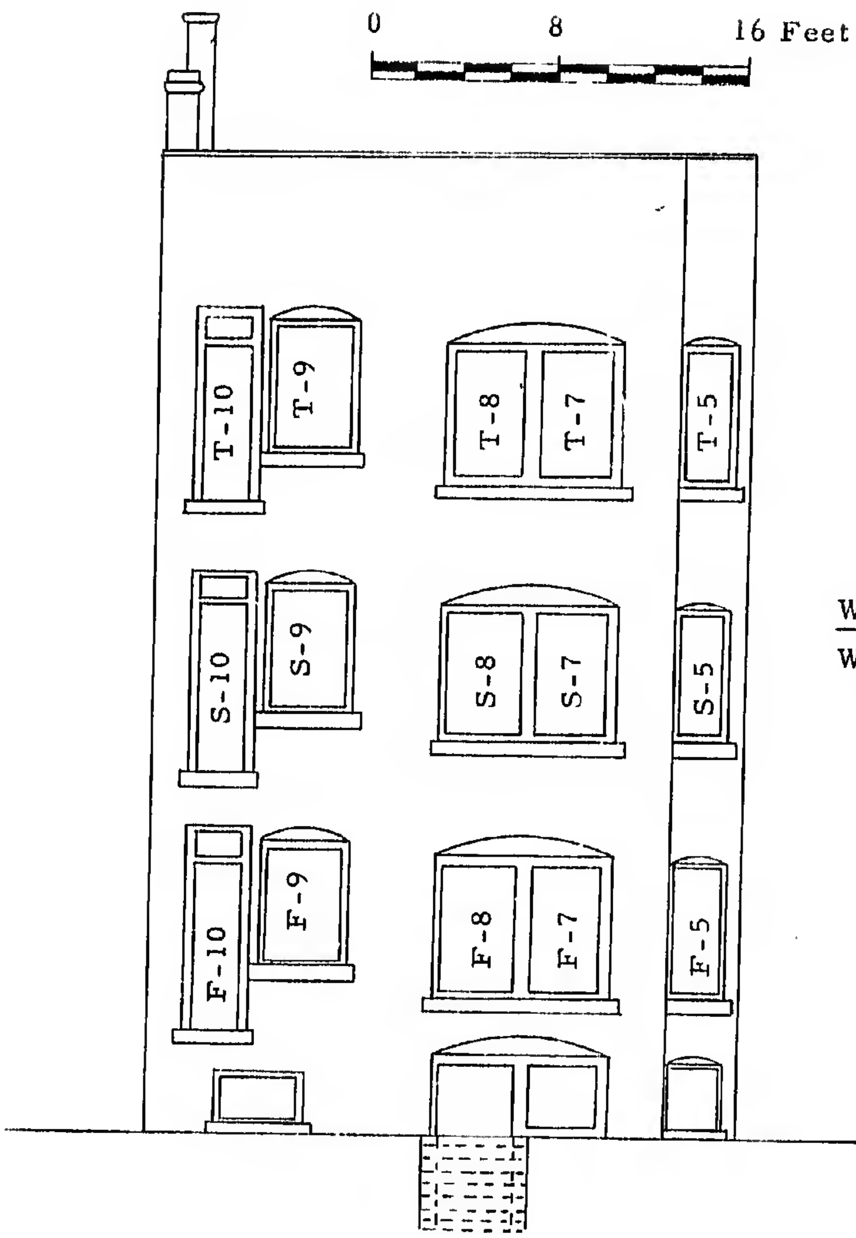
Fig. E-2b SIDE VIEW-SOUTH

$$\frac{\text{Window Area}}{\text{Wall Area}} \times 100 = 6\%$$



$$\frac{\text{Window Area}}{\text{Wall Area}} \times 100 = 3\%$$

Fig. E-2c SIDE VIEW - NORTH



$$\frac{\text{Window Area}}{\text{Wall Area}} \times 100 = 25\%$$

Fig. E-2d REAR VIEW - WEST

Doors were in place at the entrance to each apartment. The glass panels in doors were replaced with 3/8" plywood at the first story, and 1/4" plywood at the second and third stories.

C. Fire Load

The weight of combustible materials in the structure and of the contents is summarized in Table E-1. The fire load of the structure represents the total weight of combustibles at each story, distributed (averaged) over a floor area of 1200 ft^2. For example, the first story fire load includes the first floor assembly, plus wood studdings in partitions, wood lath on partitions and furred walls, and interior trim; the wood lath on the ceiling of the first story is included with the fire load of the first story. The underside of the first floor (basement ceiling) was unfinished, open joist construction. The roof and dropped ceiling assembly was considered as a fuel load combination which burned together.

To simulate conditions existing within a real residential occupancy, each room was furnished as shown in Fig. E-3. A realistic fuel distribution, consistent with the type of occupancy under investigation, is considered to be an important variable, essential to the proper characterization of the fire and its spread within the structure. The contents fire load is also given in Table E-1.

Considering the total combustibles in the building, the over-all fire load was 68.1 lbs/ft^2 distributed over 1200 ft^2 of land.

D. Instrumentation

Descriptions of instruments used in the experimental program are given in Appendix G of this report. Thermocouple, anemometer, and gas sampling locations are shown in Fig. E-4; radiometer locations are

Table E-1

ELLIS PARKWAY BUILDING FIRE LOAD DISTRIBUTION[1]

Location	Structure		Contents		Weight of Fuel in Building
	Fire Load	Fuel Weight	Fire Load	Fuel Weight	
	lb/ft^2	lbs	lb/ft^2	lbs	lbs
Roof and dropped ceiling assembly	8.9	10,680	None	None	10,680
Third Story	17.5	21,000	2.1	2520	23,520
Second Story	17.5	21,000	2.4	2880	23,880
First Story	17.5	21,000	2.2	2640	23,640
Fire Load Totals	61.4	73,680	6.7	8040	81,720

Overall Fire Load for Building[2] 68.1 lb/ft^2

1. Building floor area 1200 ft^2 per story
2. Based on 1200 ft^2 i.e., 81,720/1200 = 68.1 lb/ft^2

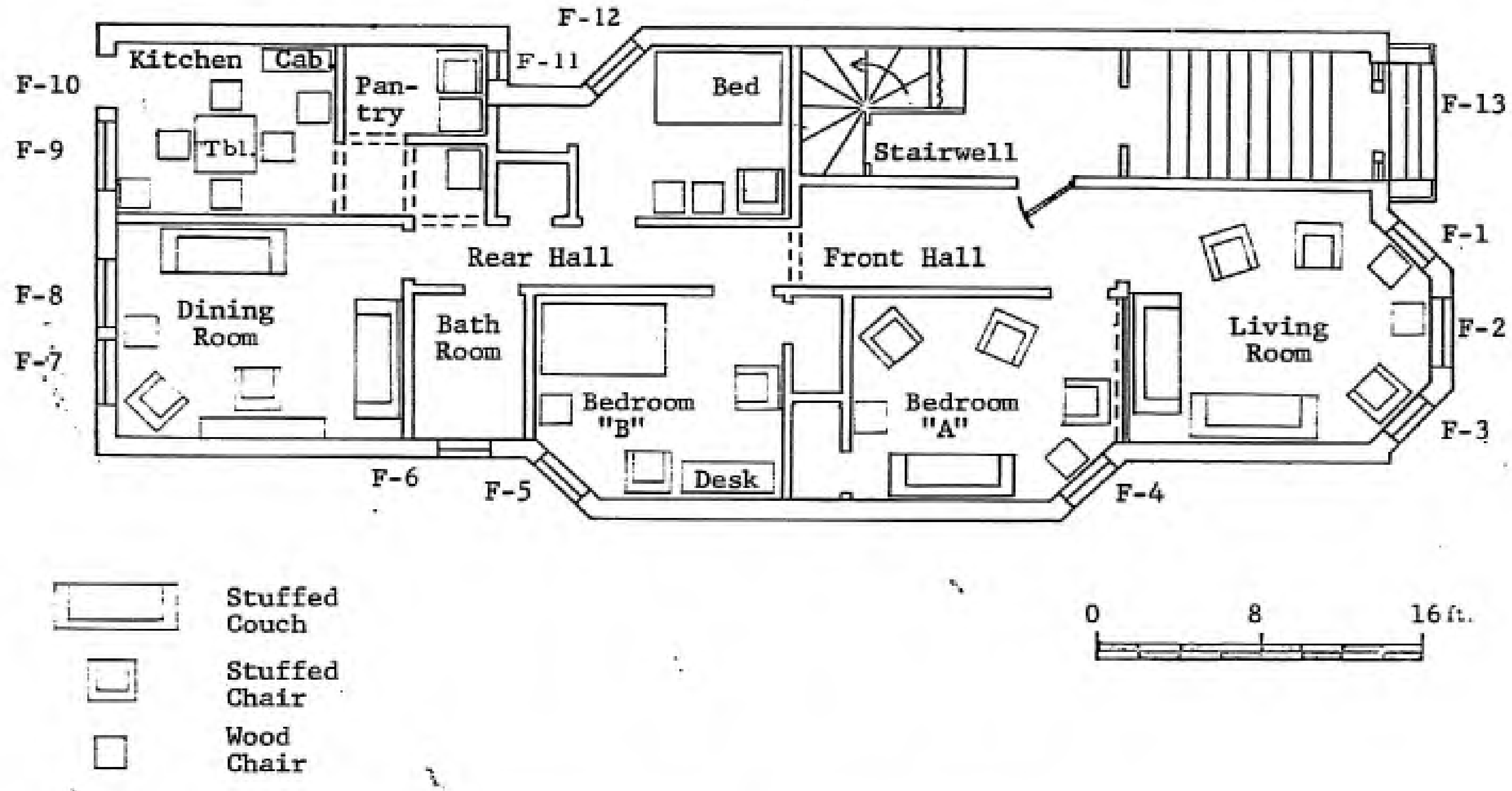


Fig. E - 3(a). ELLIS PARKWAY BUILDING, FIRST STORY CONTENTS

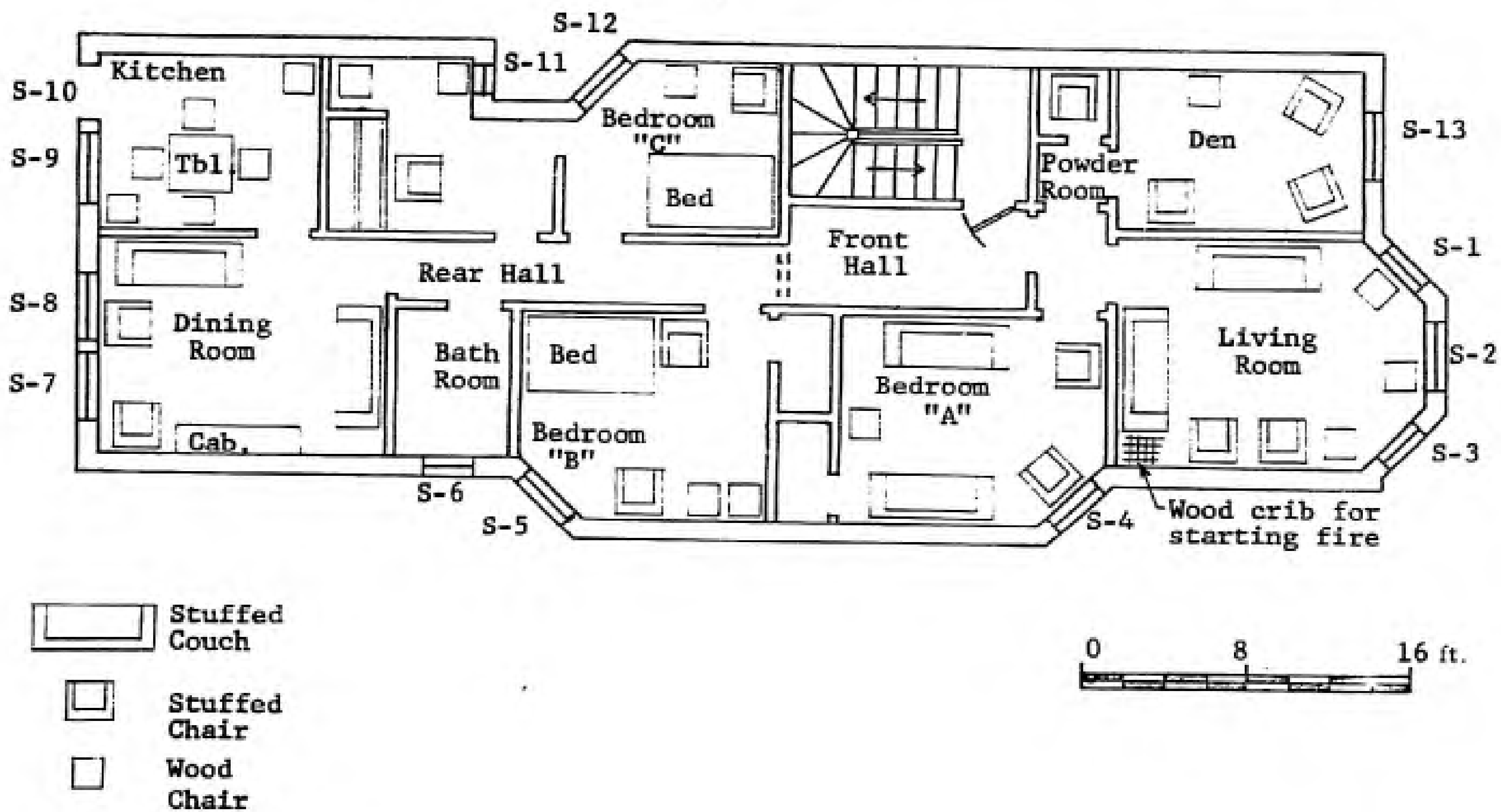


Fig. E-3(b). ELLIS PARKWAY BUILDING, SECOND STORY CONTENTS

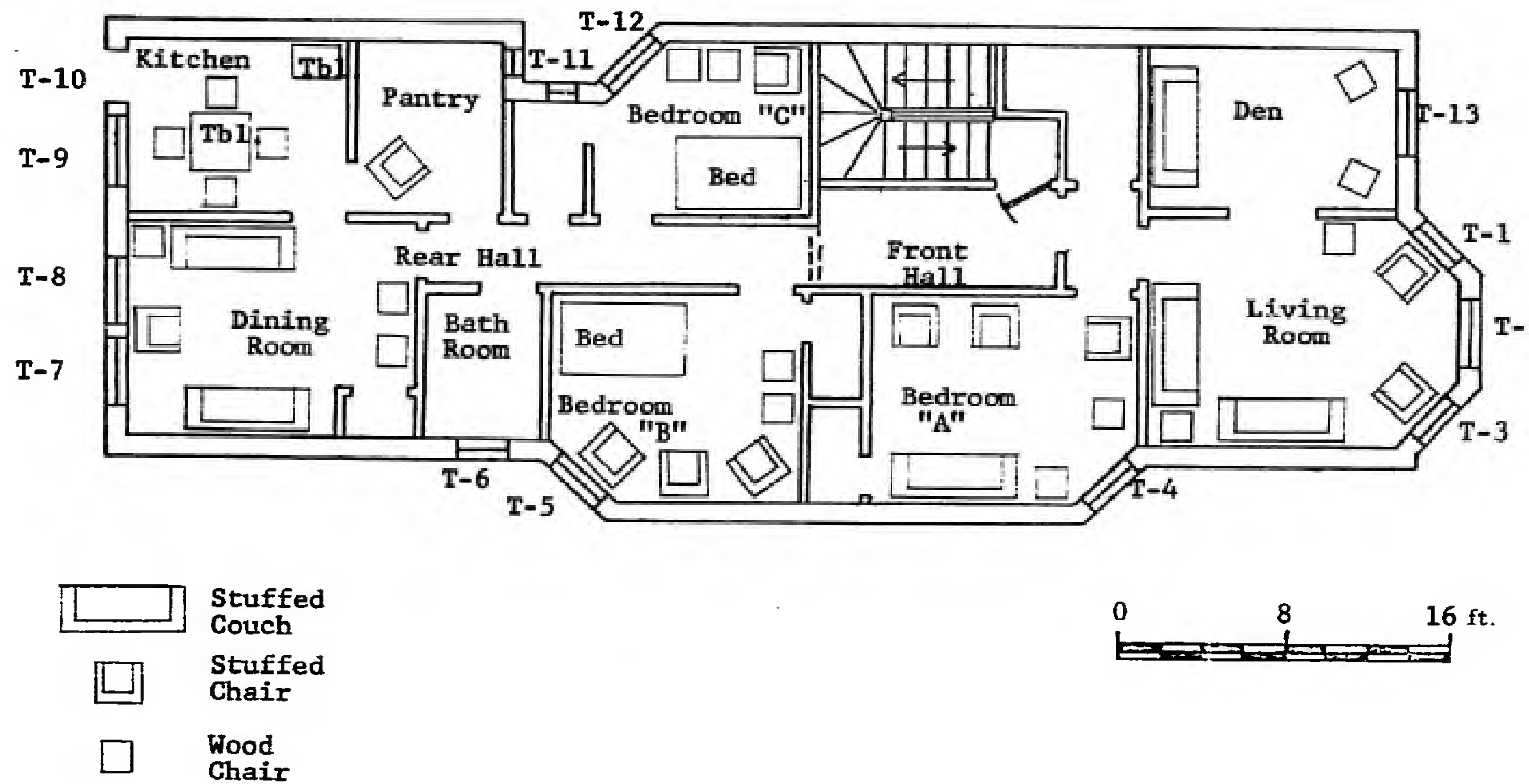


Fig. E-3(c). ELLIS PARKWAY BUILDING, THIRD STORY CONTENTS shown in Fig. E-5.

Thermocouples were used to measure gas temperatures to follow the spread of fire through the building. Groups of ten thermocouples were connected to a common terminal strip which was wrapped in a plastic bag and placed in a metal container filled with ice and water as a reference junction. Since containers were either placed inside the building, or hung on the wall outside the building, they were exposed to heat from the fire. Hence, it was necessary to thoroughly encase each container in asbestos cement for heat insulation. This system was chosen to conserve the chromel-alumel thermocouple wire; copper wire could then be run to the terminals of the recording instruments. A duplex thermocouple wire was used, with asbestos insulation on each wire and fiber glass insulation outer covering.

The measurement of the air velocity through windows was accomplished by means of hot-wire anemometers. Eight anemometers were located at windows in the first and second stories, as shown in Fig. E-4(a) and (b). No anemometers were located at the third story level. The anemometers were mounted along the vertical center-line of each window, one-third of the window height above the sill. At this location it is considered that edge effects are minimized and velocity measurements would be made below the neutral axis (atmospheric pressure plane) in the fresh air supply to the fire.

The atmosphere within the fire was continuously sampled at several locations by withdrawing gas through tubes connected to analyzers. Eight gas aspiration tubes were located as shown in Fig. E-4(a), (b), and (c). Three were in the basement, two on the first story, one on the

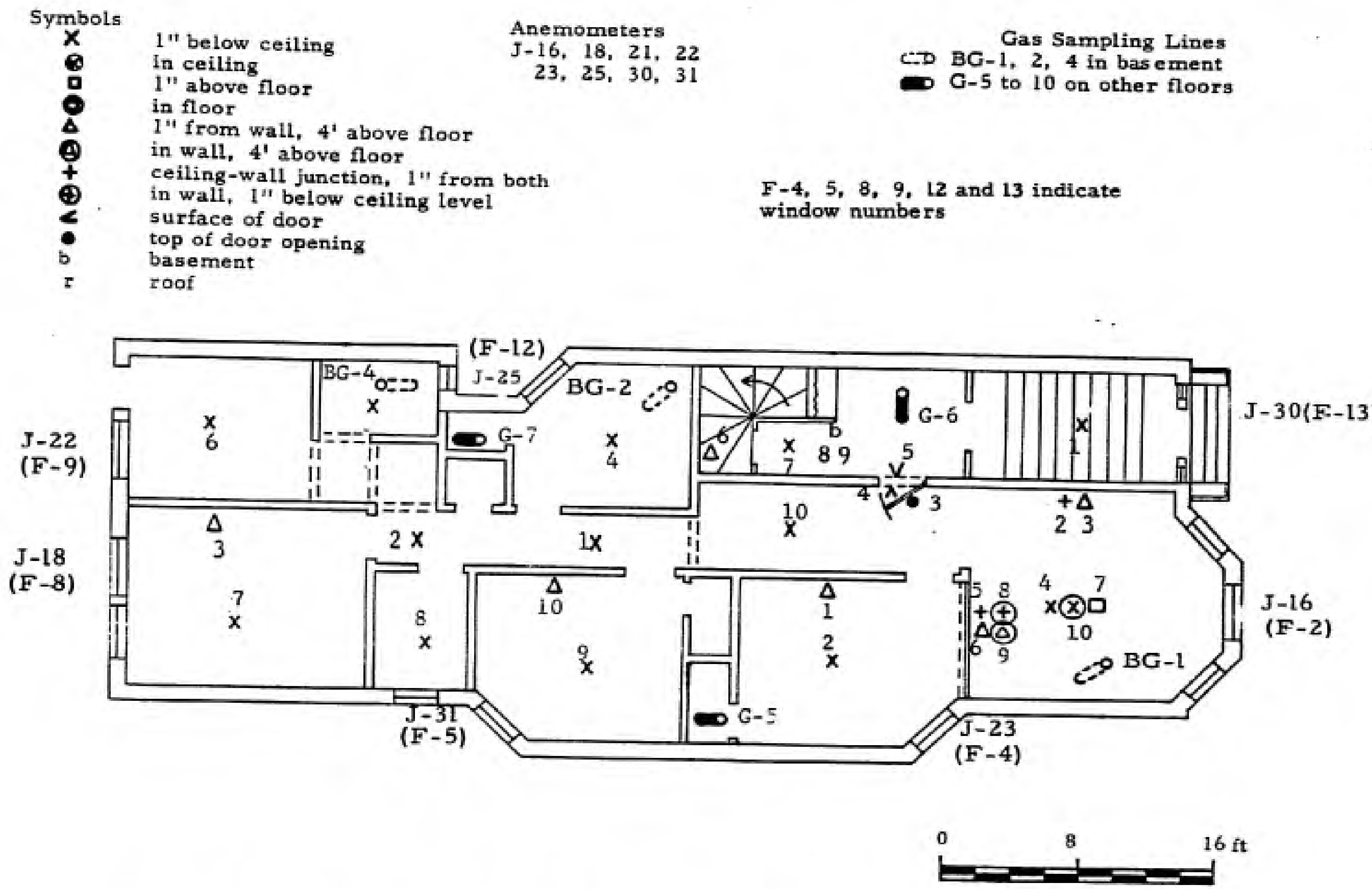


Fig. E-4a ELLIS PARKWAY BUILDING, FIRST STORY, LOCATIONS OF THERMOCOUPLES, ANEMOMETERS AND GAS SAMPLING TUBES

See Fig. E-4a for legend

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(S-10)

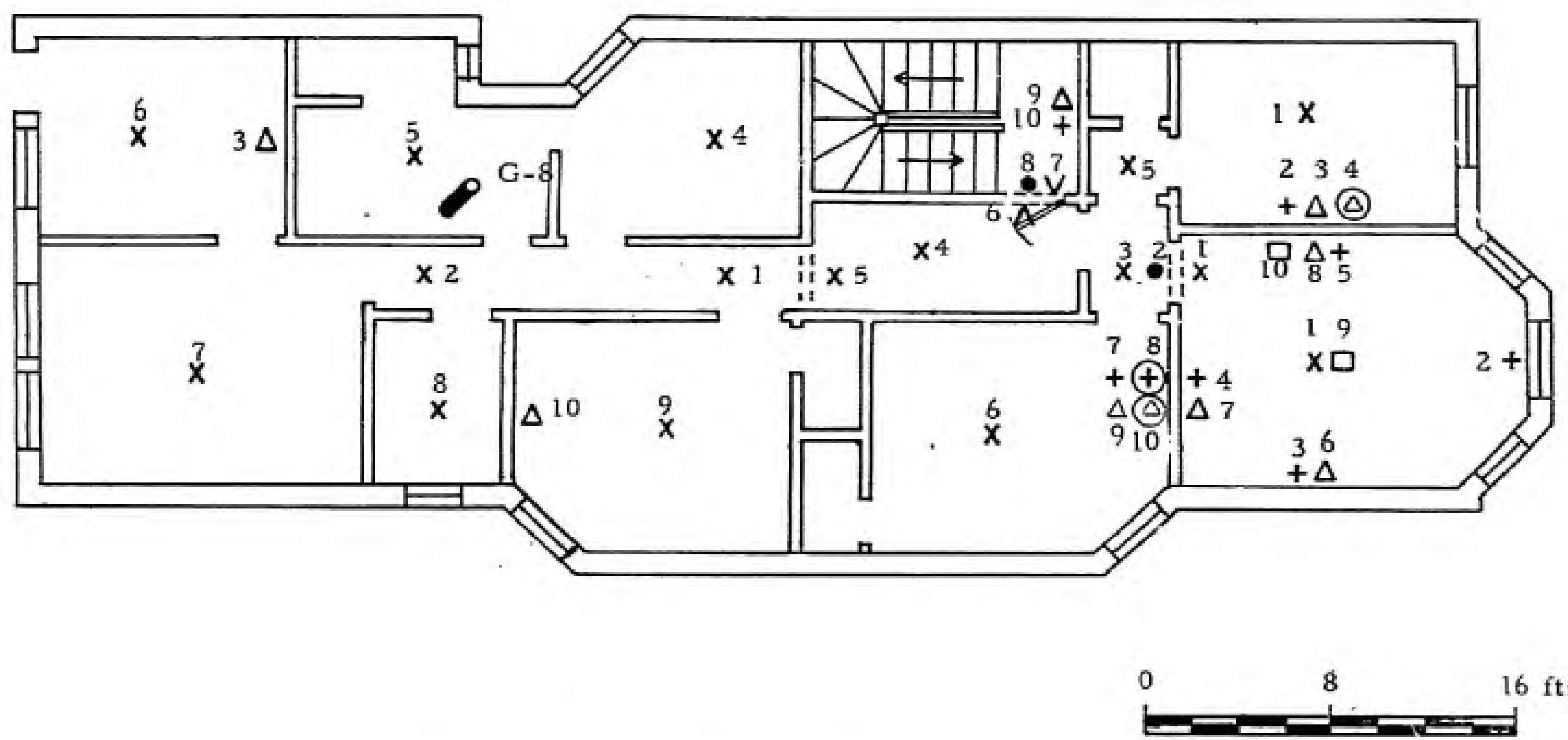


Fig. E-4b ELLIS PARKWAY BUILDING, SECOND STORY, LOCATIONS OF THERMOCOUPLES, ANEMOMETERS AND GAS SAMPLING TUBES

See Fig. E-4a for legend

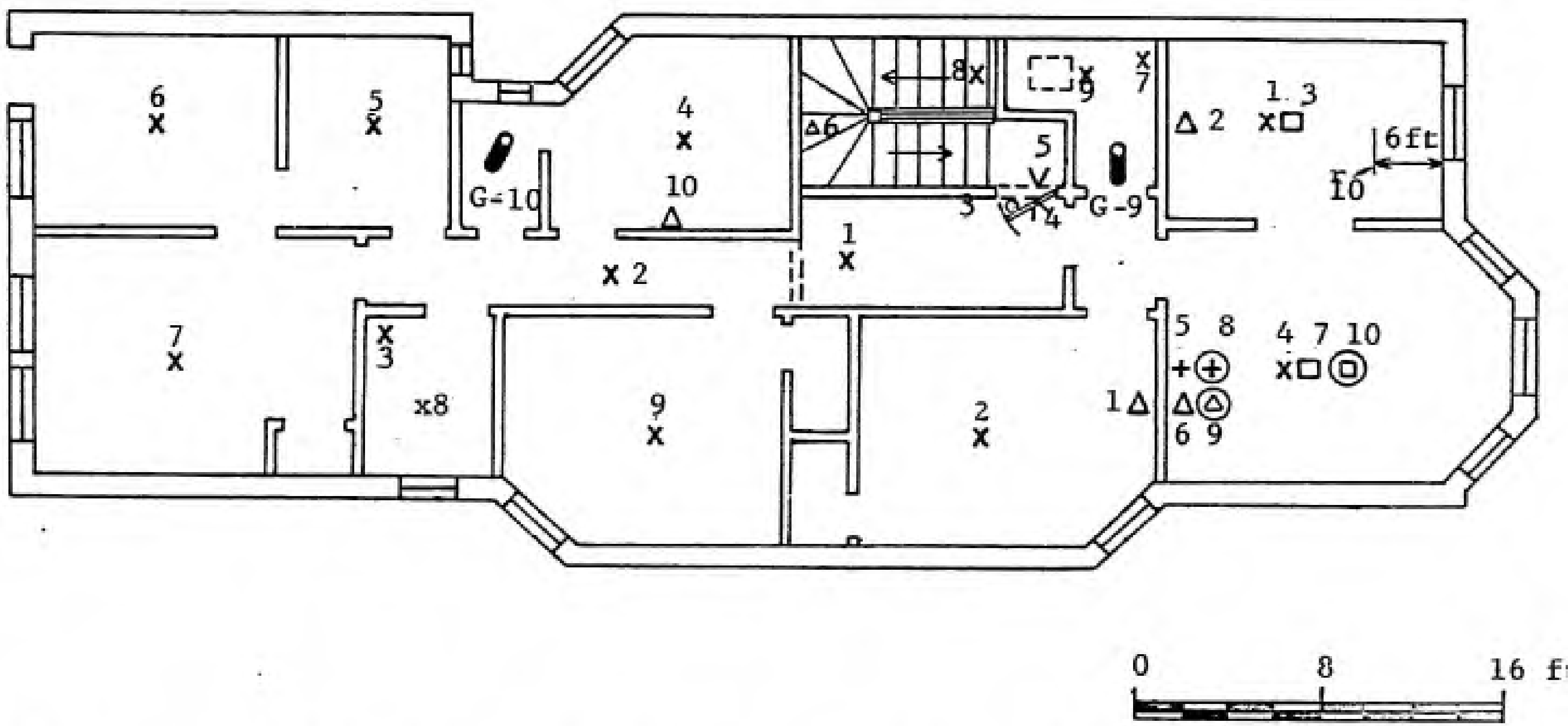


Fig. E-4c ELLIS PARKWAY BUILDING, THIRD STORY, LOCATIONS OF THERMOCOUPLES, AND GAS SAMPLING TUBES second story, and two on the third story. Tube inlets were positioned approximately three feet above the floor. The oxygen content was determined by a paramagnetic analyzer, while the carbon monoxide content was determined with a combustibles analyzer. The gas concentrations were recorded on charts.

The measurement of radiant heat flux from windows and from flames projecting out of windows was accomplished by means of radiometers. The radiometers were mounted on stands about five feet above the ground and located as shown in Fig. E-5.

Additional data were obtained by time-lapse color photography, using two 16 mm Bolex Rex cameras operated at 50 frames per minute by Lafayette time sequencers. Synchronized electric clocks were located in the field of view of each camera. One camera was located at the front of the building; the other camera was on the north side of the building, looking south toward the smoke and flames coming out of the rear of the building as well as from the openings in the north wall. A third 16 mm camera was used by a roving photographer recording events not exposed to the other cameras. Visual observations were made by two men equipped with two-way radio communication; their timed comments were recorded on tape.

Recording instruments were housed in a semi-trailer, located approximately 100 feet north of the experimental building. All electric power to the trailer was supplied by a connection to public utility service lines.

E. Ignition

The primary interest in the experiment was to observe the fire

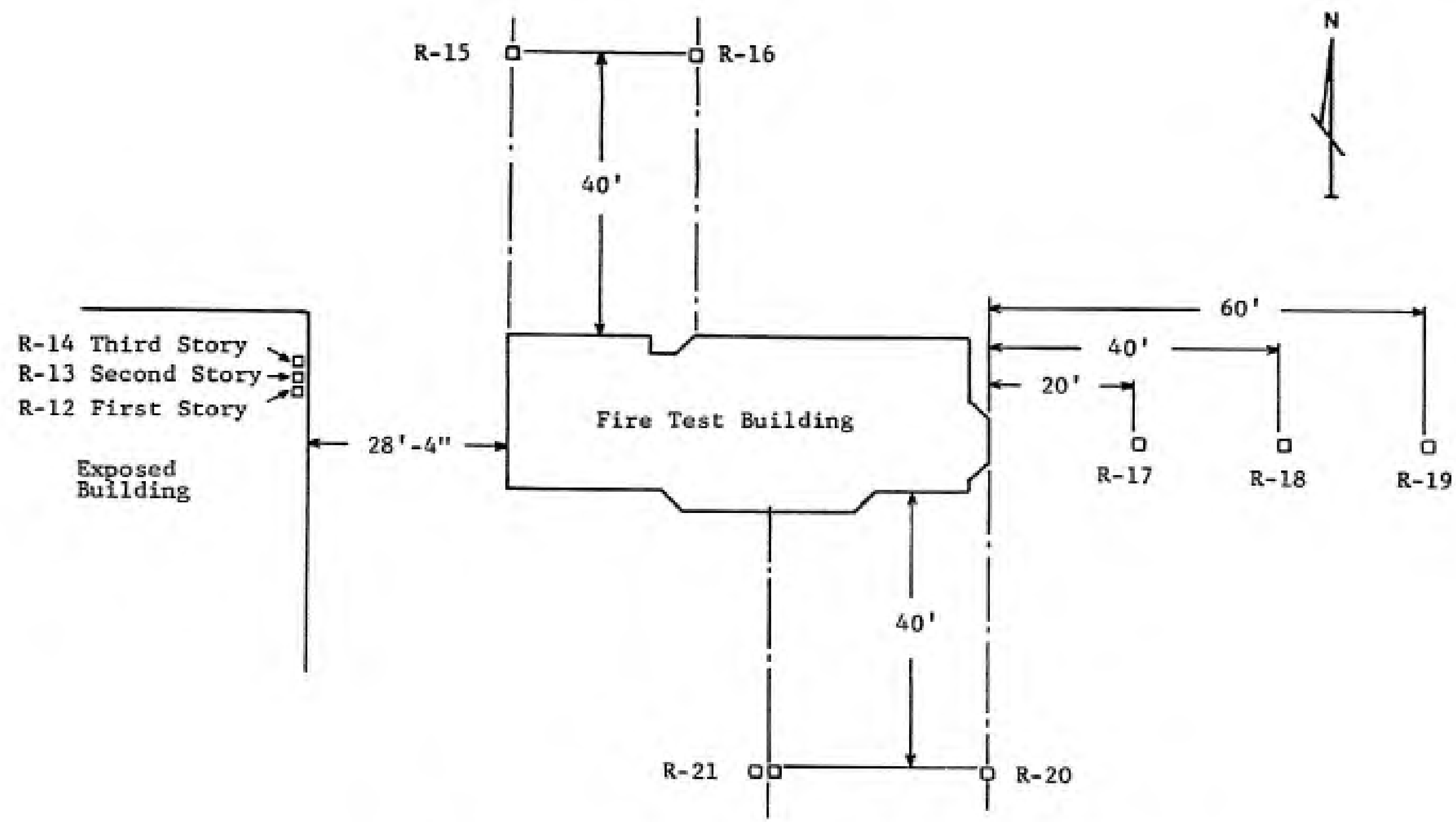


Fig. E-5 ELLIS PARKWAY BUILDING RADIOMETER LOCATIONS behavior after the initial flashover. Therefore, the size of the ignition source was important only insofar as it would assure flashover in the room of origin within a reasonable length of time. For this reason, no particular attention was paid to the design of the ignition source, except to make it large enough to perform its task.

The fire was started at 9:52.25 A.M. by ignition of a JP-4 primed wood crib located near the southwest corner of the second story living room. A photograph of the wood crib in place prior to ignition is shown in Fig. E-6. The crib consisted of thirty-five 1" x 2" pine sticks 18 inches long, arranged five sticks per tier and seven tiers high. The crib weighed 12.5 lbs. The crib was primed with approximately one-half pint of JP-4 fuel just prior to ignition.

F. Results and Discussion

1. General

The time history of the fire is described by a list of observations given in Section IV of this Appendix. An attempt has been made to include in this list all events which might have meaningful interpretation in the analysis of the fire. The events and their respective times were determined by a cross-check of pertinent data in various forms, i.e., visual, photographic, temperature and gas analysis records. Supplemented by data records, the observations represent the primary body of information used in the analysis of the fire.

Consistent with the location of the primary ignition on the second story, the fire spread through the building essentially as two independent fires, the second fire caused by ignition from the first fire. For discussion purposes these fires will be referred to as Fire A and Fire B.

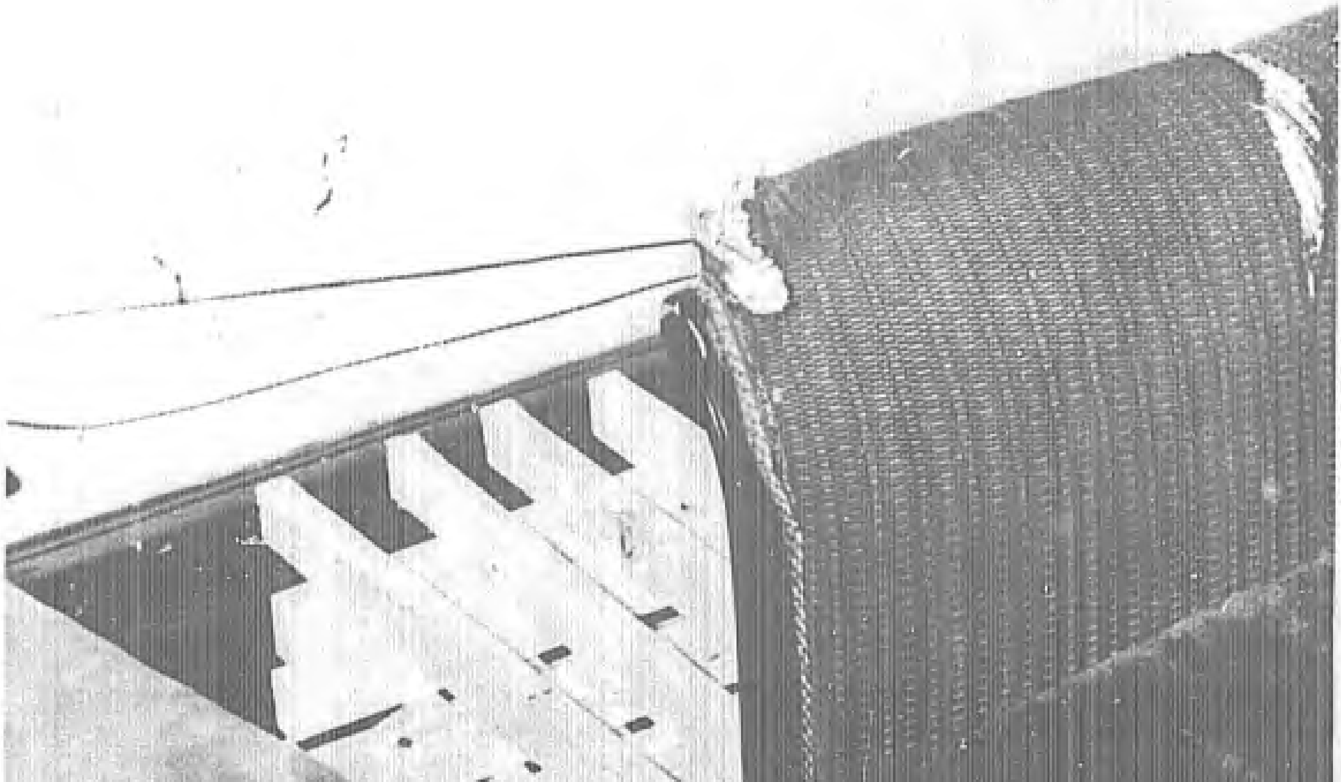


Fig. E-6 WOOD CRIB USED FOR IGNITION OF ELLIS PARKWAY BUILDING

Fire A involved burning of the partitions, interior trim, wood lath and combustible contents of the second story, as well as the total fire load of the third story, and the roof and dropped ceiling assembly.

Fire B involved burning of the partitions, interior trim, wood lath and combustible contents of the first story, as well as the floor assembly of the second story. Table E-2 describes the fuel distribution by weight and location, as defined above. The basement fire ultimately consumed the first story floor assembly, but this is not included in the above two fires.

The fire in the basement to some extent burned independently of the other two fires. However, other than to notice that there was a fire in the basement, no further observations were intended.

2. Volumetric Fire Spread By Flashover Analysis

a. Flashover in Each Story

Flashover of a particular space in a burning building is a readily recognizable event in the time history of a fire. Referring to Table E-3, Columns 1 and 2 represent a tabulation of the building spaces and the actual fire time at which flashover has occurred. Indications of flashover in a given space was based on visual observation, inspection of temperature, and gas concentration records. A sharp rise in temperature up to at least 900 to 1000°F, coupled with a sudden decrease in oxygen concentration, and increase in carbon monoxide concentration is a posivite indication of flashover. It was found, however, that most reliable results are obtained using temperatures measured at about half-way down the wall of a room rather than at the ceiling where the thermocouple may be exposed to licks of flames or hot gases prior to flashover.

Table E-2

ELLIS PARKWAY BURN. FUEL DISTRIBUTION AS CONSUMED BY FIRES A AND B

FIRE "A"			FIRE "B"		
Structure	Contents	Total Weight of Fuel	Structure	Contents	Total Weight of Fuel
lbs	lbs	lbs	lbs	lbs	lbs
10,680	None	10,680			
21,000	2520	23,520			
10,000[1]	2880[1]	13,480	10,400[1]		10,400
				2640	2,640
42,280	5400	47,680	10,400	2640	13,040
Total Fire Load[2] 13.2 lb/ft^2			Total Fire Load[2] 10.9 lb/ft^2		

1. In the Second Story, partitions, interior trim, wood lath on ceiling and contents burned with Fire "A"; Second floor assembly burned with Fire "B".

2. Fire "A": 47,680/3,600 = 13.2 lb/ft^2.
   Fire "B": 13,040/1,200 = 10.9 lb/ft^2.

Table E-3

ELLIS PARKWAY BURN - BUILDING VOLUME - TIME FLASHOVER DATA FOR EACH STORY

(1) Designation	(2) Actual Fire Time	(3) Continuous Time After Ignition τ	(4) Continuous Time After First Flashover (τ_o = 3.75min) $\tau_f = \tau - \tau_o$	(5) Adjusted Time After First Flashover	(6) Time After First Flashover at Each Story	(7) Individual Room Volume	(8) Cumulative Building Volume V_τ	(9) Volume Ratio V_τ/V_o
	hr. & min.	min.	min.	min.	min.	cu. ft.	cu. ft.	
Second Story Data								(V_0 = 1438)
Living Room	9:56.0	3.75	0.00	0.00	0.00	1438	1438	1.00
Front Hall	10:02.0	9.75	6.00	6.00	6.00	720	2158	1.50
Den	10:09.0	16.75	13.00	13.00	13.00	864	3022	2.10
Stairwell	10:18.0	25.75	22.00	22.00	22.00	1512	4534	3.15
Bedroom "A"	10:21.0	28.75	25.00	25.00	25.00	1170	5704	3.97
Rear Hall	10:27.0	34.75	31.00	26.00*	31.00	513	6217	4.32
Bedroom "C"	10:28.0	35.75	32.00	27.00*	32.00	720	6937	4.82
Pantry Area	10:28.0	35.75	32.00	27.00*	32.00	792	7729	5.37
Dining Room	10:28.6	36.35	32.60	27.60*	32.60	1386	9115	6.34
Kitchen	10:29.5	37.25	33.50	28.50*	33.50	891	10006	6.96
Bedroom "B"	10:30.0	37.75	34.00	29.00*	34.00	1080	11086	7.71
Bathroom	10:32.0	39.75	36.00	31.00*	36.00	378	11464	7.97
Third Story Data								(V_o = 1438)
Living Room	10:24.5	32.25	28.50	28.50	0.00	1438	1438	1.00
Den	10:28.0	35.75	32.00	32.00	3.50	864	2302	1.60
Bedroom "A"	10:28.5	36.25	32.50	32.50	4.00	1170	3472	2.41
Powder Room	10:29.0	36.75	33.00	33.00	4.50	288	3760	2.61
Front Hall	10:32.4	40.15	36.40	33.40**	7.90	720	4480	3.12
Rear Hall	10:32.6	40.35	36.60	33.60**	8.10	513	4993	3.47
Pantry Area	10:32.9	40.65	36.90	33.90**	8.40	792	5785	3.90
Bedroom "C"	10:33.0	40.75	37.00	34.00**	8.50	720	6505	4.39
Dining Room	10:33.0	40.75	37.00	34.00**	8.50	1386	7891	5.49
Kitchen	10:33.2	40.95	37.20	34.20**	8.70	891	8782	6.11
Bathroom	10:33.6	41.35	37.60	34.60**	9.10	378	9160	6.37
Bedroom "B"	10:35.0	42.75	39.00	36.00**	10.50	1080	10240	7.12
First Story Data								(V_o = 756)
Stairwell	10:47.0	54.75	51.00	51.00	0.00	756	756	1.00
Bedroom "C"	11:06.5	74.25	70.50	70.50	19.50	720	1476	1.95
Front Hall	11:06.5	74.25	70.50	70.50	19.50	720	2196	2.90
Dining Room	11:18.6	86.35	82.60	82.60	31.60	1386	3582	4.74
Bathroom	11:22.5	90.25	86.50	86.50	35.50	378	3960	5.24
Rear Hall	11:22.5	90.25	86.50	86.50	35.50	513	4473	5.92
Pantry Area	11:26.6	94.35	90.60	90.60	39.60	792	5265	6.96
Living Room	11:31.0	98.75	95.00	95.00	44.00	1456	6721	8.89
Kitchen	11:33.5	101.25	97.50	97.50	46.50	891	7612	10.07
Bedroom "A"	11:33.6	101.35	97.60	97.60	46.60	1170	8782	11.62
Bedroom "B"	11:35.3	103.05	99.30	99.30	48.30	1153	9935	13.14

* Adjusted by 5 minutes after collapse of second story living room; See Fig. E-7(a)

** Adjusted by 3 minutes after opening of stairwell roof; See Fig. E-7(a)

Columns 3, 4 and 6 of Table E-3 represent the same times as those in Column 2 calculated to a different zero base. Ignition is zero time in Column 3; flashover in the second story living room is zero time in Column 4; and flashover in the first room at each story is zero time in Column 6.

The cumulative building volume in each story which has become involved by flashover is listed in Column 8 of Table E-3. These volumes were calculated by accumulating the sums of the individual room volumes listed in Column 7.

The rate of fire spread in the building, as indicated by the progress of flashover, was first analyzed separately for each story. Figure E-7(a) and (b) represents a plot of the data in Columns 4, 5 and 8 of Table E-3. Column 4 is a continuous time scale for the entire fire, zero time being flashover in the second story living room, and the last entry (99.3 minutes) being the time at which flashover occurred to complete the spread of fire throughout the first story. The solid lines of curves in Fig. E-7(a) represent the actual accumulated volume spread of fire in the second and third stories. The step in each curve represents a delay in fire spread coincident with the change in flame and hot gas flow patterns, resulting from partial collapse of the structure, as noted on the curve for each story. The dotted lines of curves in Fig. E-7(a) represent an adjusted time for the flashovers, as they would have occurred without the delay in the progress of the fire; after collapse of the second story living room ceiling, a 5-minute adjustment of the time scale removed the step in the curve; a 3-minute adjustment of the time scale removed the step in the third story fire spread curve caused by opening of the stairwell roof.

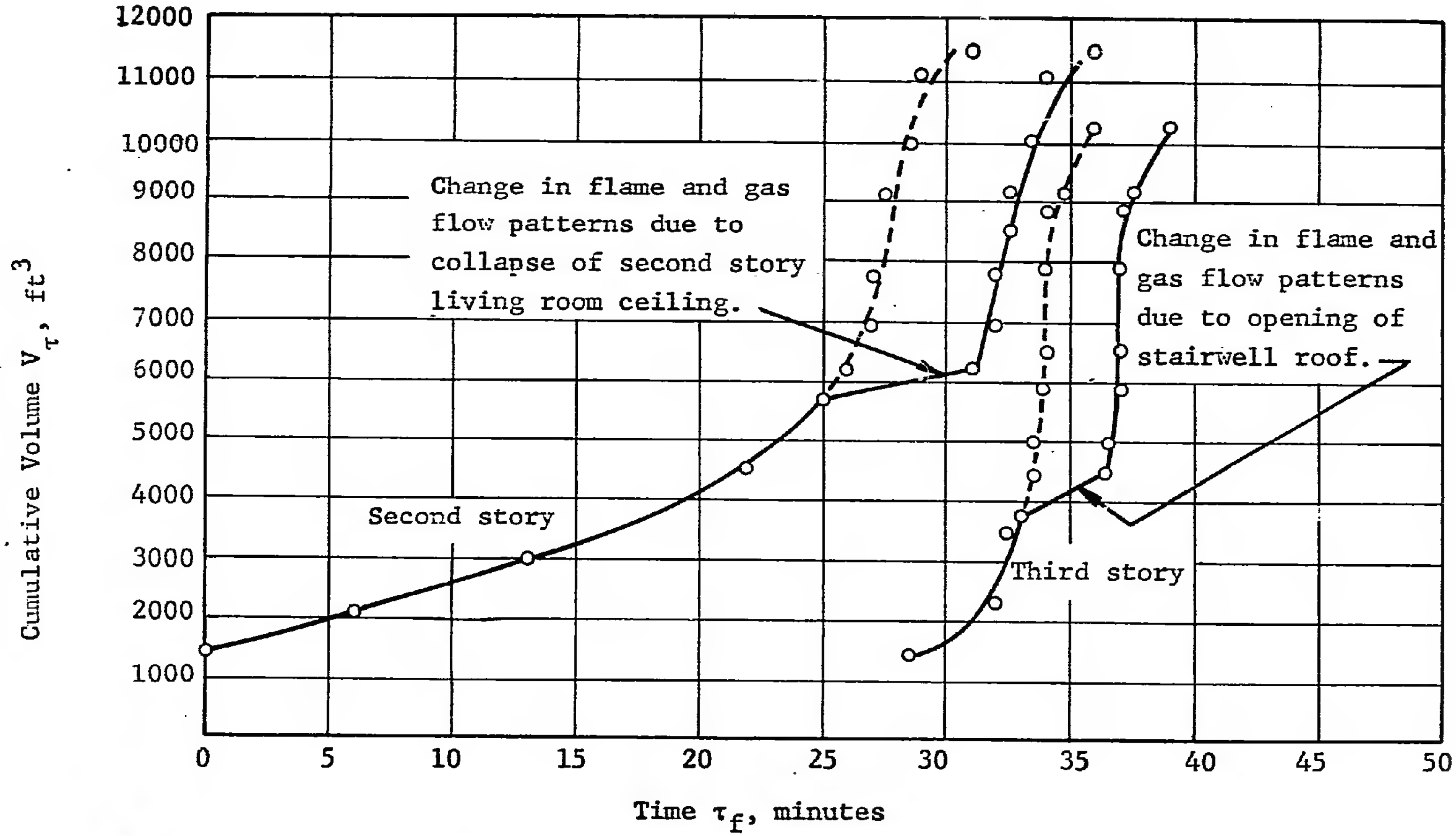


Fig. E-7(a). ELLIS PARKWAY BURN. SECOND AND THIRD STORIES VOLUME-TIME FLASHOVER DATA.

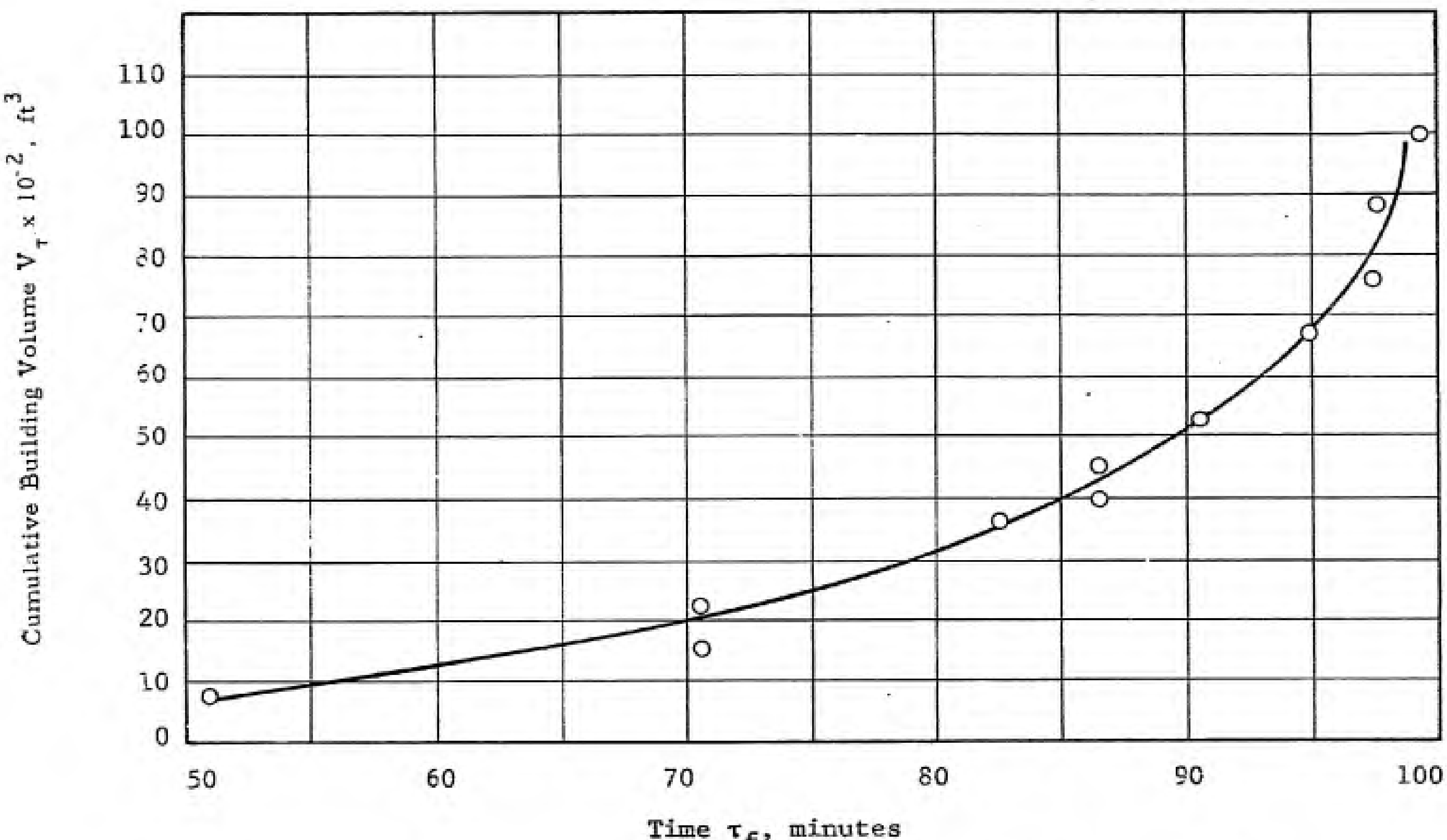


Fig. E-7(b). ELLIS PARKWAY BURN. FIRST STORY VOLUME-TIME FLASHOVER DATA.

The adjusted time scale is given in Column 5 of Table E-3. It is believed that such events control the spread of fire by temporarily reversing the flame and flow of hot gases.

One instance of a pseudo-flashover was recognized when the second story flashover data was assembled. Specifically, the door from the front hall into the stairwell was penetrated, and temperature records indicated a flashover. However, at this time the stairwell was a "dead-space" with no outlet to permit flow of gases. It was found necessary to include in the data analysis the pseudo-flashover of both the second and third story stairwell, rather than the true flashover which occurred at a later time after the roof had burned through and caused flow of gases through the stairwell.

The first story fire spread is shown in Fig. E-7(b). The initial flashover at this level occurred 51 minutes after flashover in the second story living room. Since the fire in the building originated in this room and spread downward, the data indicate that the second and third stories were completely involved at least 12 minutes before the initial flashover in the first story. Observations (Section IV) indicate that the downward spread of fire occurred as the result of burning material falling down the stairwell to the first story level. Figure E-7(b) shows that the fire spread in the first story as an independent fire. However, there is no doubt that this fire was under the continuous influence of the well established convective flow up the stairwell.

b. Combined Fire A and Fire B Flashover Data Analysis

The combined flashover data for the second, third and first stories are given in Table E-4. The time scale ($\tau - \tau_o = \tau_f$) in Column 2 is the same as that given in Column 4 of Table E-3, in which zero time

Table E-4

ELLIS PARKWAY BURN. CUMULATIVE BUILDING VOLUME-TIME FLASHOVER DATA SECOND, THIRD, AND FIRST STORIES (IN THAT ORDER)

(1)	(2)	(3)	(4)	(5)	
Actual Fire Time	Time After Flashover in 2nd Story Living room	Cumulative Building Volume V_τ	Fire A Volume Ratio V_τ/V_o	Fire B Volume Ratio 1st Story Only V_τ/V_o	Notes
Hr. and Min.	Min.	Cu. Ft.	V_o = 1438 ft^3	V_o = 756 ft^3	
9:56.0	0.0	1438	1.00		1. Flashover in 2nd story living room.
10:02.0	6.0	2158	1.50		
10:09.0	13.0	3022	2.10		
10:18.0	22.0	4534	3.15		2. Flashover in stairwell at 2nd and 3rd stories.
10:21.0	25.0	5704	3.96		
10:24.5	28.5	7488	5.20		3. Flashover in 3rd story living room.
10:27.0	31.0	8267	5.75		
10:28.0	32.0	9802	6.81		4. Collapse of 2nd story living room ceiling.
10:28.5	32.5	11,972	8.32		5. Change in flame pattern -- flaming ceases from 2nd story living room windows; flaming increases from 3rd story living room windows.
10:29.0	33.0	13,510	9.39		
10:29.75	33.75	14,703	10.22		6. Change in flame pattern -- temperature at top of stairwell (near skylight) reaches 1600°F; glass begins to flow out of skylight causing opening in stairwell roof.
10:32.4	36.4	15,944	11.00		
10:32.6	36.6	16,457	11.36		
10:32.9	36.9	17,249	11.90		
10:33.0	37.0	19,355	13.35		
10:33.2	37.2	20,246	13.97		
10:33.6	37.6	20,624	14.23		7. Flashover has involved entire 2nd and 3rd stories.
10:35.0	39.0	21,704	14.98		
10:47.0	51.0	22,460		1.00	8. Flashover in 1st story stairwell.
11:06.5	70.5	23,180		1.95	
11:06.5	70.5	23,900		2.90	
11:18.6	82.6	25,280		4.74	
11:22.5	86.5	25,664		5.24	
11:22.5	86.5	26,177		5.92	
11:26.6	90.6	26,969		6.96	
11:31.0	95.0	28,425		8.89	
11:33.5	97.5	29,316		10.07	
11:33.6	97.6	30,486		11.62	
11:35.3	99.3	31,639		13.14	9. Flashover has involved entire 1st story.

is flashover in the second story living room. The cumulative building volume in which flashover has occurred in sequence throughout the three levels is given in Column 3 of Table E-4. This data, as plotted in Fig. E-8, represents a volume summation of the three curves in Figs. E-7 (a) and E-7 (b). The steps in the second and third story curves are decreased by the summation. The curves show that the second and third stories burned as one fire (Fire A); and, that the first story fire, labeled Fire B, burned separately.

Various methods were tried to describe the volume flashover data of Table E-4 as a function of time. The method found best to correlate the data is discussed below.

c. Correlation of Flashover Data

Consideration of the curves of Fire A and Fire B in Fig. E-8, together with flashover data from other experimental building fires [1], suggest that, for every increment of time, the flashover volume increases by some constant multiple of the initial volume. To explore this possibility, the cumulative building volume (V_τ) at time τ_f, given in Column 3 of Table E-4, was divided by the building volume V_o at $\tau_f = 0$, for the respective Fires A and B (Columns 4 and 5). Since the first story burned as an independent fire (Fire B), the ratio V_τ / V_o was calculated as if the second and third stories were not present. The curves in Fig. E-9 represent a plot of these data for an equation of the following form:

$$V_\tau / V_o = e^{\tau_f / m} \qquad \text{(E-1)}$$

The values of the constants for the curves in Fig. E-9 are given in Table E-5.

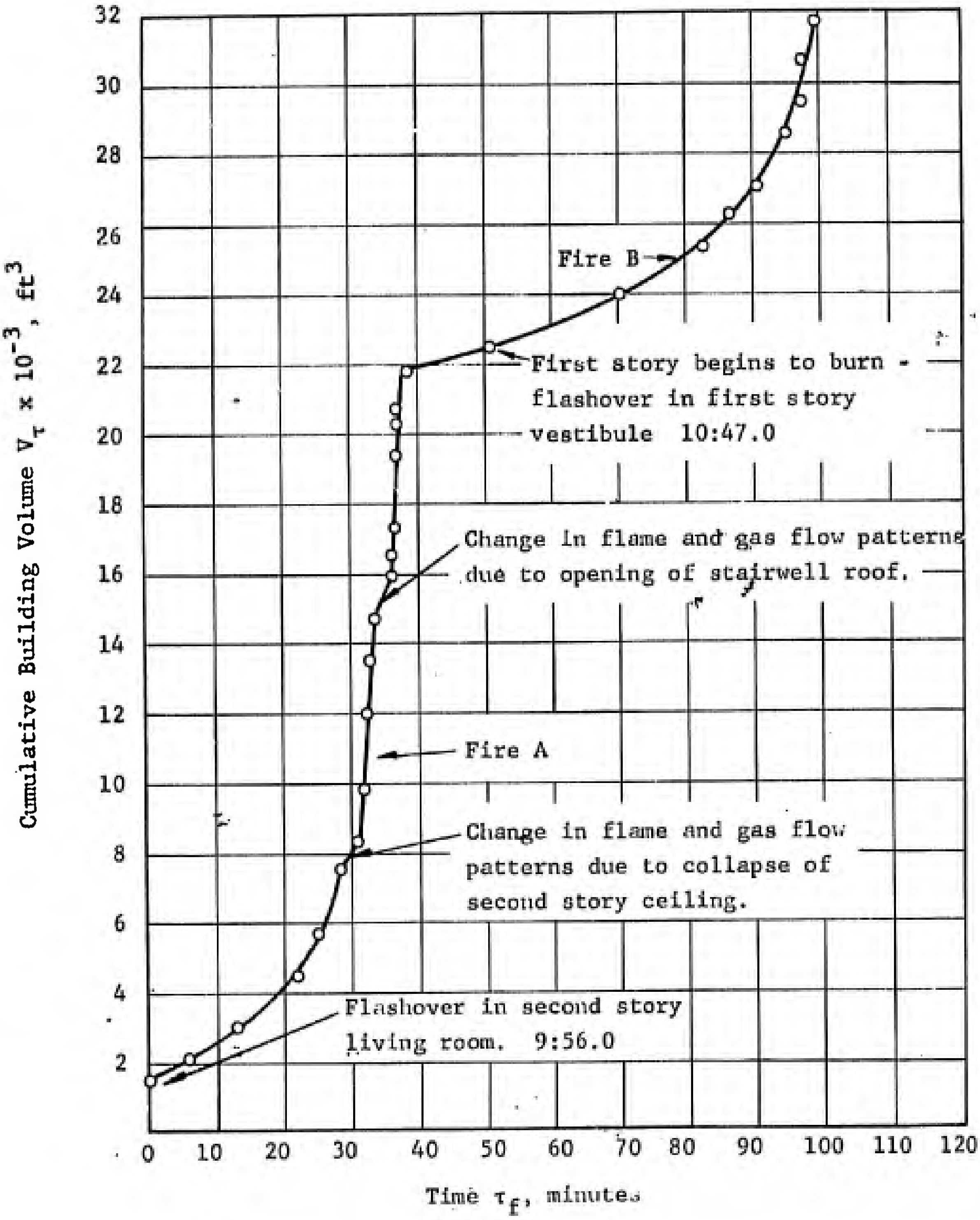


Fig. E-8. ELLIS PARKWAY BURN. CUMULATIVE VOLUMETRIC FLASHOVER DATA FOR FIRE A (SECOND AND THIRD STORIES) AND FIRE B (FIRST STORY)

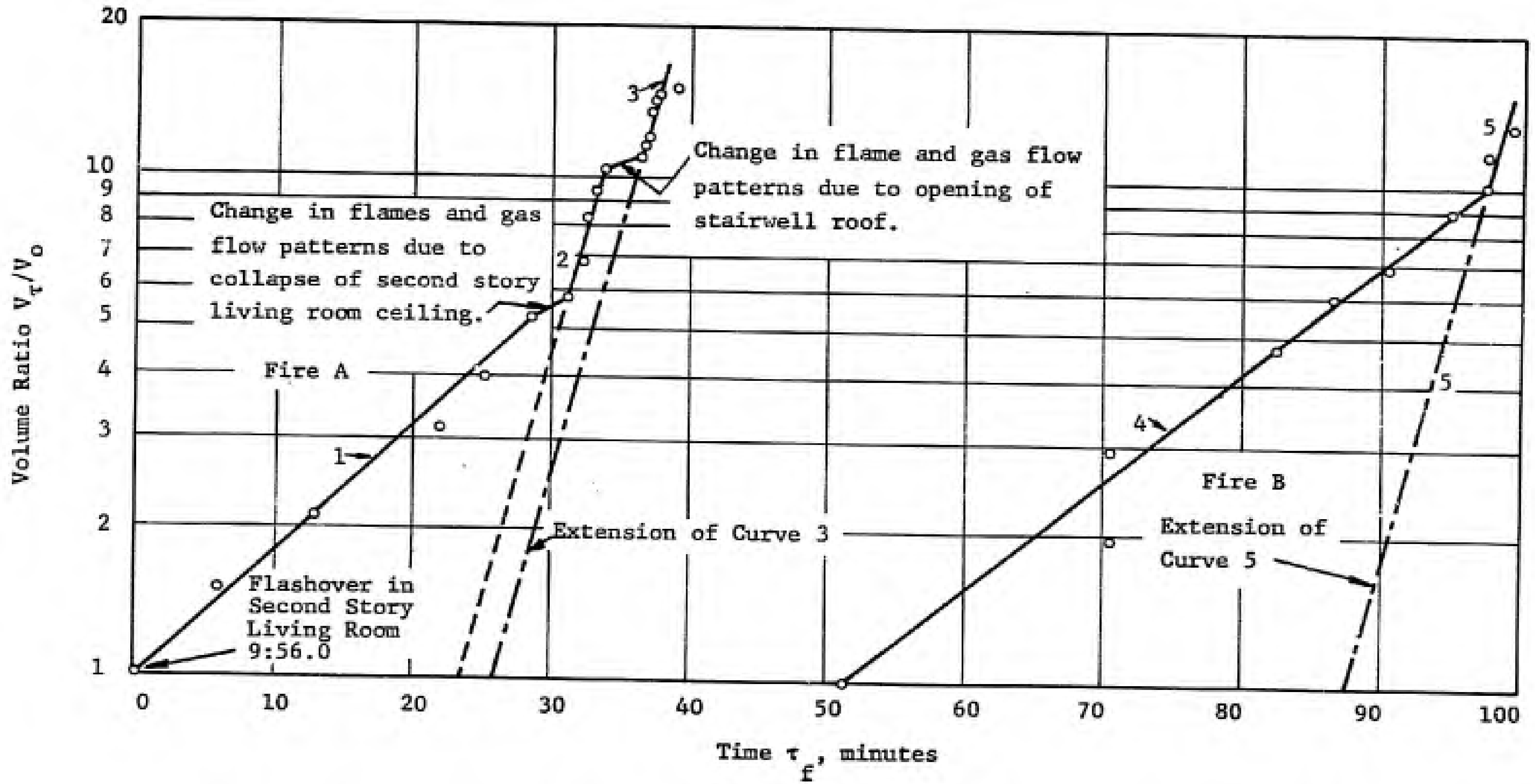


Fig. E-9. ELLIS PARKWAY BURN. CORRELATION OF VOLUMETRIC FLASHOVER DATA FOR FIRE A (SECOND AND THIRD STORIES) AND FIRE B (FIRST STORY).

Table E-5

ELLIS PARKWAY BURN CONSTANTS FOR CURVE IN FIGURE E-9

Description of Constants For the Equation: $V_\tau / V_o = e^{\frac{\tau_f}{m}}$	Fire A Second and Third Stories			Fire B First Story	
	Curve 1	Curve 2	Curve 3	Curve 4	Curve 5
Initial flashover volume at the origin of each fire. Vo (cu. ft.)	1438	1438	1438	756	756
Initial flashover time on continuous time scale. τ_o (min); i.e., $\tau_f = (\tau - \tau_o)$	3.75	3.75	3.75	3.75	3.75
Time Constant m (min.)	17.3	4.34	4.34	20.2	4.34
Time to double the volume $V_\tau / V_o = 2$ when $\tau_f = 0.693 \cdot m$ (min.)	12.0	3.0	3.0	14.0	3.0

Inspection of Fig. E-9 indicates that the suggested equation satisfactorily represents the data, including the steps in the curves described by previous plots. Except for wind effects, Fire A (Curve 1 of Fig. E-9) burned undisturbed in the second story for the first 25 minutes (see Fig. E-7(a); at τ_f = 32 (10:28.0) the second story living room ceiling collapsed near the end of a seven-minute delay in spread, as indicated by flashover volume. This event is located at the step between Curves 1 and 2. After penetration to the third story (Curve 2), the volume rate of flashover increased by four (4), doubling the flashover volume every three (3) minutes, instead of every twelve (12) minutes, as given in Table E-5 for Curve 1.

Penetration of the stairwell roof occurred at the time shown by the step between Curves 2 and 3 of Fig. E-9, resulting in a three-minute delay in fire spread. Apparently this event did not change the volume rate of flashover, since Curves 2 and 3 have the same slope. The data do not suggest a change in slope.

At τ_f = 39 (10:35.0) the fire had spread to the entire volume of the second and third stories. From τ_f = 39 to τ_f = 51 (10:47.0), fire spread downward in the stairwell to the first story. As indicated by Curve 4 of Fig. E-9, Fire B spread through 9179 ft^3 of building volume in 48.3 minutes, doubling its flashover volume every fourteen (14) minutes. It is likely that spread of Fire B was reduced for a time by the convective flow up the stairwell. Curve 5 of Fig. E-9 was drawn parallel to Curves 2 and 3 because of the trend of the two points, and for lack of evidence to do otherwise. No explanation of Curve 5 is offered. The slightly slower spread rate of Curve 4 as compared to Curve 1, may indicate the influence on Fire B of the convective flow up the stairwell.

The above discussion shows that the developed correlation describes well the fire spread rate indicating various events in the overall time history of the fire.

3. <u>Gas Analysis Data</u>

The volume per cent concentration of oxygen (O_2) and carbon monoxide (CO) derived from the gas analysis records is plotted as a function of time in Fig. E-10. The eight gas sample locations are identified by the same numbers shown in Fig. E-4 (a), (b), and (c). Discussion of the data follows the order in which fire spread through the building.

<u>Second Story</u>

The list of observations (Section IV) shows that flashover occurred in the pantry area and in bedroom "C" at 10:28.0 (τ_f = 32 min). For this location (G-8), the characteristic pattern of O_2 and CO curves at flashover, i.e., a sharp rise in CO concentration combined with a sudden decrease in O_2 concentration, is shown in Fig. E-10. In this instance, CO concentration reached a maximum in excess of 5 per cent while the O_2 concentration was reduced to about 0.5 per cent. At the same time, the temperature in these spaces increased from 400°F to 1400°F. Considering these high temperatures, together with high CO and low O_2 concentrations, it is obvious that at the time of flashover and for some time prior to flashover life can no longer exist.

<u>Third Story</u>

Fire penetration of the ceiling of the second story living room was observed at 10:21.5 (τ_f = 25.5 min) and collapse of this ceiling occurred at 10:28.0 (τ_f = 32.0 min). According to Fig. E-10, gas sampling locations

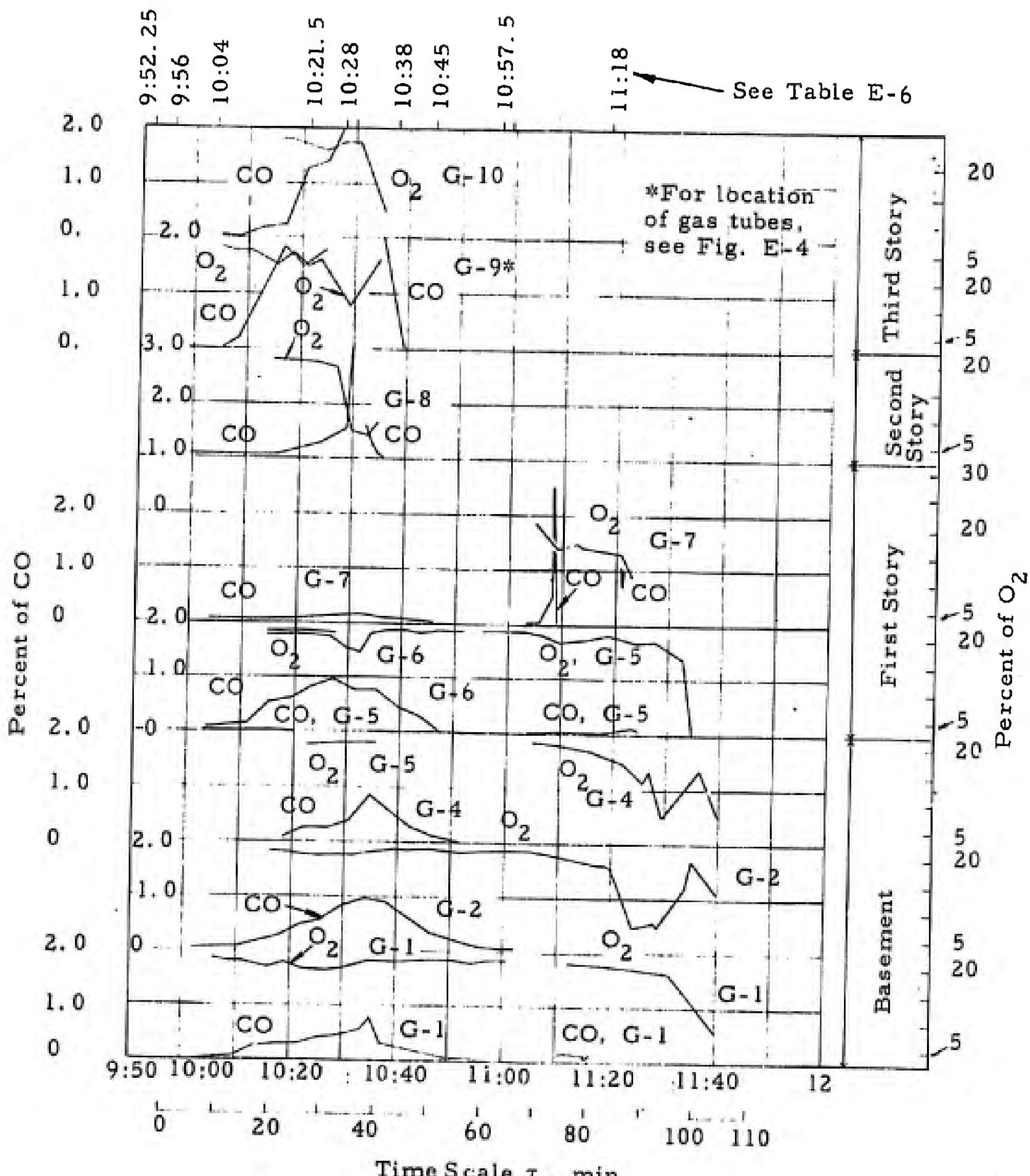


Fig. E-10 ELLIS PARKWAY GAS ANALYSIS DATA

Table E-6

REMARKS TO FIGS. E-10, 11, AND 12

TIME	EVENT
9:52.25	Ignition
9:56.0	Flashover in 2nd story living room
10:04.0	Penetration of 2nd story apartment door
10:09.0	Flashover in 2nd story den
10:21.0	Flashover in 2nd story bedroom "A"
10:21.5	Penetration of 2nd story living room ceiling
10:24.5	Flashover in 3rd story living room
10:28.0	Collapse of 2nd story living room ceiling Flashover in 3rd story den
10:28.5	Flaming increases from 3rd story living room windows
10:28.5 - 10:29.5	Flashover in 3rd story bedroom "A", 2nd story dining room and 2nd story kitchen
10:30.0	Temperature at stairwell skylight reaches 1600 °F
10:33.0 - 10:33.2	Flashover in 3rd story dining room and kitchen Gas sampling lines 6, 9 and 10 disconnected
10:40.0	Wind velocity 6 mph S-SW
10:45.0	Front half of roof is open (collapse)
10:50.0	Center section of roof is open (collapse)
10:55.0	Rear third of roof has opened
10:57.5	Gas analyzer lines 5 and 7 reconnected
10:59.5	Flames from 1st story apartment now going into stairwell
11:18.0	Active fire in basement
11:31.0	Flashover in 1st story living room
11:34.7	Collapse of 1st story ceiling at rear of building
11:35.5	1st story living room ceiling starting to collapse
11:50.3	1st story ceiling completely collapsed
11:52.0	Most of 1st story collapsed to basement
11:54.3	Basement completely on fire
11:57.0	Collapse of north wall at rear of building
12:05.5	Collapse of south wall at rear of building

G-9 and G-10, the CO concentration began to increase at about 10:09 (τ_f = 13.0 min) and reached a maximum in excess of 5 per cent just after collapse of the ceiling. The gas sampling location, G-9, being closer to the living room (first penetrated) tended to lead the G-10 location in CO concentration by about eight minutes. During the same period of time the O_2 concentration decreased to between 5 and 10 per cent.

Gas sampling lines connected with locations G-8, G-9 and G-10 were disconnected at 10:38.0 (τ_f = 42 min).

First Story

Penetration by fire of the door to the second story apartment occurred at 10:04.0 (τ_f = 8 min). Beginning at about the same time, this event, by permitting fire gases to flow into the stairwell, could account for the steady rise of CO concentration at G-6 gas sampling location, indicated in Fig. E-10. However, it is more likely that the CO was coming from the basement, since the fire gases are lighter than air and tend to flow upward. The CO concentration at G-6 reached a maximum value of just under 1 per cent at about 10:27.5 (τ_f = 31.5 min) after which a steady decline occurred until 10:47.5 (τ_f = 51.5 min).

Between the times 10:26.5 and 10:35.0 (τ_f = 30.5 to 39.0 min) the O_2 concentration decreased to a minimum value of 17 per cent at 10:32.5 (τ_f = 36.5 min). It is believed that the fire gases were trapped in the stairwell until 10:30.0 (τ_f = 34 min). At this time, the temperature at the top of the stairwell reached 1600°F and the wired glass began to flow out of the skylight permitting gas flow out of the stariwell. At 10:43.5 (τ_f = 47.5 min) the front half of the roof collapsed and gas flow up the stairwell is believed to have increased to a substantial rate, tending to purge the stairwell of fire gases.

Since no adequate record was obtained, the data from gas sampling lines G-5 and G-7 are not considered to be significant. However, it is of interest to note that flashover was observed in bedroom "C" (location of G-7) at 11:06.5 (τ_f = 70.5 min); this event may account for the sudden change in CO and O_2 concentration indicated in Fig. E-10.

Basement

The CO and O_2 concentration records of gas sample locations G-1, G-2 and G-4 shown in Fig. E-10 prior to 11:30 (τ_f = 64 min) appear to have the same general form as that described for G-6 located in the first story stairwell. The peak CO concentrations at G-1, G-2 and G-4 were 0.75 0.95 and 0.85 per cent, respectively. All occurred at about 10:35 (τ_f = 39 min), about 7.5 minutes after the peak CO concentration at G-6. The presence of CO in the basement at this stage of the fire is believed to be the result of generation of fire gases under pressure within walls causing flow downward as well as upward from the second story through the hollow partitions and channels in the furred exterior wall finish. Since the basement and first story stairwell were connected by an open stairway, flow of fire gases from the basement into the stairwell would first be detected by G-6. Gas sample locations G-1, G-2 and G-4, being about three feet above the basement floor, would therefore lag the G-6 location. During this same period of time, prior to 11:30 (τ_f = 64 min), the O_2 concentrations at G-1, G-2 and G-4 varied less significantly; in fact, the lack of a sudden decrease in concentration supports the conclusion that a flashover had not occurred in the basement at this time.

For the period after 11:00 (τ_f = 64 min), records of gas sample locations G-1, G-2 and G-4 shown in Fig. E-10 appear to indicate flashover in the basement. The sudden decrease in O_2 concentrations coincides with the observation of active fire in the basement at 11:18 (τ_f = 82 min). The CO records, if obtained, would show another rise in concentration, probably much higher than those obtained earlier in the basement.

4. Analysis of Anemometer Data

Records produced by the eight anemometers, installed as described in Section D (Instrumentation) are plotted as a function of time in Fig. E-11. The anemometer and window identification numbers are the same as those given in Fig. E-4. Discussion of these data follows the order in which fire spread through the building. Due to the fact that all windows were open during the fire, the entire building would be expected to "breathe", subject to interference by doors between the stairwell and each apartment.

The record of wind velocity and direction is given in Table E-7. By inspection of the table it appears that 5 MPH (7.3 ft/sec) is a fair average wind velocity; also, the wind direction was reasonably steady southwest to south-southwest. It should be pointed out that the influence of wind was not as much as might be expected. A large 4-story building, located approximately thirty feet west of the rear of the experimental building, extended to the south and acted as a wind barrier.

For a number of reasons it has been found difficult to interpret the anemometer records in a meaningful way in terms of the sequence of observations (Section IV) made during the fire. These reasons were:

1. The anemometers only indicate magnitude of flow and not the direction.

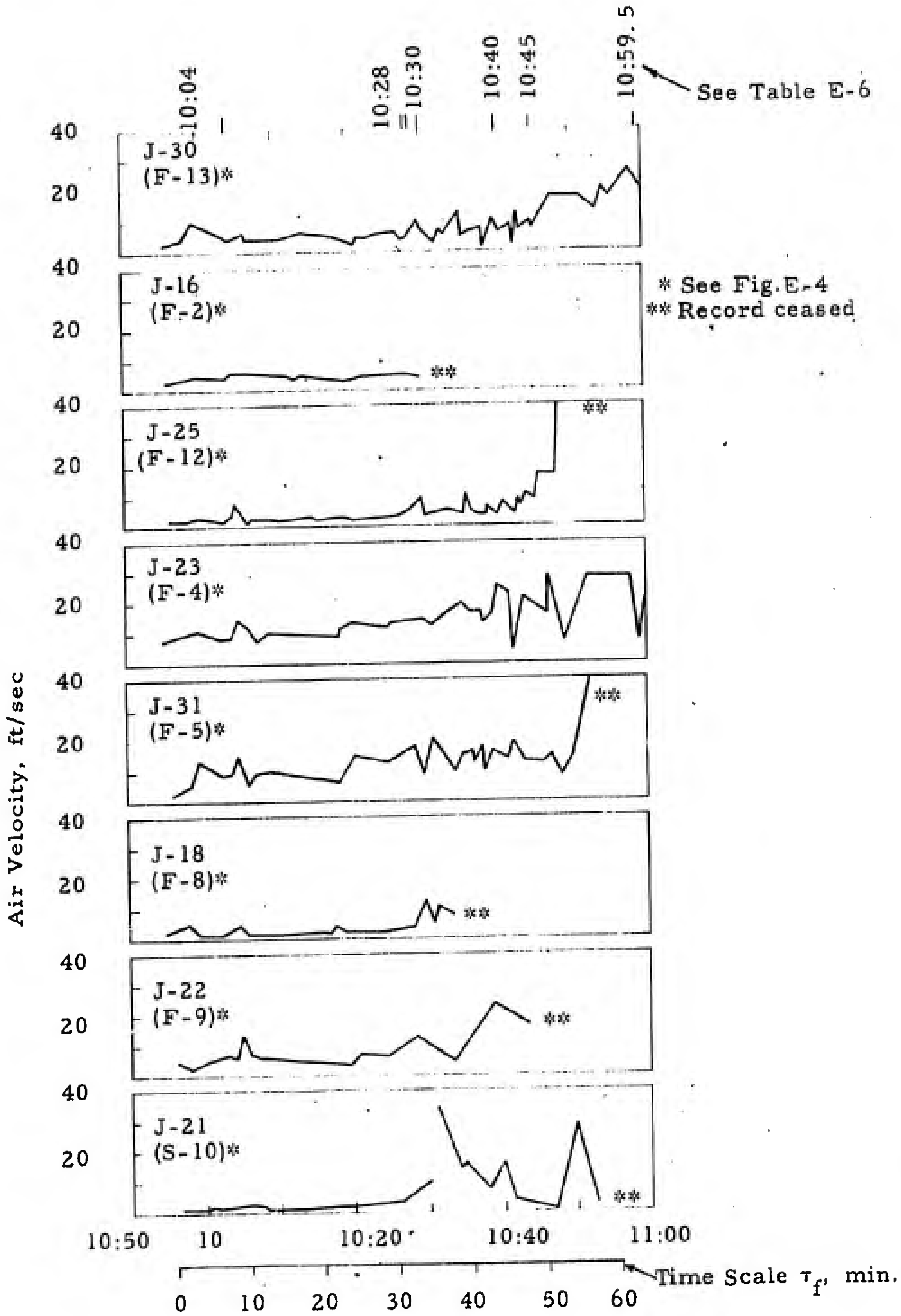


Fig. E-11 ELLIS PARKWAY BURN ANEMOMETER DATA

Table E-7

ELLIS PARKWAY BURN
RECORD OF WIND VELOCITY AND DIRECTION

Clock Time	Fire Time τ_f, Min	Wind * Velocity MPH	Wind Direction
10:04.0	8.0	5	S.W.
10:19.5	23.5	4-6	S.W.
10:31.0	35.0	4-10	S.W.
10:51.5	55.5	10	S.W.
10:58.0	62.0	4-5	--
11:03.0	67.0	5-8	S.S.W.
11:11.0	75.0	5	S.S.W.
11:15.0	79.0	5-7	S.S.W.
11:27.0	91.0	5	--
11:28.5	92.5	9	S.S.W.
11:38.3	102.3	4	S.S.W.
11:40.5	104.5	6	S.S.W.
11:46.0	110.0	7	S.S.W.
11:49.0	113.0	3	S.S.W.

*Note: 1 Mph = 1.467 ft/sec.
10 ft/sec = 6.82 Mph.

2. Anemometers were not located at every wall opening. No anemometers were located at the third story level.

3. The anemometers are very sensitive to flow of air at normal atmospheric temperatures, become less sensitive as gas temperatures increase, and useless in the presence of flames and high temperature fire gases.

Hence, in view of these limitations, it is possible only to interpret the records in terms of gross effects, neglecting the intermediate fluctuations in air velocities.

Inspection of Fig. E-10, including the remarks taken from the list of observations, reveals a marked contrast between recorded fluctuations in air velocities prior to and after 10:30 (τ_f = 34.0 min). Except for a small peak at 10:05 (τ_f = 9.0 min), the record indicates air velocities at the various locations were rather well stabilized between 2 to 10 ft/sec from the initial flashover until about 10:28.5 (τ_f = 32.5 min). It is conceivable that penetration of the second story apartment door into the stairwell at 10:04 (τ_f = 8 min) is responsible for the above-mentioned peak at 10:05.

Anemometer records of air velocities after 10:30 (τ_f = 34.0 min) show a considerable increase in nu r of fluctuations, as well as amplitude. It is believed that the increase in recorded air velocities is associated with progressive increase in flow of fire gases between stories and up the stairwell. When first penetrated at 10:04 (τ_f = 8 min) the stairwell at the second and third story level was a pocket of hot gases. Collapse of the second story living room ceiling occurred at 10:28.0 (τ_f = 32 min). This event no doubt caused the change in lame pattern recorded in the observations at 10:28.5. Shortly after, at 10:30 (τ_f = 34.0 min), the temperature at the top of the stairwell reached 1600°F; at this temperature the wired glass in the skylight would soften and begin to flow away from the wire mesh, marking the beginning of the opening at the top of the stairwell. From this time on, flow of fire gases would increase due to enlargement of the opening by roof collapse. Collapse of various portions of the building interior would no doubt contribute to the fluctuation of air velocities.

5. Radiometer Data

a. General

Records produced by the ten radiometers installed as described in Section D (Instrumentation) are plotted as a function of time in Fig. E-12. The records have been grouped according to the location of the .diometers. The radiometer identification numbers given in Fig. E-5 corresp. nd to those assigned to the records shown in Fig. E-12. The window identification numbers correspond to those given in Fig. E-2. The following discussion compares first the flame radiation from model room burns (Appendix B) and the full-scale building fire. Subsequently, calculated radiation intensities are compared with radiometer records for the front (east) and south sides of the building.

Conditions at the front and south side of the building enabled direct comparison of flame radiation between the full-scale building fire and the model room burns described in Appendix B of this report. In general, the flame size encountered with the model rooms was larger than that observed in the full-scale building. This is consistent with the belief that the fire in the full-scale building was predominantly ventilation controlled. In the latter condition, more of the fuel gases tend to burn

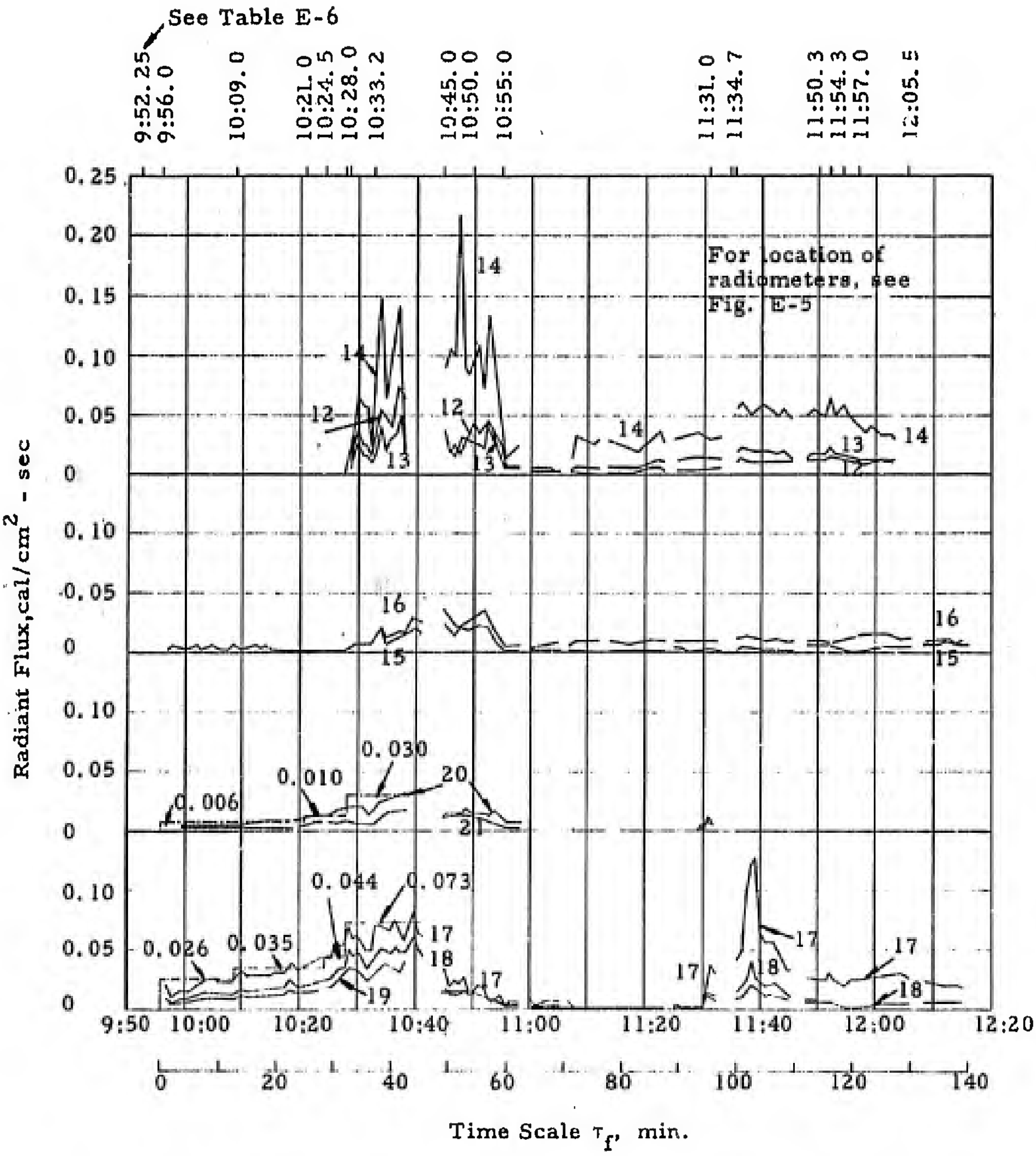


Fig. E-12 ELLIS PARKWAY BURN. RADIOMETER DATA outside of the windows. According to the presently used equations (see Appendix B) the burning rate is given by $R_v = 1.5 A_w \sqrt{h}$ for a ventilation controlled fire in a room, or $R_s = 0.09 A_s$ for a fuel controlled fire. The fuel surface area (A_s) in the second story living room was estimated as 496 ft^2, including the wood floor area. The window area (A_w) was 48.3 ft^2 with a window height (h) of 5.8 ft. With these data one obtains R_v = 175 lb/min and R_s = 44.6 lb/min. This indicates that the fire in the second story living room was fuel controlled since the burning rate cannot be more than the lesser of these two values. For a fuel controlled fire in a room with extreme excess ventilation, no flames will be present above the window since all combustion occurs inside the room. As the amount of fuel is increased (or window area decreased) flames will appear above the window as a result of escaping combustibles not burned inside the room. In the transition region, the flame increases in height until it reaches a maximum as ventilation controlled conditions are approached.

b. Comparison of Calculated and Recorded Radiation Intensities

Radiant flux from the front of the building was monitored by three radiometers, R-17, R-18 and R-19, located a distance of 20, 40 and 60 feet from the center of the bay as shown in Fig. E-5. Radiometer R-20 was positioned in the plane of the front face and forty feet south of the building to include windows as well as to view the side of the flames issuing from the front windows. Following successive flashovers in the second story living room, den and bedroom "A" and in the third story living room, these radiometers indicate a steady increase in radiant flux. After 10:28.0 (τ_f = 32 min) marking the collapse of the second story living room ceiling, followed by a flashover in the third story den and bedroom "A", the records continue to show the same increasing trend but with many more fluctuations in values. Fire conditions before and after collapse lead to vastly different flame patterns and, therefore, important changes in radiant flux. These conditions are discussed as the One-Story Case (before collapse) and the Two-Story Case (after collapse). Flame temperatures were found to be higher in the Two-Story Case (1600°F) than in the One -Story Case (1500°F).

1. One-Story Case

Since the fire in the second story living room was found to be fuel controlled, resulting in flame size smaller than that encountered with the model rooms, it is expected that the flame radiation from these windows will be less than that observed for the model room experiments. This should also be true for other locations radiating according to the same flame model.

Consider the flame radiation from the second story living room windows prior to 10:09 (τ_f = 13 min). Calculation of the radiant flux received by radiometer R-17 using a 1500°F flame temperature, an emissivity of one (1) and the radiating source being the S-1, S-2 and S-3 (Fig. E-2) window areas only (no flame above windows) gives a value of I = 0.026 cal $cm^{-2}sec^{-1}$. This value is shown by a dotted line in Fig. E-12. The next two levels in the stepped (dotted) curve in Fig. E-12 represent calculations of radiant flux received by radiometer R-17 using the same flame model. The flux was increased by radiation from windows S-13, T-1, T-2, and T-3 because of successive flashovers in the second story den and the third story living room. In this case the flux leaving the radiator was about two-thirds (2/3) of that observed in the model room burns. While flame was visible above the windows, it was thin and apparently a sufficiently poor radiator that it can be neglected in these calculations.

Similarly calculated was a stepped curve, shown in Fig. E-12, for radiometer R-20 viewing the side of the flames from the south side of the building. The first two steps ($I = 0.006$ and 0.010 cal $cm^{-2}sec^{-1}$) represent the radiant flux received from window S-3 and the side view of flame from window S-2, followed by the radiation from window S-4 after flashover in bedroom A. The flame model for windows S-3 and S-4 is the same as that used above for windows S-1, S-2, and S-3, neglecting flame above the windows. The radiation from the side view of flame above window S-2 was calculated using temperature of 1500°F, an emissivity of one (1) and the radiating area having a height h and width h/2, where h = window height. Since the flame thickness was equal to the window width, the radiation from the side of the flame was significant, even though radiation from the front view was negligible.

3. Two-Story Case

The fourth step in the dotted curve ($I = 0.073$ cal $cm^{-2}sec^{-1}$) fitting the data of radiometer R-17 in Fig. E-12 was calculated for the conditions at the front of the building after 10:28 ($\tau_f = 32$ min) corresponding to the collapse of the second story living room ceiling and flashover in the third story den. Since the living room and den at the third story level were connected by a large archway, calculations were made on the basis that fresh air would flow into the second story living room windows and flames and hot gases would flow under forced draft out of the windows of the third story living room and den. The radiant flux received by radiometer R-17 was calculated using a 1600°F flame temperature, an emissivity of one (1) and the radiating source as outlined below:

1. Flame radiation from windows S-1, S-2, S-3, T-1, T-2, T-3 and T-13.
2. Radiation from flame above windows T-1, T-2, T-3 and T-13.
3. An exception to the above, window S-13 in the second story den was not considered influenced by the forced draft conditions and, therefore, radiated at 1500°F, an emissivity of one (1) with no flame above the window, according to the previous model.

To calculate the radiant flux, flames above the third story windows were assumed to have a width (w) equal to that of the window and height equal to one and one-third (1-1/3) of the window height, (h). For lack of supporting information, this flame model was arrived at by considering that the total radiation under forced draft conditions in the full-scale burn would be equal to two-thirds (2/3) of that obtained in model burns. In the latter case the total radiating area is 5 h x w. Hence, the assumed two-thirds (2/3) reduction gives a total radiating area of three and one-third (3-1/3) h x w for the full scale burn. Since the radiating area of the windows is 2 h x w, the flame height above the second story window is 1-1/3 h.

Similar calculations were made for the third step in the curve following radiometer R-20 in Fig. E-12, indicating that $I = 0.030$ cal $cm^{-2}sec^{-1}$. The radiant flux received by radiometer R-20 was calculated using a 1600°F flame temperature, an emissivity of one (1) and the radiating

Table E-8

FLAME MODELS FOR THE ELLIS PARKWAY BURN

	FRONT VIEW			SIDE VIEW		
	Temp. °F	Emissivity	Flame area above windows	Temp. °F	Emissivity	Flame area above windows
One Story Case	1500	1	None	1500	1	$h^2/2$
Two Story Case	1600	1	1-1/3 hw*	1600	1	1-1/3 hw

*h = window height
w = window width

source as outlined below:

1. Flame radiation from windows S-3 and T-3.

2. Radiation from flame above windows T-2 and T-3.

3. An exception to the above, windows S-4 and T-4 in bedroom "A" at the second and third stories, respectively, were not considered influenced by the forced draft conditions and therefore radiated at 1500°F, an emissivity of one (1), with no flame above the windows, according to the previous model.

For the purpose of calculations, flames above the third story windows were assumed to have a width equal to that of the windows and a height equal to one and one-third (1-1/3) the window height. These assumptions were made for reasons previously described.

Comparison of the calculated (dotted) curves in Fig. E-12 with the records for radiometers R-17 and R-20 indicates that the suggested flame models represent fairly well conditions resulting from a fuel-surface controlled building fire. The flame models, summarized in Table E-8, permit the calculation of omitted radiant flux at various stages of fire spread throughout the building. This information is of vital importance for determining the fire spread between structures.

6. Penetration and Collapse Time

In this section comparison is made between predicted and observed fire penetration and collapse times of structural members. As indicated below, the agreement seems to be quite satisfactory.

It was previously reported[2] that the fire penetration time for walls, floors and partitions may be estimated by subtracting four (4) minutes from the fire resistance time, as determined by the A. S. T. M.

E-119, "Standard Methods of Fire Tests of Building Construction and Materials". This rule was limited to structural assemblies which fail in the fire test by burn-through or collapse. This rule is extended in Appendix B (Fig. B-12) of this report, in which comparison is made of actual fire behavior of various fire barriers to their fire resistive rating. The penetration curve shows that the penetration time may be determined by subtracting four (4) minutes from the fire resistance rating for barriers having a rating exceeding about 25 minutes. Evidence supporting this rule was found in the Ellis Parkway Burn.

Specifically, the observations given in Section IV show that after flashover, 25.5 minutes was required for the fire to penetrate the second story living room ceiling. This ceiling and floor assembly consisted of nominal 1-inch hardwood flooring on a 1-inch soft wood sub-floor, supported by 2" x 10" wood joists and sheathed on the under side with wood lath and plaster. The accepted fire resistance rating for this barrier is 30 minutes; subtracting four (4) minutes, according to the rule discussed above, gives 26 minutes for the penetration time. The time from flashover on one side of a fire barrier with a 30-minute rating to flashover on the other side is given in Fig. B-2 of Appendix B as 28 minutes. This time was obtained by subtracting two (2) minutes from the fire resistance rating. The observations show that flashover occurred in the third story living room 28.5 minutes after flashover in the second story living room.

In 1952, Lawson, Webster and Ashton[3] presented a method of calculating the fire endurance of timber beams and floors. This method predicts 39 minutes collapse time for the second story living room ceiling, 15 minutes protection provided by the wood lath and plaster covering the underside of the joists. According to the observations given in Section IV of Appendix E, the actual collapse time in this fire was 32 minutes.

Downward spread of fire occurred in the Ellis Parkway Burn only because of burning materials falling down the stairwell to the first story. This is a common mechanism responsible for downward spread, in comparison to direct downward penetration through a combustible floor. Usually debris will collect on the wood floor and provide some protection against burn-through.

III. OTHER EXPERIMENTAL BUILDING FIRES

This section gives a brief description of four of the full-scale building fire experiments performed in addition to the Ellis Parkway Burn. The Gary Dwelling Burn was a free-burning fire with no attempt to extinguish or control at any time. It was found possible to compare directly the flashover data of the Gary Dwelling Burn with that of the Ellis Parkway Burn. The other three burns were free-burning fires combined with extinguishment studies, and therefore had limited application and are treated here in less detail.

A. Gary Dwelling Burn

An experimental fire was set in an instrumented one-story dwelling located in Gary, Indiana. Since the building was to be razed, the IITRI obtained the permission and cooperation of the Gary, Indiana, Fire Department to use this building for an experimental fire.

The building was 27 feet wide by 50 feet long (1350 ft^2), one story high with basement and attic. A photograph of the building is shown in Fig. E-13. The elevation and plan views of the building are shown in

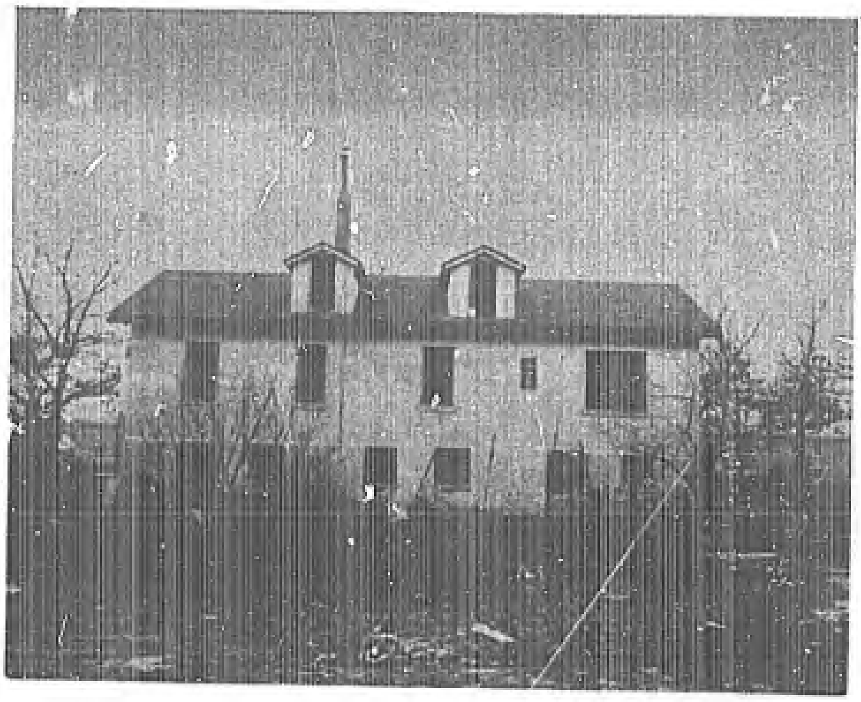


Fig. E-13 PHOTOGRAPH OF DWELLING USED IN GARY, INDIANA, FIELD EXPERIMENTS

Fig. E-14 (a) and (b). Exterior walls were made from hollow concrete blocks. The first floor was constructed of laminated railroad ties supported on the concrete block foundation wall and a central wood beam and three wood posts. The finished floor surface was concrete. The roof was composition shingles on 1-inch boards, supported on 2" x 8" rafters. The 8-foot high ceiling over the first floor was 2" x 8" joists supporting 1-inch sheathing, covered with a skim coat of plaster. Interior partitions were wood lath and plaster on 2" x 4" wood studdings. All glass was broken out of the windows when the building was acquired; prior to the fire, the windows were covered with a polyethylene film.

The structural fire load was calculated to be 13.8 lbs/ft^2 of floor area. This value includes the interior partitions, ceiling joists, and wood sheathing and the wood roof assembly. Since the fire did not involve the wood floor construction during the time period of interest, this part of the structure was not included in the fire load. The contents fire load was determined to be 2.8 lbs/ft^2 of floor area; this included household furniture, rugs and clothing distributed throughout each room of the dwelling. The attic space was empty. The total fire load for the dwelling amounted to 16.6 lbs/ft^2 of floor area, not considering the attic or basement as another floor.

Two 16 mm time-lapse cameras were used to photograph the entire fire history. As shown in Fig. E-14 (b), the cameras were located opposite the northeast and the southwest corners of the building with synchronized electric clocks in the field of view of each camera. A third 16 mm camera was used by a roving photographer accompanied by an aide to make notes of each exposure and the time.

Fig. E-14a. ELEVATION VIEWS OF GARY DWELLING

Note: TC indicates thermocouple locations. All thermocouples located on the wall five feet above the floor. Ceiling height is eight feet.

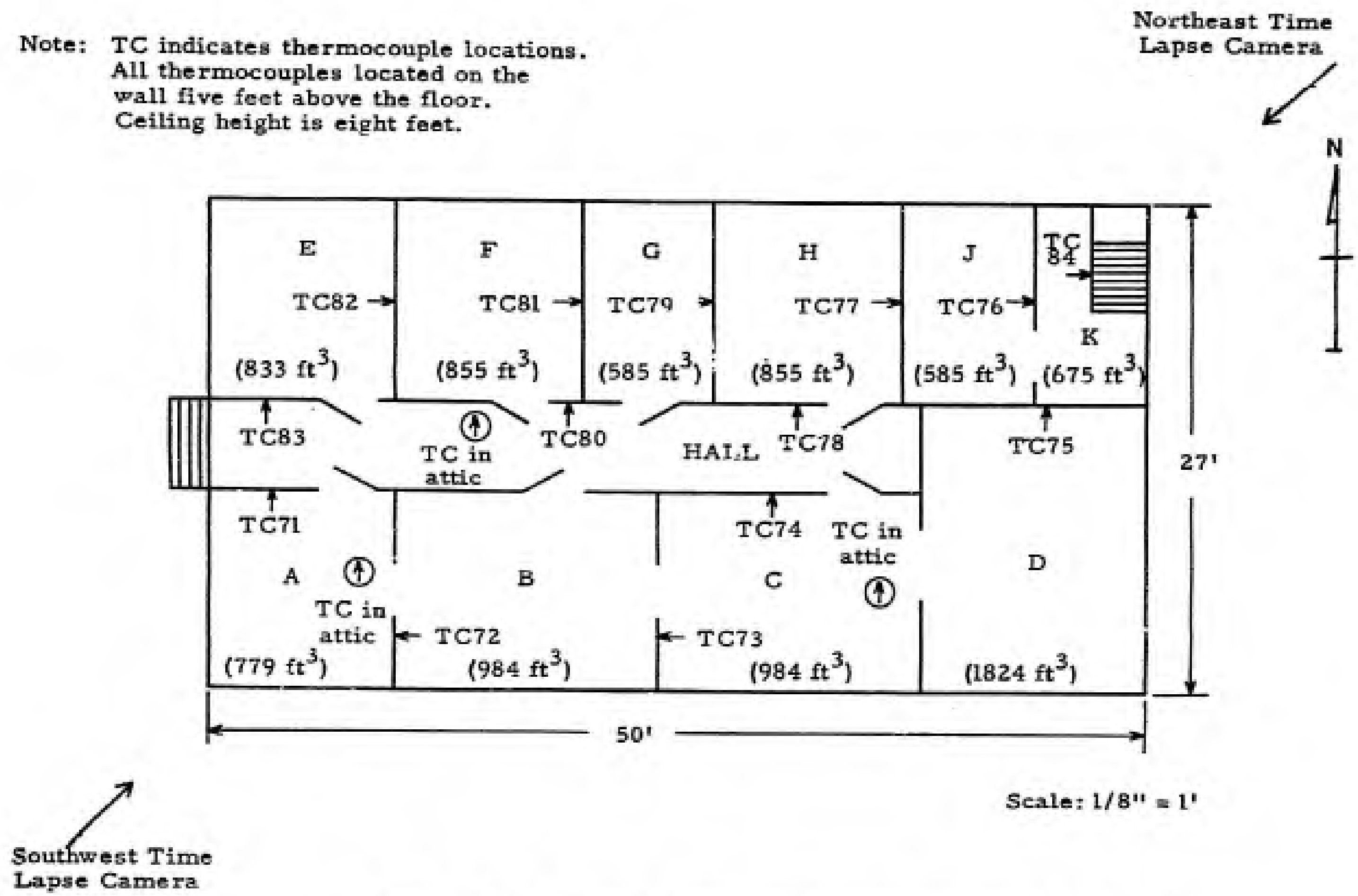


Fig. E-14(b) FIRST STORY PLAN VIEW OF GARY DWELLING

Room temperatures in the first story were monitored by fourteen thermocouples located as shown in Fig. E-14(b), and positioned five feet above the floor. Three additional thermocouples were located in the attic and two in the basement. All thermocouples were connected to continuous recorders located in the instrumentation trailer.

During the fire the wind speed was about 20 to 25 mph. Wind direction during the early part of the fire was west-by-south, later changing to west-by-north.

Since the wind direction during the early part of the fire was west-by-south, Room A was chosen as the location for ignition. JP-4 fuel was lightly sprayed on the blanketed surface of a completely equipped bed used as part of the furnishings. The method of ignition was not important, except to insure flashover of Room A within a reasonable time. The primary fire period of interest was after the first flashover. The fire was started in Room A at 1:29.7 P. M. ($\mathcal{T} = 0$) and flashover occurred 23.7 minutes later ($\mathcal{T}_f = 0$).

The spread of fire through this dwelling was analyzed similarly to the Ellis Parkway Burn. The Volume-Time Flashover Data is given in Table E-3. It should be pointed out that the basement and other volumes were excluded from volume-time flashover data. The basement did not become involved until after the fire period of interest had expired. Fire spread quickly through the ceiling boards of Room A into the attic which then burned essentially as a separate fire. Hence, the analysis considers only the fire spread through the first story.

Figure E-15 shows a plot of the data in Columns 3 and 5 of Table E-9, the cumulative building volume subject to flashover ($V_{\mathcal{T}}$) as

Table E-9

VOLUME-TIME FLASHOVER DATA GARY, INDIANA EXPERIMENTAL FULL-SCALE BUILDING FIRE

(1) Building Space Designation	(2) Time After Ignition τ (Min.)	(3) Time After First Flashover $\tau_f = \tau - \tau_o$, $\tau_o = 23.7$ (Min.)	(4) Individual Room Volume (cu. ft.)	(5) Cumulative Building Volume V_τ (cu. ft.)	(6) Volume Ratio V_τ/Vo (Vo=779)
A	23.7	0	779	779	1.00
B	32.4	8.7	984	1763	2.26
West Half of Hall	35.7	12.0	544	2307	2.96
E	39.2	15.5	833	3140	4.03
C	43.8	20.1	984	4124	5.29
East Half of Hall	43.9	20.2	544	4668	5.99
D	48.3	24.6	1824	6492	8.33
F	48.8	25.1	855	7347	9.43
H	49.9	26.2	855	8202	10.53
G	50.1	26.4	585	8787	11.28

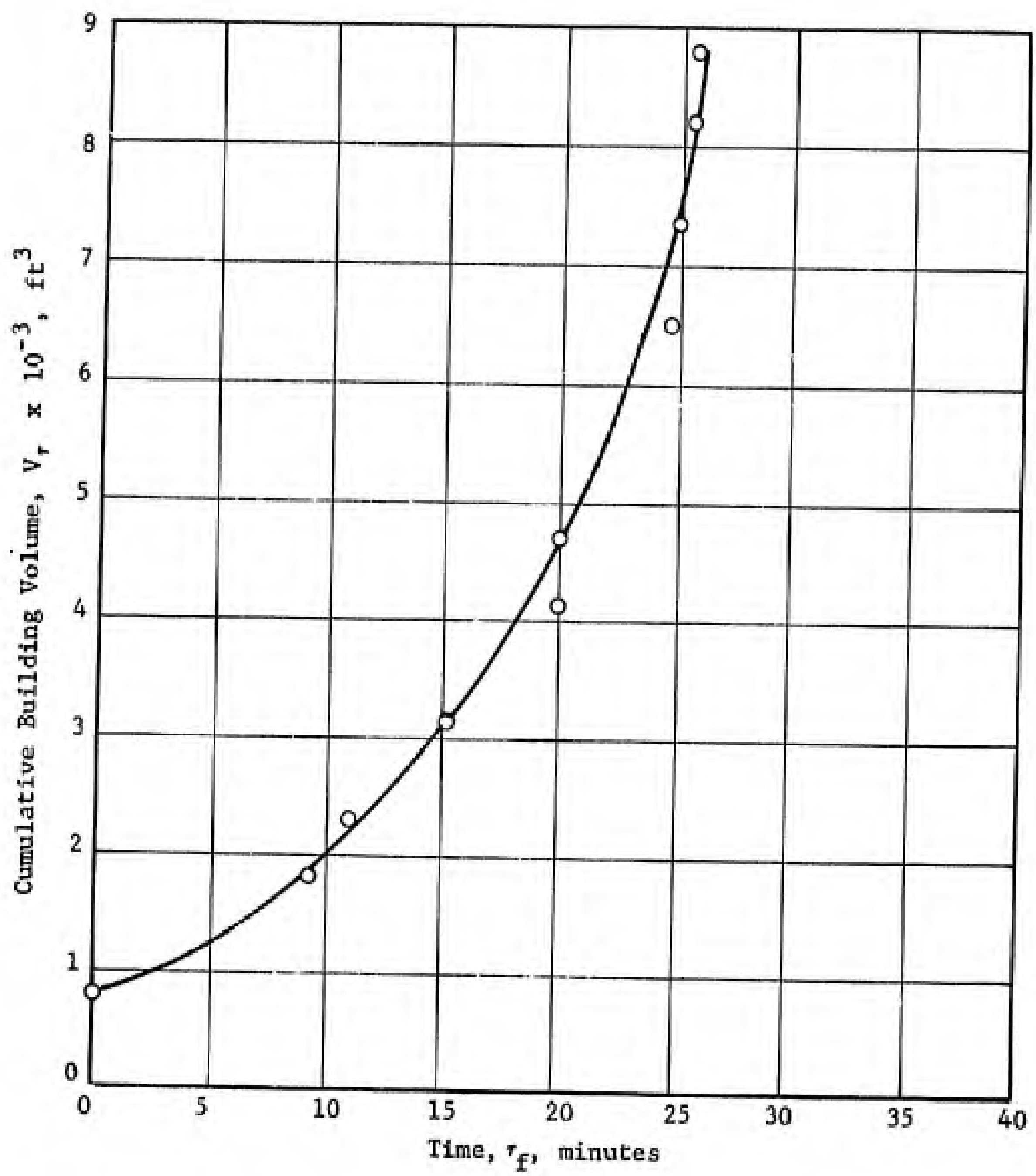


Fig. E-15 GARY DWELLING BURN. VOLUME-TIME FLASHOVER DATA a function of time after the first flashover in Room A. This curve is similar to the curve for Fire A given in Fig. E-7 of the Ellis Parkway Burn.

The plot of the volume ratio V_τ/V_o as a function of time τ is shown in Fig. E-16. Inspection of Fig. E-16 indicates that the curve represents the data quite well. Comparison of Fig. E-9 with Fig. E-16 and Table E-5 of the Ellis Parkway Burn supports the view that the correlation

$$V_\tau / V_o = e^{\tau_f/m} \qquad \text{(E-1)}$$

provides a meaningful way for describing the fire spread through a building. For the Gary Burn, m = 11.19 min., the time required to double the flashover volume is 7.75 min., which is 4.25 min. shorter than that determined in the Ellis Parkway Burn. This difference may be attributable to the high wind velocities prevailing during the Gary Burn.

B. <u>Plato Center, Lake Forest and Homewood, Illinois, Experimental Fires</u>

In an effort to obtain information on flashover in rooms of various sizes and flame radiation from building fires, as well as to verify laboratory results, additional experiments were performed as follows:

1. Two-story brick building, formerly a school, located at Plato Center, Illinois.
2. One-story frame dwelling located at Lake Forest, Illinois.
3. One-story frame dwelling located at Homewood, Illinois.

A brief description of these buildings and experimental results is given below. Figure E-17 shows a photograph of each of these three buildings.

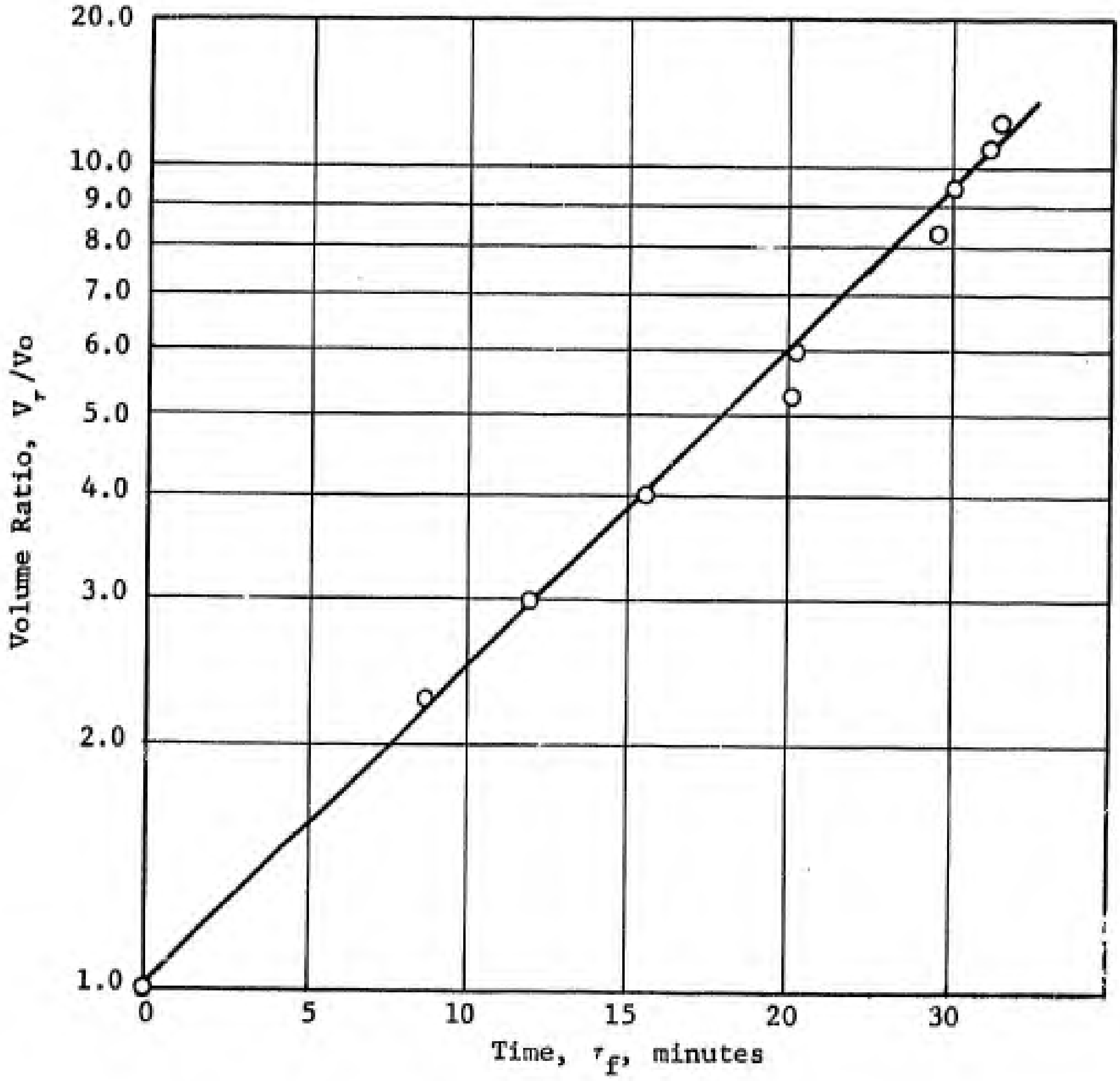
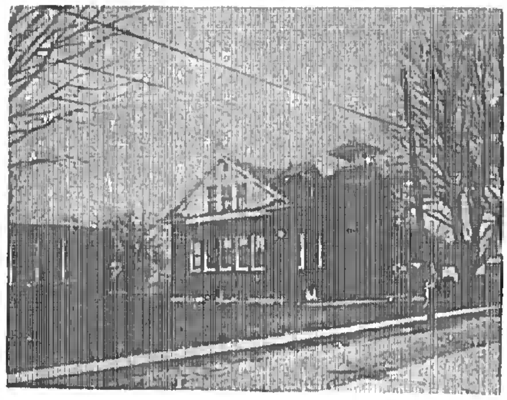


Fig. E-16 GARY DWELLING BURN. CORRELATION OF VOLUME-TIME FLASHOVER DATA



Plato Center, Illinois

Lake Forest, Illinois

Homewood, Illinois

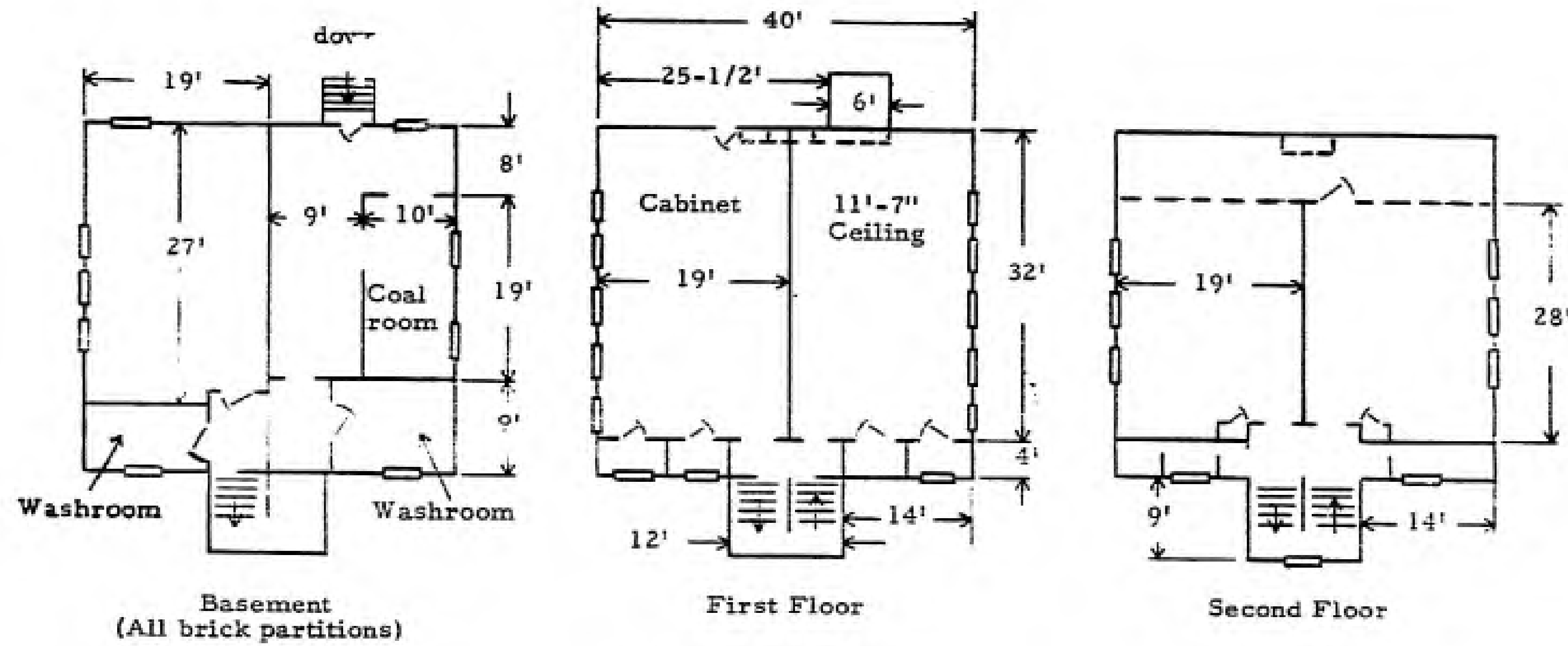
Fig. E-17 PHOTOGRAPHS OF BUILDINGS USED IN FIELD EXPERIMENTS

1. Plato Center Burn

The experiments in Plato Center involved a two-story and basement brick structure, formerly used as a school. The plan view of the structure is shown in Figure E-18. Because of large room areas (between 19 x 32 ft. and 28 x 38 ft.) mercantile occupancies were simulated, consisting of a clothing store, a furniture store and storage areas.

The instrumentation consisted of thermocouples, gas analyzers and photographic equipment. The thermocouples were located in the center of the ceiling and at five (5) feet above the floor level of each room. Three gas aspiration tubes were located in the basement and one was placed on the first floor.

The first experiment was in the east room of the first floor, simulating a furniture store. The room was loaded with fifteen sofas and eight chairs. The estimated weight of the furniture was 3800 pounds, representing a fire load of 4.6 lbs/ft^2 of floor area. JP-4 fuel was sprayed on the furniture items located near the windows and a trail ran to a sofa near the rear door in the south wall. The sofa near the door was ignited, with the intent that the fire would spread to other furniture items. Apparently, however, the JP-4 trail evaporated before spread could occur. As a result, the fire developed very slowly, confined mainly to the south half of the room. Thirty-six minutes after ignition, glass in all of the upper halves of the windows cracked. Ceiling gas temperatures at that time were between 1200°F and 1300°F. At the same time, the panels in the rear door burned through. Flashover was observed in the south half of the room thirty-nine minutes after ignition. The flashover volume was approximately 3500 ft^3. This could occur because the fire was initially well confined and ventilation controlled. Maximum ceiling



Plato Center School
Scale: 1"=10'

Fig. E-18. PLAN VIEW OF TWO STORY BRICK BUILDING USED IN FIELD EXPERIMENTS (PLATO CENTER, ILLINOIS) temperatures reached were 1630 and 1740°F, at the center and southeast corners of the room, respectively. Ceiling temperature at the northwest corner of the room was 1340°F, and five feet above the floor was 1130°F, respectively, indicating that the north section of the room had also flashed by the time extinguis .ment was begun.

No oxygen content data was obtained because of malfunction of the equipment. Carbon monoxide content in the basement near the rear stairs showed no buildup until about five minutes after flashover. At this time, with the CO concentration of 0.24 per cent, the system had to be shut down to prevent contamination of the apparatus by water and distillation products from the fire. The gases in the west room adjacent to the burning room showed a concentration of about 0.40 per cent of CO at 41 minutes after ignition and about 0.16 per cent 44 minutes after ignition, 5 minutes after flashover.

Floor penetration through the first floor to the basement occurred under the upholstered sofa, which was the point of ignition. The sofa, located with its back to the west partition wall, burned actively on the bottom and back for some time with little or no other burning. The burning between the floor, bottom of sofa, wall and back of sofa provided a mutual radiation effect before debris could provide a protective layer. It is believed that fire penetrated the wall-floor juncture and extended to the basement as a result of this concentrated burning. To prevent further damage to the structure which might end the planned series of experiments, the fire was extinguished and preparation made for the second experiment.

The second experiment was in the coal room on the west side of the basement. Fuel load consisted of about 400 lbs. of paper, wood and plywood. One window was open to provide ventilation. Five minutes after ignition, the upper half of the second window was broken to increase ventilation. Temperatures of 1000 - 1100°F were reached by the thermocouple in the northeast corner of the coal room at about 10 to 12 minutes after ignition, after which time the temperature decreased. Similarly, temperatures measured at the ceiling in the center of the room reached 700°F after 12 minutes and then fell off. The thermocouple five (5) feet above the floor behind the south wall of the coal room indicated a relatively uniform temperature of about 250° to 300°F after six (6) minutes of burning. Because it appeared that only localized burning would take place without resulting in a flashover, the fire was extinguished at 16 minutes after ignition.

The oxygen record for the sampling tube located in the room south of the coal room indicated a decrease to 15.5 per cent within two minutes after ignition with a gradual increase thereafter to 18 per cent after fifteen minutes. This decrease in oxygen content of the air seems to be due to the rapid burning of the ignition fuel (JP-4) and the fire before additional ventilation was supplied by the breaking out of the upper half of a window. Then, since the gas sampling tube was in a cul-de-sac with no appreciable air circulation, the gradual rise in oxygen content was due to diffusion. No CO content was observed during the experiment.

The next experiment was in the first floor west room, furnished to simulate a clothing department or store. Seven parallel 8 foot long racks loaded with clothing: men's and women's suits, coats, dresses, etc., were positioned perpendicular to the east wall of the room. In addition, two rows of counters totaling about 60 feet ran parallel to the window wall. Loosely piled miscellaneous items of apparel were placed on tops of counters as well as on the lower shelves and in drawers. Built-in cabinets at the south east corner and shelving along the south wall were similarly loaded.

About three minutes after ignition, the clothing in the built-in cabinets in the southeast corner ignited. At this time, the celing thermocouples in the southeast and southwest corners of the room indicated temperatures of 875 and 700°F, respectively. As this clothing burned out after 6 minutes, these temperatures decreased to between 500 and 600°F until the start of flashover, occurring sixteen minutes after ignition. At flashover, these ceiling thermocouples (in the southeast and southwest corner). showed peak temperatures of 960 and 1100°F, while thermocouples at the ceiling and at the five (5) foot level in the northeast corner attained peak temperatures of 1120 and 1170°F, respectively. Extinguishment of the fire was begun about three minutes after flashover corresponding to nineteen minutes after ignition.

Analysis of the gases from the tube in the southeast corner of the room showed the oxygen content decreasing to about 18.5 per cent shortly after ignition, a very gradual decline to about 15.5 per cent after 10 minutes of burning then an increase to about 17 per cent, and finally a sharp drop to about 11 per cent at flashover. The carbon monoxide content showed a fluctuating increase to about 0.5 per cent over the first two minutes of the burn, after which the system went out of calibration.

A fire involving the entire second floor of the building was the fourth and final experiment in this building. The floor, with the movable partition partially open, was loaded with an assortment of upholstered furniture, wooden chairs, book cases and miscellaneous plywood and lumber, the equivalent of a receiving and storage area of a furniture store. The floor area was approximately 1000 square feet. The lower halves of all windows in both the east and west walls were open for ventilation purposes. To insure a fast ignition, thereby preventing penetration of the already weakened walls, most of the area was well wetted down with JP-4 fuel. As a result, the room flashed over within three minutes after ignition. The fire was attacked five minutes after ignition. Thermocouples in the east room showed maximum temperatures of about 1150°F, while the ones in the west (leeward) room reached peaks of 1300 and 1420°F. No gas analyzer data was obtainable.

2. Lake Forest Burn

The building in Lake Forest, Illinois, was a frame structure on a concrete block foundation. The basement consisted of an open area with an entrance at the rear and five windows. The layout of the first floor is shown in Figure E-19. The structure was furnished for normal dwelling occupancy.

Temperature readings were taken in each ignited room at five (5) and eight (8) foot levels. In addition to the visual observations, the development of fire was recorded photographically.

The first experiment originated in a rear bedroom. Due to the dampness of this long-unoccupied building, difficulty was experienced in reaching the flashover of the room. The long period of pre-burn time permitted the penetration of the fire through the wall and subsequent involvement of the attic and the rear portion of the roof. Extinguishment was begun about 35 minutes after the ignition.

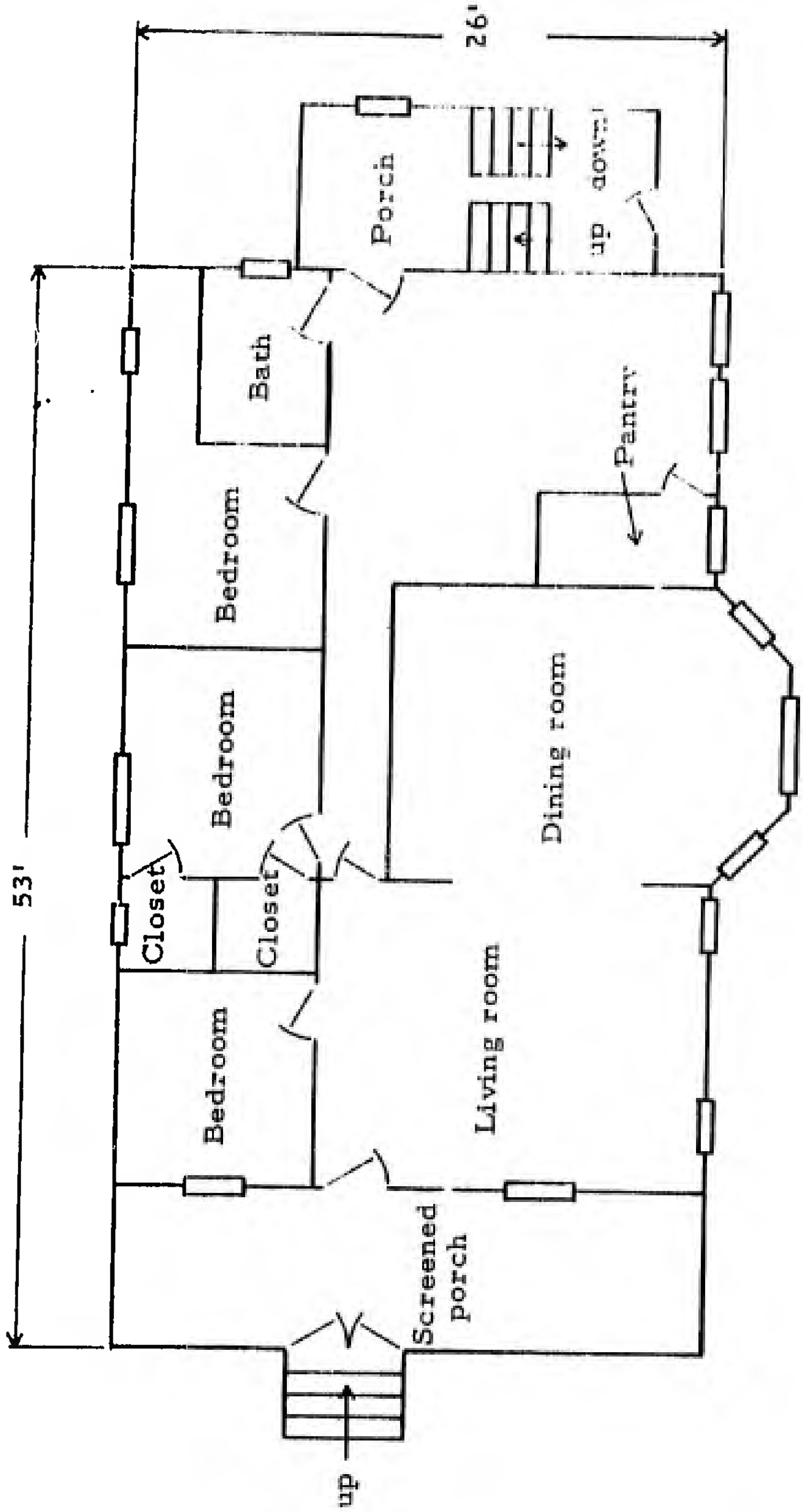


Fig. E-19. PLAN VIEW OF ONE STORY FRAME DWELLING USED IN FIELD EXPERIMENTS (LAKE FOREST, ILLINOIS)

In the second experiment, the fire originated in the clothes closet located between the front and the middle bedrooms and was permitted to extend to both bedrooms. The maximum ceiling temperature recorded was 905°F. Extinguishment commenced at approximately 14 minutes after ignition.

3. Homewood Burn

The Homewood building was also a frame structure on a concrete block basement. A plan view of the first floor is shown in Figure E-20. Thermocouples were positioned above weak spots in the plaster in order to detect possible penetration of the fire.

The first experiment, in the bedroom at the rear of the building, was conducted with the lower half of the window open. The bed was sprayed lightly with JP-4 fuel for fire initiation purposes. Flashover occurred after about 6 minutes. The maximum temperature reached by the thermocouples in the room was 1270°F.

The second experiment, involving the living room, dining room and kitchen developed more slowly, requiring 20 minutes to flashover. However, due to the through-ventilation, temperatures reached only 1040°F at thermocouples located at five (5) feet above the floor. Ceiling thermocouples indicated 920°F.

The burn in the basement was arranged as a demonstration of extinguishment by high expansion foam. The fire was set by igniting JP-4 fuel in paper cups in a long narrow storage area along the east side of the basement. Both basement windows in this area, as well as the door between the storage area and the basement, were open. The area flashed over about eight (8) minutes after ignition and thermocouple

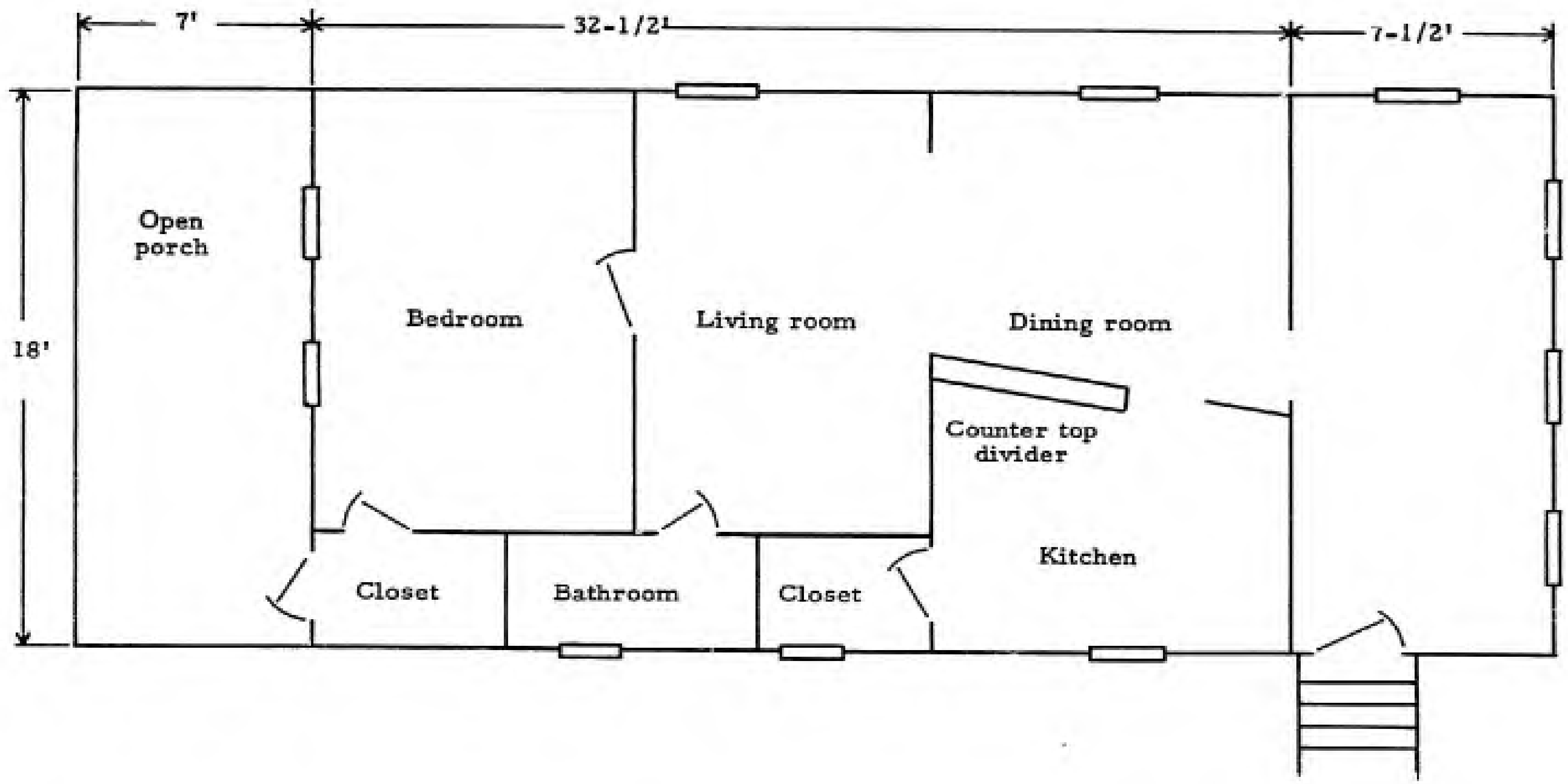


Fig. E-20. PLAN VIEW OF A ONE STORY FRAME DWELLING USED IN FIELD EXPERIMENTS (HOMEWOOD, ILLINOIS) peak temperature rached 1535°F.

A total of nine experiments were conducted in the portion of the work described in Section III - B of this Appendix. The first experiment at Plato Center Burn involved a furniture store type occupancy which contained a contents fire load of 4.6 lbs/ft^2 of upholstered furniture. The entire room was 7000 ft^3 in volume, about half of which flashed thirty-nine minutes after ignition; the remainder flashed a few minutes later. This kind of flashover behavior can be expected when a fire is predominently ventilation controlled in a large compartment. Regarding the flame radiation from windows, it was found that, in this respect, all these burns behaved more nearly like the model fires than the Ellis Parkway Burn, which was substantially fuel-surface controlled because of the large window size and low fire load.

IV. ELLIS PARKWAY BURN OBSERVATIONS

The following table represents a list of events which were documented during the entire period of fire and ultimate collapse of the building.

TABLE 10 - ELLIS PARKWAY BURN OBSERVATIONS

TIME (hr:min)	EVENT
9:52.25	Ignition in 2nd story living room
9:56.0	Flashover in 2nd story living room
9:57.4	Several particles fall from ceiling of 2nd story living room
9:58.0	Smoke from windows of 3rd story den

TABLE 10 (CONTINUED)

9:59.3	Smoke from rear of 2nd and 3rd stories
10:00.0	Some plaster falls from ceiling of 2nd story living room
10:01.5	Rear of building - heavy smoke from 2nd story; 1st story clear
10:02.0	Flashover in front hall, 2nd story
10:03.0	Rear of building - smoke from 2nd story; 1st and 3rd stories clear
10:03.5	Intense smoke from 3rd story front
10:03.7	First smoke visible from bedroom "A", 2nd story
10:04.0	Wind velocity, 5MPH, southwest
10:04.0	Penetration of 2nd story apartment door
10:05.0	Very heavy smoke from rear of 2nd story
10:05.5	Intense smoke from bedroom "A", 2nd story
10:06.0	Plaster falls from ceiling, 2nd story living room
	Smoke from 2nd story rear becomes pale
10:06.5	Smoke from attic vents in walls near roof, both sides of building
10:08.0	Flashover within wall separating living room and bedroom "A", 2nd story
	Hole in brick work 3rd story north wall of den showing heavy smoke (probably from furring space)
10:09.0	Flashover in 2nd story den
10:10.0	2nd floor flames ignite window frame 3rd story den; heavy smoke from window
10:11.0	Center hall 2nd story, ceiling temperature reaches 1000°F
10:11.5	Heavy smoke from 3rd story living room
10:12.5	Very dense smoke from 2nd story, bedroom "A"
10:13.0	Flames licking ceiling 2nd story bedroom "A"

TABLE 10 (CONTINUED)

10:13.5	Chair on fire in 2nd story bedroom "A"
10:13.7	Flames momentarily fill 2nd floor bedroom "A"
10:15.2	Center hall 2nd story filled with flame
10:16.0	Rear of 2nd and 3rd stories filled with smoke
10:16.7	Flames again fill 2nd story bedroom "A"
10:17.0	As yet no flames visible at rear of building
10:17.5	Door frame burning in 2nd story bedroom "C"
10:18.0	Door frame burning in 2nd story bedroom "B"
	Flames entering 2nd story bathroom through doorway
	Temperature rise in stairwell indicates door collapse in 2nd story apartment (Flashover in 2nd and 3rd story stairwell)
10:19.0	No indication of flames in 2nd story kitchen or dining room
10:19.5	Wind southwest 4-6 MPH
10:20.0	Wall paper burning in 2nd story bedroom "B"
10:21.0	Flashover in 2nd story bedroom "A"
	Walls and door frames in 2nd story rear hall burning
10:21.5	Flames visible in 3rd story living room (Penetration of 2nd story living room ceiling)
	General air flow direction through 2nd story bedroom "B" is from window to hall
10:22.0	Floor burning at entrance to 2nd story dining room from rear hall
10:22.8	Temperature at top of stairwell (near skylight) reaches 1000°F
10:23.0	Dense white smoke coming from rear of 3rd story
10:24.5	Flashover in 3rd story living room

TABLE 10 (CONTINUED)

10:26.5	Flame direction (previously toward front of building) now from rear hall into 2nd story dining room
10:27.0	2nd story - rear hall doorway to dining room burning, floor ignited (Flashover)
	Falling debris visible in hall of 2nd story when viewed from rear
10:28.0	Collapse of 2nd story living room ceiling
	Flashover within wall separating living room and bedroom "A" on 3rd story
	Flashover in 3rd story den
	Flashover - 2nd story pantry area
	Flashover - 2nd story bedroom "C"
	Considerable accumulation of debris in 2nd story center and rear hall
10:28.2	Flames spreading in 2nd story dining room
10:28.4	Flames spreading in 2nd story kitchen
10:28.5	Flashover in 3rd story bedroom "A"
	Change in flame pattern -- flaming ceases from 2nd story living room windows; flaming increases from 3rd story living room windows
10:28.6	Flashover in dining room of 2nd story
10:29.0	Flames fill upper half of 2nd story kitchen, floor not ignited as yet
	Flashover in 3rd story powder room
	Front portion of roof burning
10:29.5	Flashover in kitchen 2nd story
10:29.6	Flaming from rear of 2nd story has ignited 3rd story kitchen doorway and porch roof
	Fire on doorway dies out almost immediately
10:30.0	Flashover in 2nd story bedroom "B"

TABLE 10 (CONTINUED)

	Temperature at top of stairwell (near skylight) reaches 1600°F, (glass begins to flow)
10:30.5	3rd story dining room window frames starting to burn
10:30.7	Plaster starting to fall from ceiling of 3rd story living room
10:31.0	Southwest wind; velocity fluctuating between 4 and 10 MPH
10:31.5	Roof covering over rear porch burning
10:32.0	2nd story bathroom filled with flame (Flashover)
	Flames visible in 3rd story bedroom "B"
10:32.4	Flashover in 3rd story front hall
10:32.6	Flashover in 3rd story rear hall
10:32.9	Flashover in 3rd story pantry
10:33.0	Flashover in 3rd story bedroom "C"
	Flashover in 3rd story dining room
10:33.2	Flashover in 3rd story kitchen
10:33.5	Collapse of 2nd story den ceiling
10:33.6	Flashover in 3rd story bathroom
10:34.0	Roof coping burning at rear of building
10:35.0	Flashover in 3rd story bedroom "B"
10:36.0	3rd story ceiling collapse at front of building
10:38.0	Gas sampling lines Nos. 8, 9 and 10 have been disconnected
	Roof fell in just south of skylight (collapse)
10:39.0	Change in flame pattern -- flames moving from 3rd story bedroom "B" toward center hall
	Telephone Pole (located 20 feet from northwest corner of building) ignited
	Flames going from 3rd story bathroom into the hall

TABLE 10 (CONTINUED)

10:39.5	Debris falling from ceiling of 3rd story bedroom "B"
	Plaster falling from 3rd story bathroom ceiling
10:40.0	Change in flame pattern -- flames again coming out of window 3rd story bathroom
10:41.5	Fire spreading down to 1st story stairwell
10:42.0	Flames in 1st story stairwell
10:43.5	Front half of roof collapsed
	Flames are now going up through opening in roof, none from 2nd or 3rd story windows
10:45.0	View from roof shows front half of roof is open (collapsed)
	2nd story interior walls on the south are gone, north walls are starting to collapse
10:47.0	1st story stairwell is completely aflame (Flashover)
10:48.0	3rd story living room is clear of smoke and flame
10:50.0	Whole center section of roof is gone
10:51.0	View from trailer shows part of roof, from smoke-stack west, is still there
	Wall is starting to crack on south side between 2nd and 3rd story and between 3rd story and roof
10:51.5	Wind velocity 10 MPH southwest
10:53.0	Nothing occurring on south side of 1st story, looking at apartment entrance door
	View from trailer shows flames coming up from rear central part of building on north side
10:54.0	1st story apartment entrance door starting to show flame at the panel, as viewed from south
10:55.0	Rear third of roof has opened-up
	Flames on 1st story apartment entrance door
	Cracks in outer south wall increasing in size

TABLE 10 (CONTINUED)

10:55.5	Part of rear wall collapsed
	1st story apartment entrance door penetrated, door frame is burning
10:57.0	3rd story is clear of smoke and flame as viewed from the front
10:57.5	Lines 5 and 7 on gas analyzer are being reconnected
10:58.0	Wind velocity 4 to 5 MPH
10:58.5	Brickwork between 2nd and 3rd stories in front is buckling
10:59.0	Fire in 1st story stairwell
	1st story living room still clear, no smoke or flames as viewed from front
10:59.5	Flames at 1st story apartment entrance door are going into the stairwell, not into the apartment
11:02.0	Bricks fell from 3rd story at rear of building
11:02.5	1st story living room is still clear
11:03.0	Wind velocity 5 to 8 MPH south-southwest
11:05.0	1st story apartment entrance door is now fully aflame as viewed from south
11:05.5	No sign of flame in 1st story hall when looking down hall from front of building. Hall is clear from living room to dining room
11:06.0	1st story apartment door opening up (burn out)
11:06.5	Flames in 1st story front hall (Flashover)
	Flames from window, 1st story, Bedroom "C" (Flashover)
11:07.0	1st story living room still clear of smoke
	No flame visible in 1st story center hall
11:07.5	Flames no longer coming out of window, 1st story Bedroom "C"; flame intensity picking up again, flames again coming out of window

TABLE 10 (CONTINUED)

11:09.5	No flames visible in south rooms of 1st story
11:10.5	Plaster falling, 1st floor hall
11:11.0	Wind velocity, 5 MPH, south-southwest
11:11.5	No flames in 1st story center or rear hall
11:13.0	Starting to get smoke at rear of 1st story
11:14.0	1st story dining room is full of smoke
11:15.0	Wind velocity - 5 to 7 MPH, south-southwest
11:16.5	Pictures now being taken from snorkel
	1st story stairwell is acting as a chimney
11:17.0	1st story hall and stairwell burning furiously as viewed from above
11:18.0	Vortex burning in 1st story stairwell as viewed from above
	Active fire in basement
11:18.5	2nd story floor is full of debris
11:18.6	Flashover in 1st story dining room
11:19.0	1st story ceiling and stairwell are on fire as viewed from above
11:19.5	View from trailer shows that 1st story ceiling, in middle of building, is on fire
11:20.5	1st story living room is starting to fill up with smoke
11:22.5	Flashover in 1st story bathroom
11:23.0	Doorway of 1st story Bedroom "C" ignited
11:23.3	Flames starting to approach 1st story living room
11:24.0	Flames in 1st story bathroom have died down
11:25.0	1st story Bedroom "A" is still clear
11:25.5	1st story stairwell completely burned out and open into Bedroom "C"

TABLE 10 (CONTINUED)

11:26.5	Doorway of 1st story Bedroom "B" is on fire, flames are going into the hall
11:26.8	Plaster falling from ceiling of 1st story Bedroom "C"
11:27.0	Wind velocity, 5 MPH
	Plaster falling from 1st story hall walls, fire is spreading into the living room
	1st story bathroom ceiling is burning, fire has reached the lath
11:28.0	1st story ceiling starting to collapse at rear of building
11:28.3	Fire is spreading into 1st story living room
11:28.5	Wind velocity, 9 MPH, south-southwest
11:28.7	1st story Bedroom "A" is clear
11:29.0	Flames are shooting through doorway in 1st story bedroom "B"
11:30.0	Front entrance stairway is burning
11:30.3	A chair in the 1st story living room has ignited
11:30.7	Heavy smoke from 1st story living room
11:31.0	Flashover in 1st story living room
11:31.5	Furniture in 1st story Bedroom "B" is on fire
11:32.5	Front entrance stairway is greatly aflame
11:32.7	Smoke from window, 1st story Bedroom "A"
11:33.0	East wall of 1st story Bedroom "A" is burning
11:33.5	Flashover in 1st story kitchen
11:33.6	Flashover and ceiling penetration in 1st story Bedroom "A"
11:34.0	Further collapse of outer wall on north side of building
11:34.7	Collapse of 1st story ceiling at rear of building
11:35.0	Flashover of furniture, 1st story Bedroom "B"

TABLE 10 (CONTINUED)

11:35.3	Flashover of entire room, 1st story Bedroom "B", debris falling from ceiling
11:35.5	1st story living room ceiling starting to collapse
11:36.3	Active flaming above 1st story bathroom indicates a major ceiling penetration
11:37.0	Panelling on front entrance door starting to burn on the inside
11:38.3	Wind velocity, 4 MPH, south-southwest
11:38.5	Part of the north wall, above a 3rd story window, fell down
11:38.8	Fire in basement, flames spreading from center to rear
11:39.0	1st story bathroom ceiling penetrated by flames
11:39.3	1st story bathroom ceiling collapsed
11:40.0	Wind velocity, 6 MPH, south-southwest
11:40.5	Brickwork on south wall is beginning to fall
11:42.0	Flames visible at rear basement window; window frame and boards covering opening are burning
11:43.0	Front of basement is still not burning
	South wall is leaning outward
11:45.0	Fire is spreading to front of basement
11:45.3	Portion of south outer wall, from 3rd story to roof, is collapsing
11:46.0	Wind velocity, 7 MPH, south-southwest
11:46.3	North wall is leaning, no crack as yet
11:47.0	Considerable amount of spray to north of building, may affect radiometer readings
11:47.4	North wall seems to be buckling out from center
11:48.7	Brickwork on north wall, between 1st and 2nd stories, is cracked

TABLE 10 (CONTINUED)

11:49.0	Wind velocity, 3 MPH, south-southwest
	Brickwork falling from north wall at front of building
11:50.3	1st story ceiling is completely collapsed
11:51.0	View from front shows that only a few interior wall structures remain
11:51.7	North wall is leaning outward
	Portions of the south wall are collapsing
11:52.0	Most of the 1st story has collapsed into the basement
11:54.0	1st story living room is the only room that has not collapsed into the basement
11:54.3	South wall, at center of building, collapsed
	North wall, at center of building, collapsed when south wall hit the ground
	Basement is completely on fire
11:57.0	North wall, at rear of building, collapsed
12:05.5	South wall, at rear of building, collapsed
12:28.7	Occasional flame visible in basement
12:29.3	Water poured on remains

REFERENCES

1. Shorter, G. W., J. H. McGuire, M. B. Hutcheon and R. F. Leggett, "The St. Lawrence Burns", Quarterly of NFPA, Vol. 50, No. 4, 1956, pp. 300 - 316.

2. Salzberg, F., W. G. Labes, H. Nielsen and T. E. Waterman, "Prediction of Fire Damage to Installations and Built-Up Areas from Nuclear Attack-- Study of Initiation and Spread of Fires in Typical Structures", Defense Atomic Support Agency, Contract No. DA-49-146-XZ-021, December, 1960.

3. Lawson, D. I., C. T. Webster and L. A. Ashton, "The Fire Endurance of Timber Beams and Floors", The Structural Engineer, February, 1952.

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APPENDIX F

COALESCENCE OF CONVECTIVE COLUMNS FROM FREE BURNING FIRES

I. INTRODUCTION

When convective columns from a group of burning structures coalesce and form a canopy of flames and hot gases, the result is a mass fire. The mechanism which governs the formation of mass fires may be briefly summarized as follows: burning takes place when combustible gases, released from the heated contents of the structure, mix with air. The resulting products of combustion attain high temperatures and move upward due to increased buoyancy, consequently the surrounding air flows toward the flame. If the air flow is uniform on all sides, the flame tends to remain vertical, but its direction may be easily changed by wind or obstruction. If two fires occur sufficiently close to each other, the restricted flow of gases leads to a slight reduction of pressure in the region between the fires, and the flames bend toward each other. This effect becomes enhanced where more fires are involved and the flames may merge, producing a chimney effect. At this point, the fire may assume one of two forms. In one form, the column of hot gases rises almost vertically to considerable heights, and the wind created by the air moving toward the center of the fire assumes gale-like proportions. This fire is characterized by its stationary behavior and complete destruction within the fire perimeter. It is called a "fire storm." The other form which a developing fire may assume is characterized by a pillar of hot gases slanted considerably leeward as a result of prevailing winds. This form of fire is called "conflagration." Its chief characteristic is the presence of a fire front, which is an extended wall of fire moving leeward, preceded by a mass of preheated, turbial, burning gases. The destructive potential of the conflagration can be much greater than that of the fire storm, because the conflagration continues to move downwind until all combustible materials in its path have been consumed.

The fact that a nuclear burst can result in mass fire was demonstrated quite emphatically during the last war, when atomic explosions caused a fire storm in Hiroshima and a conflagration in Nagasaki. Needless to say, a mathematical model for predicting the fire damage to urban areas as a result of nuclear burst must include criteria for formation and subsequent bahavior of these mass fires.

Unfortunately, an understanding of mass fires is lacking at this time. Frequently, it has been indicated that for a mass fire to take place, a building density of over 20 per cent is required. However, as pointed out by Richardson [(1)], there are other factors which must be considered, such as layout of the target, construction feature, ignited area, etc.

Without question, the building densities, their layout, and their combustibility, or, in general, the target vulnerability to fire, is one of the major parameters affecting fire spread. Nevertheless, in over-all consideration of mass fires, the supply of oxygen (i.e., the surrounding atmosphere on which the existence of mass fire depends) cannot be neglected. The importance of this factor has already been well recognized in the studies of forest fires, which are similar in magnitude to the mass fires in urban areas. Similarly, the problem of air entrainment into the convective column has been considered in connection with theoretical analysis of single heat sources (i.e., point sources). Even in these cases, the complexity of the problem requires a number of simplifications, such as neglect of radiation heat losses from the column, neglect of wind effects, assumptions concerning temperature profiles, etc. Of course, the difficulty of the analytical treatment increases enormously when consideration must be given to mutual effect of a number of convective columns, and experimental treatment is necessary.

The following sections treat laboratory experiments involving liquid fuel fires, larger scale field experiments with liquid fuels, and laboratory experiments with wood cribs.

II. PRELIMINARY EXPERIMENTS

A. Laboratory Experiments with Liquid Fuels

This investigation proposed to create fires in various sizes and geometries by burning a liquid hydrocarbon fuel (JP-4) in shallow open pans. Liquid fuels were suggested with the hope of obtaining better experimental control through more measurably consistent fuel vapors and combustion products. Fuel pans were constructed with square dimensions and vertical side walls so that several pans could be butted together to form a similar pan of larger surface area.

Information available in the literature[2, 3] indicates that free burning fires undergo three regimes of burning depending on the area or diameter of the fuel source. These regimes are laminar, transitional and turbulent. The information indicates that turbulent fires occur when their diameter is of the order of 30 inches. Consequently, the pan size selected was a 30-inch square, in order to assure that the minimum fire size to be studied (one pan) would be in the turbulent flow regime which is characteristic of large fires.

Numerous single pan fires were conducted with little success due to sideward movement of the flame. The bottom photograph of Fig. F-1 is indicative

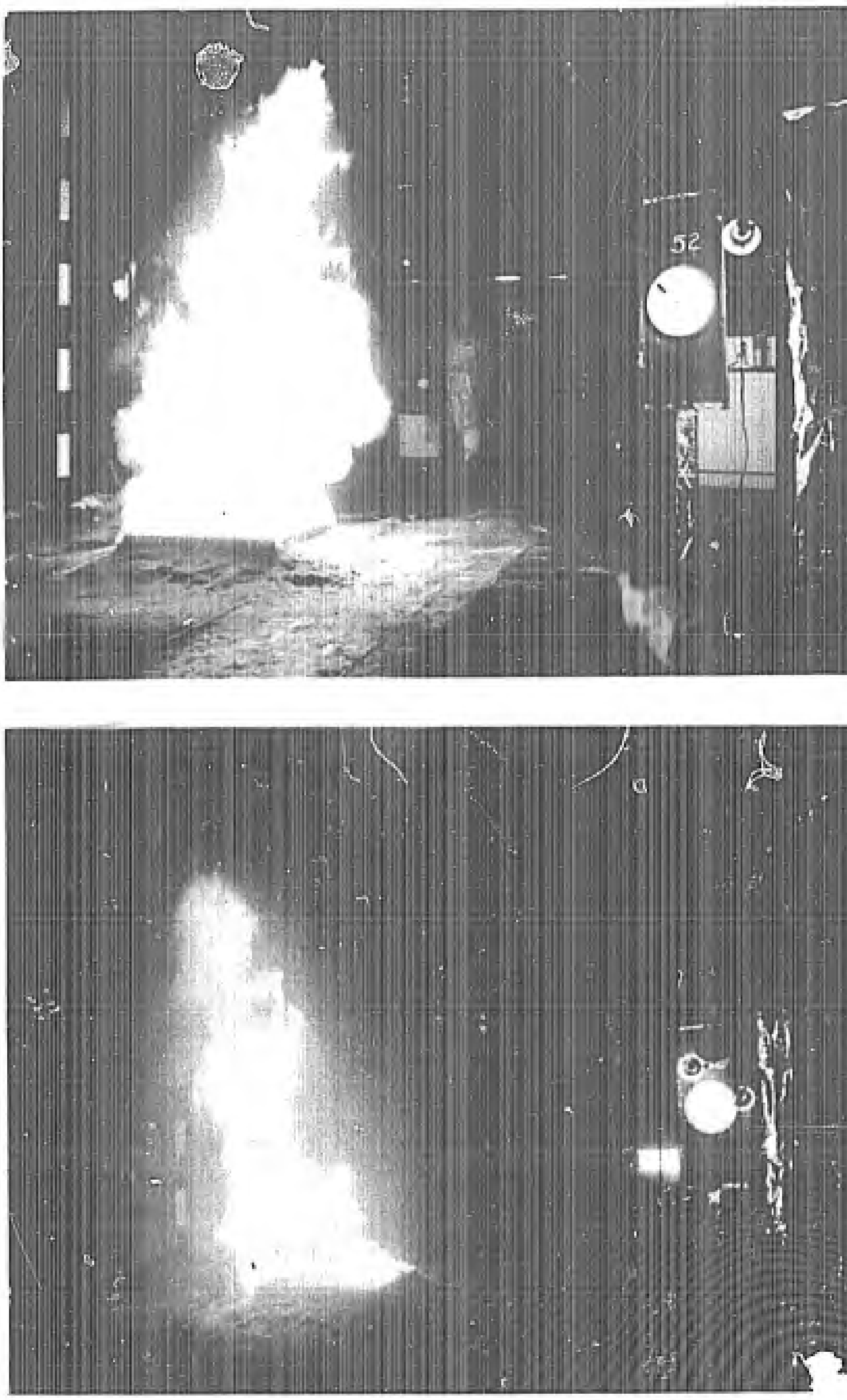


Fig. F-1 LIQUID FUEL PAN FIRES

of the situation. In many cases, fuel vapors moved horizontally across the floor for some distance before igniting with a resulting disturbance to the main flame. Distortion of the air flow and or excess heating of the fuel by the pan edges was at first blamed for this action and an experiment was designed as shown in Fig. F-2. The fuel container consisted of a 2 x 4 inch wood frame lined with polyethylene. Sand was placed around the frame to provide a smooth transition from the laboratory floor to the fuel surface. The results were unsuccessful in producing a stable flame and indicated that small inbalances in the air flow to the fire tended to trigger the instability. Attempts to balance the air flow by placing barriers at various locations near the fire resulted in the establishment of several fire whirls in orders of magnitude larger than the original flame above the fuel. At this point it was decided that the problem is mainly due to the sensitivity of the vaporization rate of the fuel to the local heating of the liquid surface. Thus, once the flames would lean momentarily to one side, perhaps due to a minor vagarity of air motion, the fuel would vaporize rapidly on that side and reinforce the fluctuation.

The severity of the problem was reduced by introducing 3/8-inch ceramic beads into the pan and maintaining the fuel level below that of the uppermost beads. In this manner, the mode of preheating the fuel became one of combined radiation and convection plus conduction. This reduced the burning rate and consequently the flame height, but produced a more stable flame. Although this method gave some control of burning, much was still to be desired.

The fire size was increased in order to increase the magnitude of the inward air flow and minimize the effect of minor fluctuations. However,

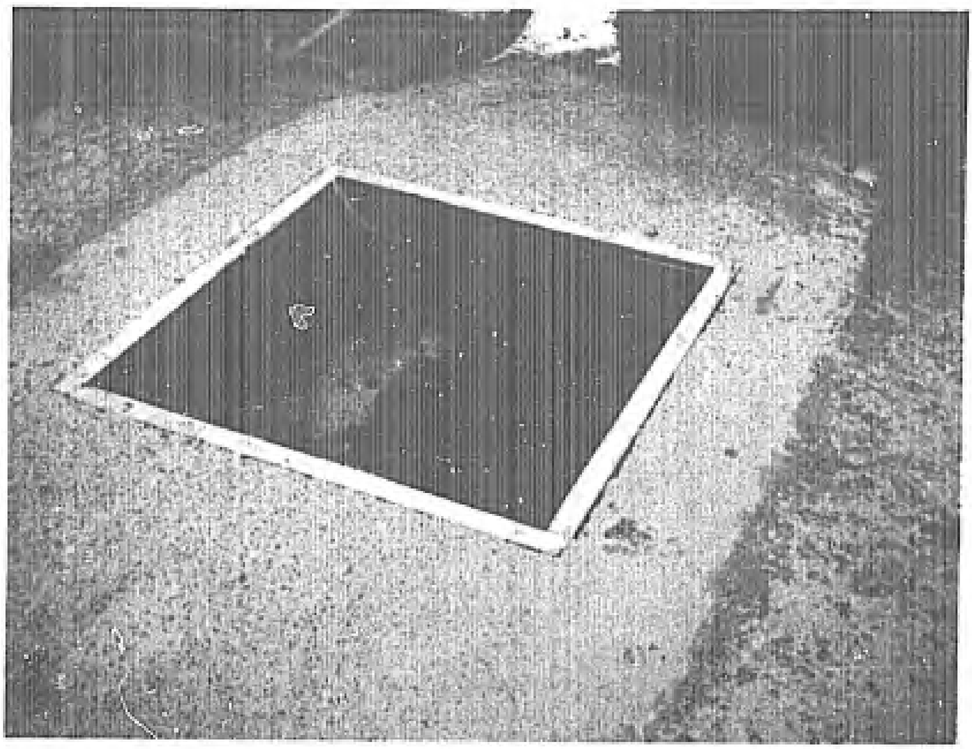
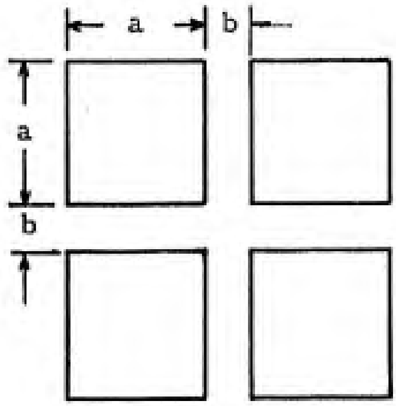


Fig. F-2 POSITION OF PAN IN LIQUID FUEL FIRES long before such an effect could be achieved, the laboratory volume (50,000 ft^3) was found to be too small to contain the combustion gases and smoke at a sufficiently dilute level to permit viewing the fire for more than fifteen to twenty seconds after ignition at distances greater than several feet. The venting of portions of the products of combustion and the introduction of make-up air returned the instability to a high level. Laboratory scale experiments were terminated and operations were moved into an open field where the fuel area could be significantly increased.

B. Field Experiments With Liquid Fuels

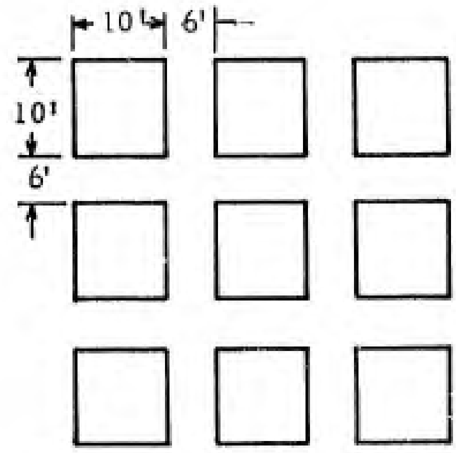
As mentioned above, attempts to model coalescence by burning pans of liquid fuel within the laboratory were largely unsuccessful due to instability of the flames. Activity was moved outdoors and a series of large scale fires was conducted as outlined in Fig. F-3. Figure F-4 shows the trays of fuel before ignition. Figure F-5 was photographed during the peak of the 36 pan fire.

The fuel containers were constructed by grading the site, placing 2 x 8-inch wood frames in the proper spacing and partially backfilling the aisles to add support to the frames. Polyethylene liners were placed in each tray and water added to fill any irregularities in the grading, thus forming a level bed for the fuel, No. 2 fuel oil. Small paper boats partially filled with JP-4, were floated on the fuel surface of each tray to promote rapid ignition. Burning rates, flame heights, flame areas, and flame angles were monitored photographically. The burning rate was measured by denoting the position of one end of a lever arm relative to a fixed scale. The other end of the lever arm was attached to a float resting on the fuel. Radiometers and anemometers placed at various distances around the fire measured radiant intensities and

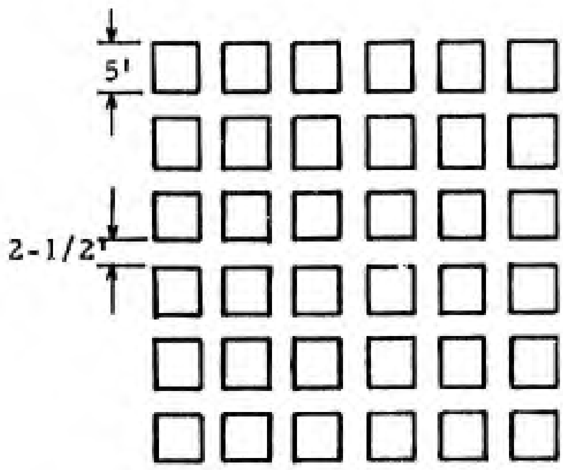


Field Fires Nos. 3, 4, 5

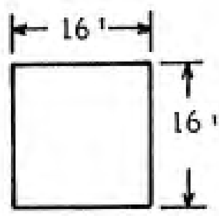
Fire No. 3, a = 16 ft., b = 6 ft.
Fire No. 4, a = 16 ft., b = 12 ft.
Fire No. 5, a = 16 ft., b = 9 ft.



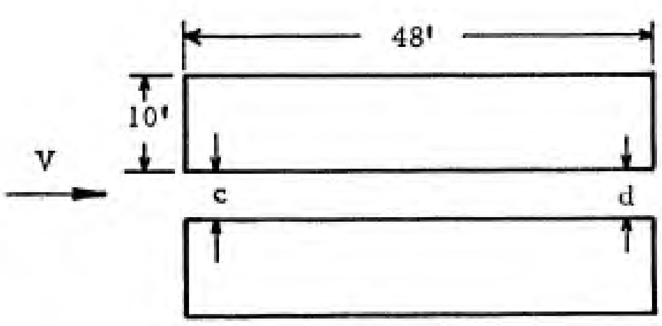
Field Fire No. 6



Field Fire No. 7



Field Fires Nos. 1, 2



Field Fire No. 8, c = d = 4 ft
Field Fire No. 9, c = 10 ft., d = 6 ft.

Fig. F-3 FUEL LAYOUTS FOR FIELD FIRES

Fig. F-4 EXPERIMENTAL SETUP OF FUEL FIRES

Fig. F-5 FUEL FIRE WITH THIRTY-SIX 5 x 5 FT. PANS SEPARATED BY 2.5 FT.

air motion. Temperatures were recorded as a function of height at selected locations above the fuel beds and aisles.

In all experiments, the burning rate per unit of fuel surface area was constant during the stable portion of the fire (before the fuel depth became too small and the water began to boil). Expressed in change of depth, the burning rate was 0.14 in./min. This constant rate indicates that the natural and induced wind velocitites were not of sufficient magnitude to have significant effect, even though coalescence was obtained for some fires and not for others.

The wind was 5-15 mph for most tests. Coalescence was obtained in the direction of the wind but to varying degrees perpendicular to the wind. A wind velocity of 5 mph was sufficient to tilt the flames approximately 30° from vertical; winds in the 10-15 mph range caused a tilt of 45° or greater. Fires in 16 x 16 ft. pans 12 ft. apart did not appear to coalesce. Coalescence was obtained on the order of 10 ft. above the pans for the 6 and 9 ft. spacings. The flames are not readily visible at this height due to the large amount of smoke produced by the fire. The arrangement of nine 10 x 10 ft. pans 6 ft. apart coalesced to about the same degree as the 16 x 16 ft. pans, the flames merging some distance above the fuel. The arrangement of thirty-six 5 x 5 ft. pans 2-1/2 ft. apart was the best demonstration of a mass fire. The degree of coalescence in the test was proportionately greater, considering the spacing in comparison to the pan size, than the other tests using comparatively few pans. The tests indicated that the coalescence is a function of not only the proximity of the fires, but also the total number of fires. Thus, although few fires of any given size and proximity may not coalesce, a sufficient number probably will coalesce due to the lack of air in the interior of the fire.

In the test using two 10 x 48 ft. pans 4 ft. apart, the wind was parallel to the 48 ft. side but some coalescence was obtained at the downwind portions of the fire. In the upwind portion, the wind may have counteracted the evacuating effect of the fire, but did not penetrate the whole length of the pan and thus coalescence was obtained on the downwind side. It should be noted that the wind in no case penetrated the entire fire. Air flows near the ground on the leeward side of each fire were observed to be in the direction of the fire itself for some distance from the fire boundary. It thus seems reasonable, in future analytical studies of conflagration, to assume the flame to be distorted but not penetrated by the wind. This may well simplify the analytical treatment of pressures on the downwind side of such fires.

Although producing some general information on the coalescence of convective columns, experiments of the above type are more suited for the purpose of assessing a theoretical treatment of the behavior of multiple fires rather than for use as a tool to generate such theory. The added complexity of an uncontrolled wind and the requirement for an extreme number of such fires, makes it difficult to analyze the many interwoven effects.

C. The Use of Wood Cribs

As a portion of the study on well ventilated fires (Appendix A), several single cribs were burned in the open. These consisted of three or six foot square arrays of 1 x 2 or 2 x 4 inch lumber of both three and six inch centers. Unlike the pan fires, the crib fires appeared quite stable. A small number of exploratory experiments involving four - 3 x 3 foot cribs (see Fig. F-6) indicated the utility of the crib fire for coalescence studies and demonstrated that both the spacing between fires and the burning rate of each fire contributed to the coalescence. Several fires coalesced during their peak burning period, but separated as the burning rate decreased.

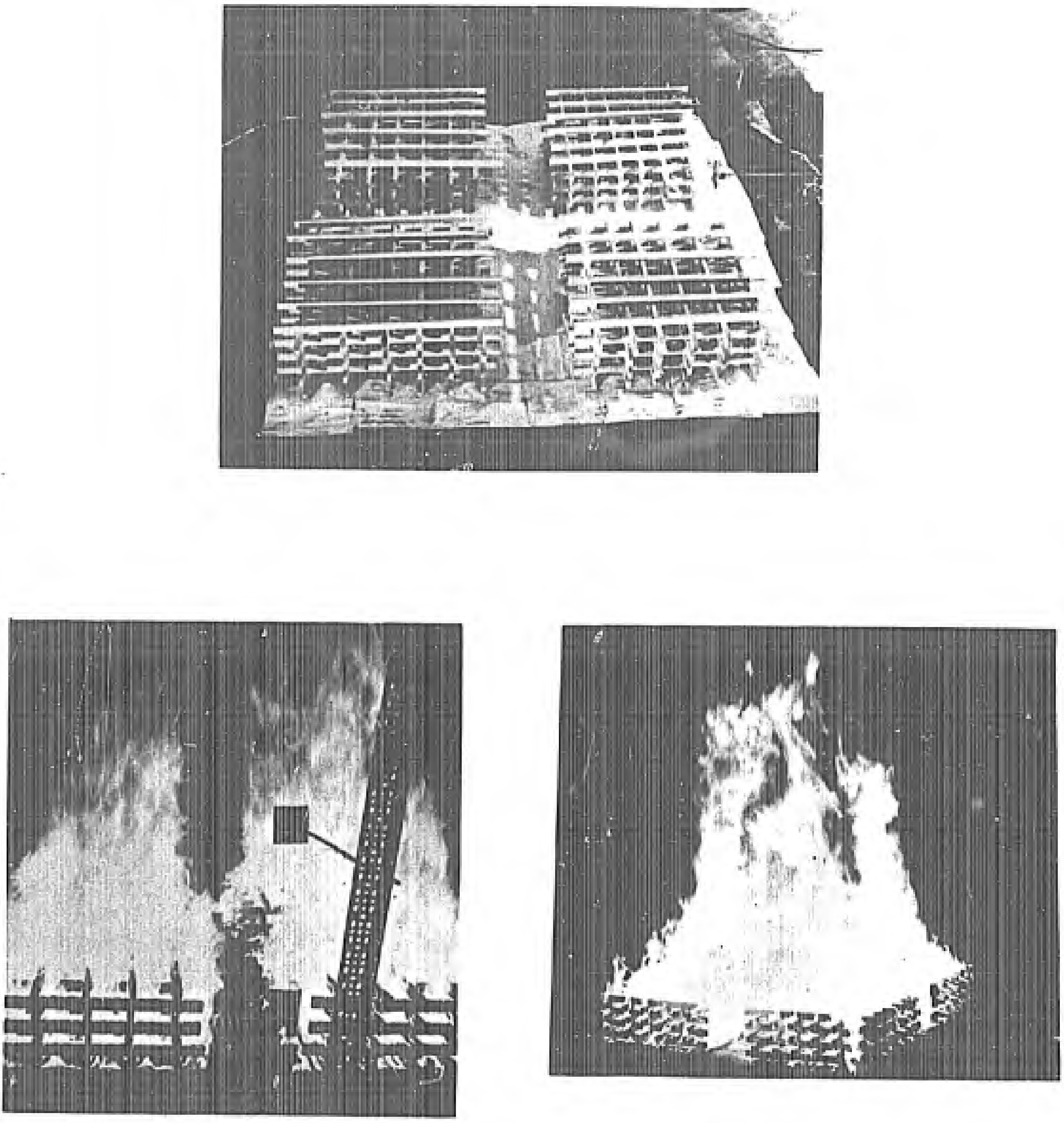


Fig. F-6 OPEN FIRE WITH FOUR CRIBS

Based on these results, a series of experiments was proposed, ranging in size from a single fire to multiple fires involving about 150 square feet of ignited area in the plane of the floor (the largest fire consistent with the size of available indoor facilities). These experimental fires were conducted and are described below.

III. THE COALESCENCE OF MULTIPLE WOOD CRIB FIRES

A. Experimental Procedure

In all, 63 experiments were conducted in this series. The fuel arrangements included (in increasing size):

1. single fires - 2 x 2, 3 x 3, and 6 x 6 ft. cribs
2. four - 3 x 3 ft. cribs
3. nine - 2 x 2 ft. cribs
4. thirty-six - 1 x 1 ft. cribs
5. nine - 3 x 3 ft. cribs
6. sixteen - 3 x 3 ft. cribs

All cribs consisted of 1 x 2 inch lumber set on three inch centers. Burning rates were varied by using cribs either four or six rows high and by switching from spruce to fir lumber. After some random initial experiments throughout the ranges of size and fuel type, the following arrangements were selected for the main study (commensurate with fuel availability):

1. sixteen - 3 x 3 ft. cribs 4 rows high (fir)
2. four - 3 x 3 ft. cribs 6 rows high (spruce)
3. four - 3 x 3 ft. cribs 4 rows high (spruce)
4. four-3 x 3 ft. cribs 4 rows high (fir)
5. nine - 2 x 2 ft. cribs 4 rows high (spruce)

Within these groupings the spacing between cribs was varied to encompass the region from fully coalesced flames to apparently individually burning fires.

Each burn was conducted in the following manner. The crib, previously dried to a moisture content of 6-8 percent, was placed on a platform which was continously weighed. Early experiments were conducted on a corregated metal platform but difficulties with warping and buckling lead to the development of a wood framed, plywood covered platform coated with a one-half inch layer of Eagle-Picher insulating cement. The cement was moistened before each test to provide additional protection to the platform and scales. A sheet of aluminum foil placed over the damp cement acted as a barrier to the moisture entering the convective column. Examination of the weight records of several fires, r[illegible]ed immediately after their active burning period, indicated that negligible moisture succeeded in leaving the platform during this portion of the fire. Exact crib spacing was achieved by carefully locating appropriately sized squares of 1/4 inch plywood on the platform and constructing each crib on its respective square.

Ignition of the cribs was accomplished by placing a layer of industrial wipers (quilted paper) under the crib lumber. A light application of JP-4 just prior to ignition assured rapid spread of the fire to all lumber. In this manner, all cribs reached a fully involved state simultaneously. Temperatures were monitored at several heights at the center of the column. Radiation levels were measured at various distances from two sides of the fires. Air velocities and directions were obtained by a combination of hot-tube anemometers and electrically ignited smoke powders. Photographic records, using 16 mm movie film, permitted assessment of flame heights, flame areas and the degree of coalescence. A second camera photographed the smoke trails.

The useful portion of each burn started about two minutes after ignition and lasted from two to four minutes. During this period the fires remained stable, showing constant rates of weight loss, radiation levels, flame heights, etc. A typical weight loss curve is shown in Fig. F-7. A series of time-oriented photographs are included as Fig. F-8. The loss of coelescence can be noted in the last pictures (reduced burning rate).

B. Results

The criterion for coalescence was initially based on visual observations and photographic records of the flames. As the program progressed, study of the records indicated that the transition from coalesced to non-coalesced fires coincided with a rapid change in the total burning rate of each array. The burning rate increased as the space between cribs was increased until the transition point was reached at which time the burning rate suffered a sudden drop in magnitude (Fig. F-9). This may be explained in the following manner. As the cribs are gradually separated, air is rapidly drawn down the channels between them, as long as the fires remain coalesced. Loss of coalescence suddenly removes the driving force and the air velocity through the channels is reduced. This reduction is reflected in the burning rate although there apparently has been no abrupt change in radiation between cribs. As some resistance to the normal convective flow to individual cribs remains due to the proximity of the adjacent fires, the burning rate may reduce to a value below that achieved for large spacings. This effect is particularly evident in Fig. F-9 for the 16 - 3 x 3 ft. cribs in which four cribs are bounded on all sides by

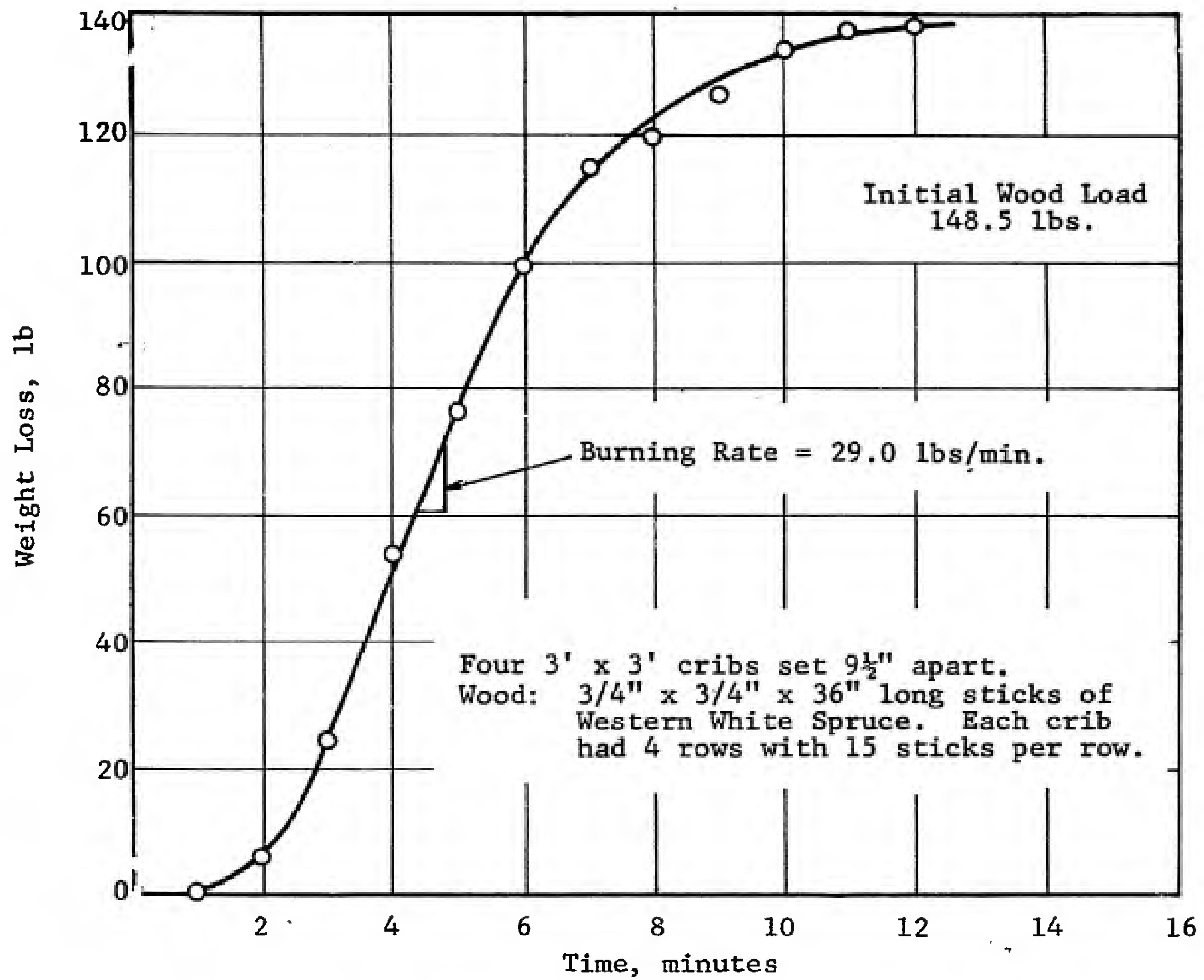
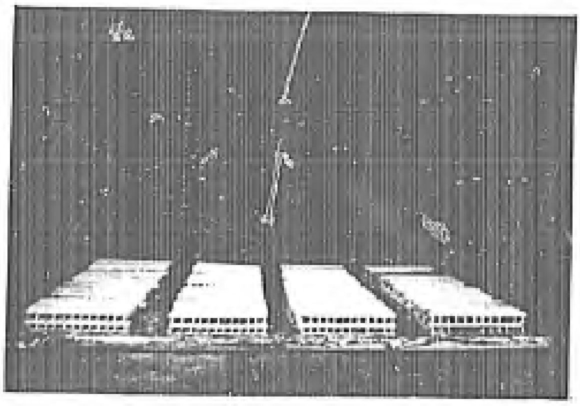
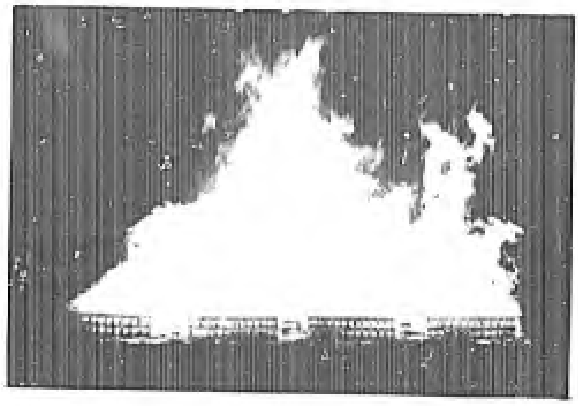


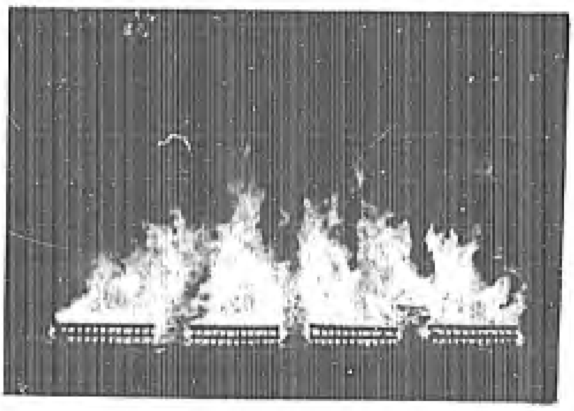
Fig. F-7 A TYPICAL WEIGHT LOSS RECORD



16 - 3 ft. x 3
12 in. apart



2-1/2 min.



5-1/2 min.

Fig. F-8 BEHAVIOR OF A COALESCED FIRE

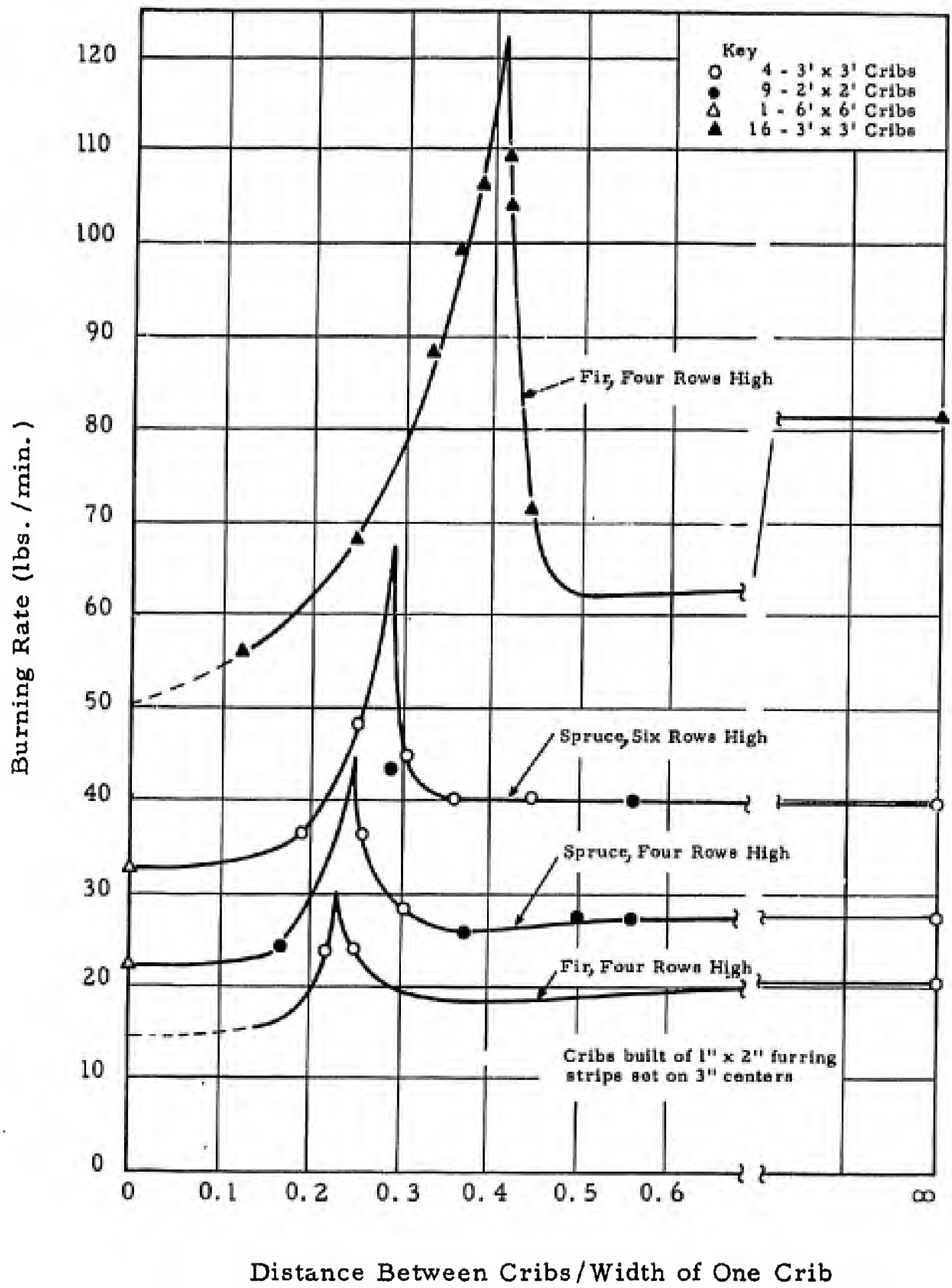


Fig. F-9 BURNING RATE AS A FUNCTION OF THE DISTANCE BETWEEN CRIBS other fires. As the total number of fires increases and a larger portion of fires are away from the perimeter, this reduction of the burning rate can be expected to be more pronounced.

In Fig. F-9, the transition point for coalescence (peak of each curve) can be seen to occur at larger ratios of crib spacing to crib dimension when either the total number of cribs is increased or the single crib burning rate is increased (crib height increased or wood type changed). Attempts were made to obtain values exactly at the transition point by first spanning the area of interest and then successively narrowing the range between the points bracketing the peak. Even so, some curve fairing was required. The error introduced is not particularly large in terms of crib separation to crib dimension ratio but may be more significant in estimating the exact peak value of the burning rate.

The effect of oxygen depletion or air flow restriction through each crib matrix is also evident from study of Fig. F-9. It may be noted that, for the stick spacing used in the cribs (3 inch centers), the burning rate of a single crib increases more slowly than its fuel surface area. For example, the burning rate of four - 3 x 3 ft. spruce (4 rows high) cribs is 28 lb/min., while one - 6 x 6 ft. crib of the same material burns at 22 lb/min. As the crib size increases, the lag in burning rate becomes even more pronounced (16 - 3 x 3 ft. cribs burn at 82 lb/min., while one - 12 x 12 ft. crib burns at 50 lb/min). A similar situation may be expected to occur with real structures. When the individual building gets extremely complex, the effects of air flows within the single building will be superimposed on the general air flow down the channels between structures. On a larger scale, a second similarity may be made using blocks of structures within a tract.

As mentioned earlier, the spacing at which coalescence occurs and the magnitude of the burning rate at this spacing, are governed by the burning rate of a single crib fire and the total number of such fires. Dividing the abscissa of Fig. F-9 by the 0.4 power of the product of the burning rate of an individual crib, R_s, and the total number of cribs, n, brings the transition peaks into a vertical line at a value of 0.069, as shown in Fig. F-10. Thus, a scaling law for coalescence becomes:

$$\left(\frac{\text{distance between cribs}}{\text{crib dimension}} \right)_{\text{Peak}} = 0.069 \, (n \cdot R_s)^{0.4} \qquad \text{(F-1)}$$

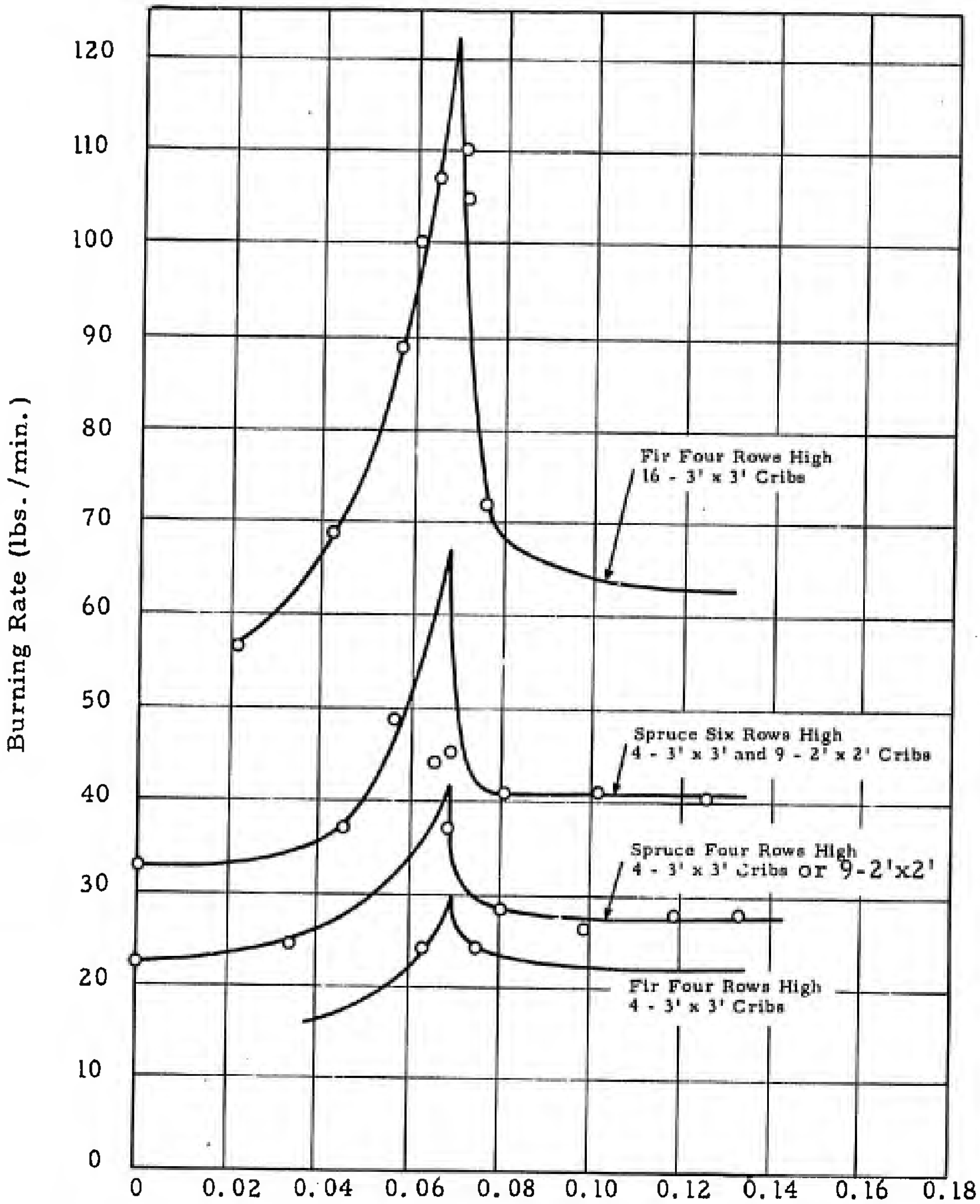
The burning rate at transition, R_{peak}, can be shown to be:

$$R_{peak} = 1.56 \, (n \cdot R_s) \qquad \text{(F-2)}$$

Other attempts to correlate the data have not yielded any useful information on the criteria for coalescence. As previously stated, the burning rate showed the greatest sensitivity in the coalescence transition region. Correlation of other parameters either singly or in various groupings did not exhibit this characteristic. For example, the dimensionless correlation of flame heights and burning rates for free burning crib fires, as presented by Thomas[4] and discussed in Appendix A, is repeated here (Fig. F-11) for inclusion of the coalesced fires from this study. The width of the single crib, w, used in Appendix A has been replaced by the width of the crib array, D. For a square array of n cribs having a crib width w and a crib separation d:

$$D = w\sqrt{n} - (1 - \sqrt{n}) \, d. \qquad \text{(F-3)}$$

This correlation as presented in Fig. F-11 does not permit determination of the spacing required for coalesced fires. However, it can be used to interpret flame heights for groups of coalesced fires, although the data scatter indicates the need for the inclusion of additional parameters.



$$\left[\frac{\text{Distance Between Cribs}}{\text{Width of One Crib}}\right] \times \left[\frac{1}{(nR_s)^{0.4}}\right]$$

Fig. F-10 BURNING RATE AS A FUNCTION OF THE ADJUSTED DISTANCE BETWEEN CRIBS

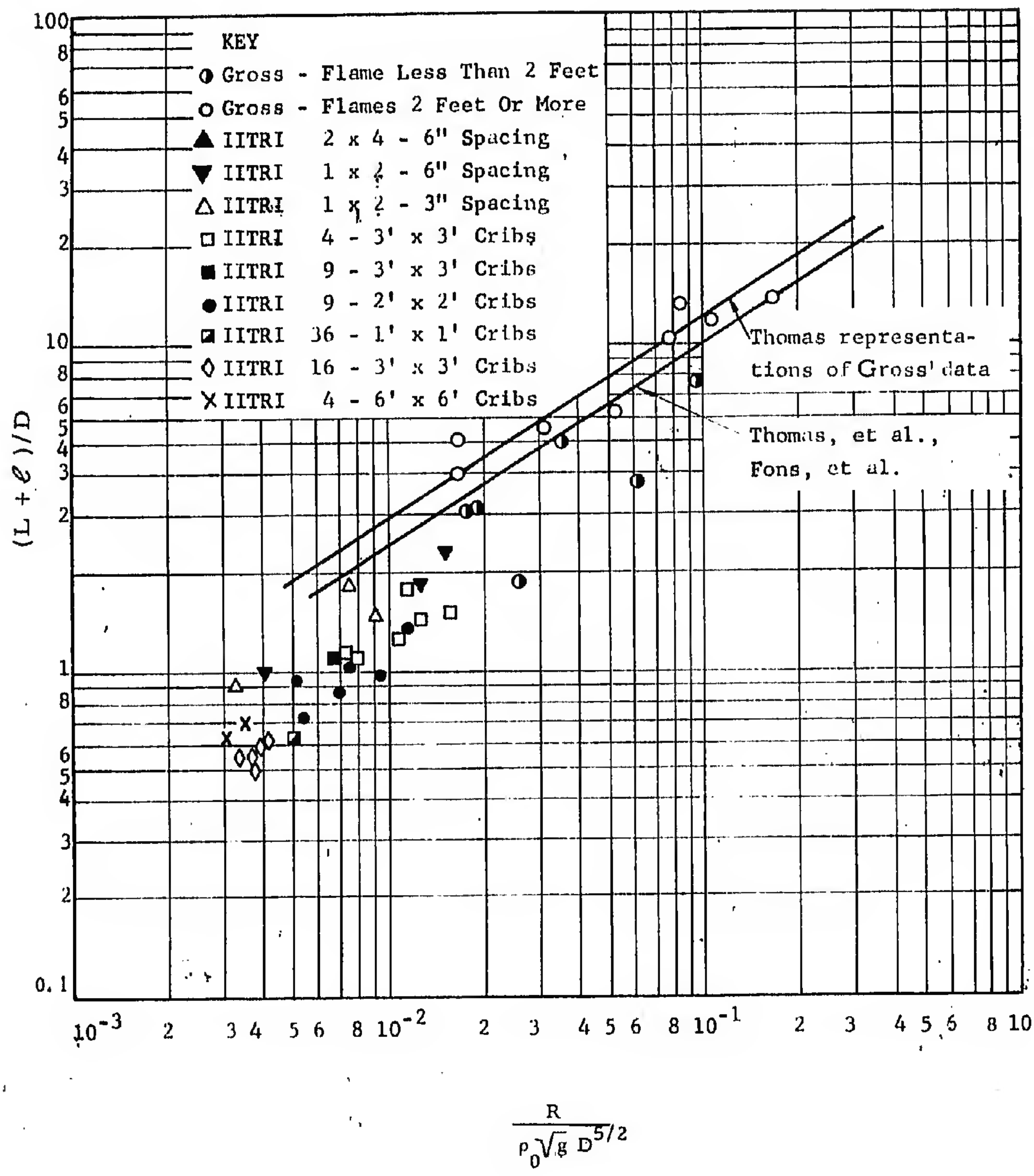


Fig. F-11. EFFECT OF BURNING RATE ON FLAME HEIGHT OF FREE BURNING FIRES.

REFERENCES

1. Richardson, G. T., "The Fire Risk from Wartime Attack", International Fire Fighter, Vol. 25, Dec., 1952.

2. Blinov, V. I., and Khudiakov, G. N., Dokl. Akad. Nauk S. S. S. R., Vol. 113, 1957, p. 1094.

3. Hottel, H. C., Fire Research Abstracts and Reviews, Vol. 2, 1959 (a review of reference 2).

4. Thomas, P. H., "The Size of Flames from Natural Fires", Ninth Symposium (International) on Combustion, 1962, pp. 844 - 859.

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APPENDIX G

INSTRUMENTATION FOR FIRE EXPERIMENTS

I. INTRODUCTION

The inherent difficulty in providing instrumentation for fire experiments is the fire itself. This is not only due to the encountered high temperatures, but also due to the measurements of small quantities, which even without any adverse effects, require refined instrumentation. In addition to this the instrumentation must have a degree of ruggedness to permit its combined use for laboratory and field experimentation. As a result, measurements of several parameters pertinent to free burning fire necessitate special instruments not readily commercially available. Such instruments have been developed. Their designs permit continuous and remote recording of the monitored quantities by measuring changes in voltage. To interpret these changes in terms of the measured quantities, they are calibrated against other standard equipment. Features of the constructed instrumentation and the techniques of calibration are discussed below.

II. RADIATION

The instrument used to measure radiant flux, as designed and constructed at IITRI, is based on a radiometer described by McGuire and Wraight.[1] The instrument indicates radiant flux levels by comparing the temperatures of two disks, one of which is exposed to the flux and the other shielded from it. (Figs. G-1 and G-2). Thin disks are used

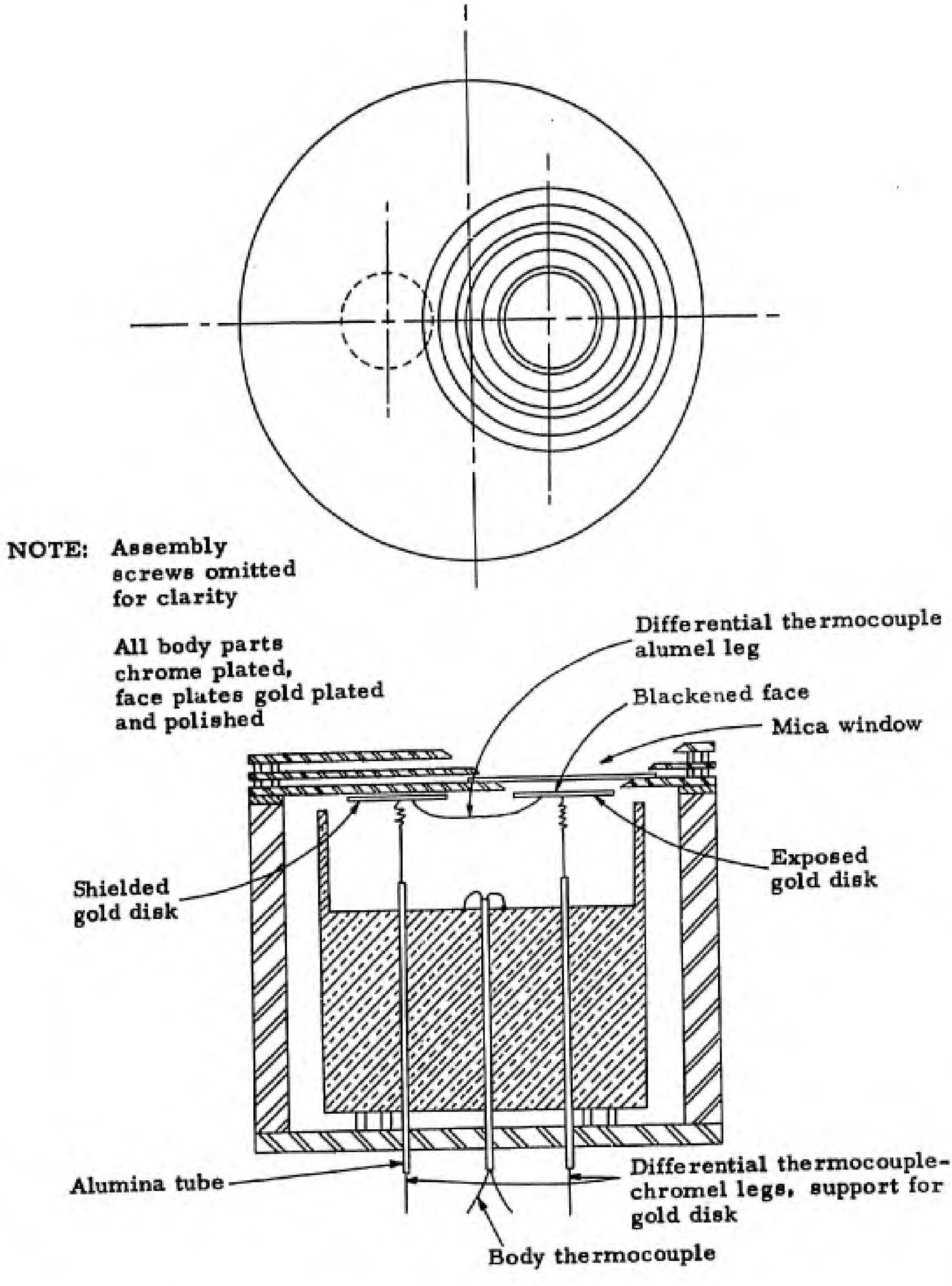
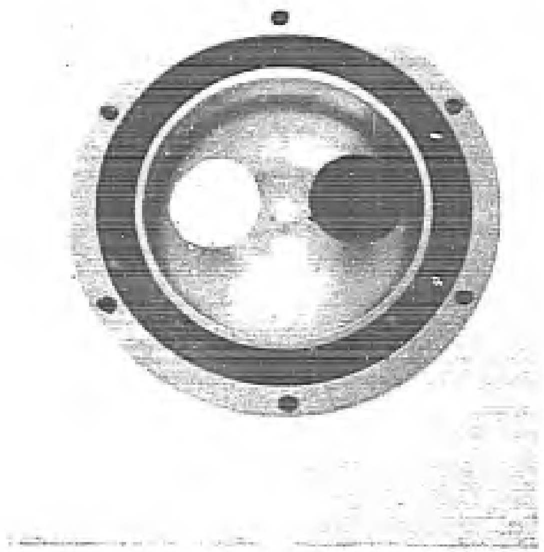
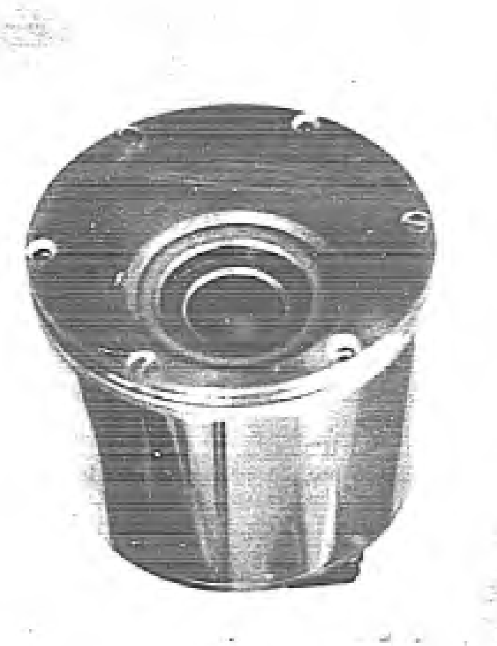


FIG. G-1 RADIOMETER FOR MEASURING HEAT FLUX FROM FIRES



Radiometer with shield removed

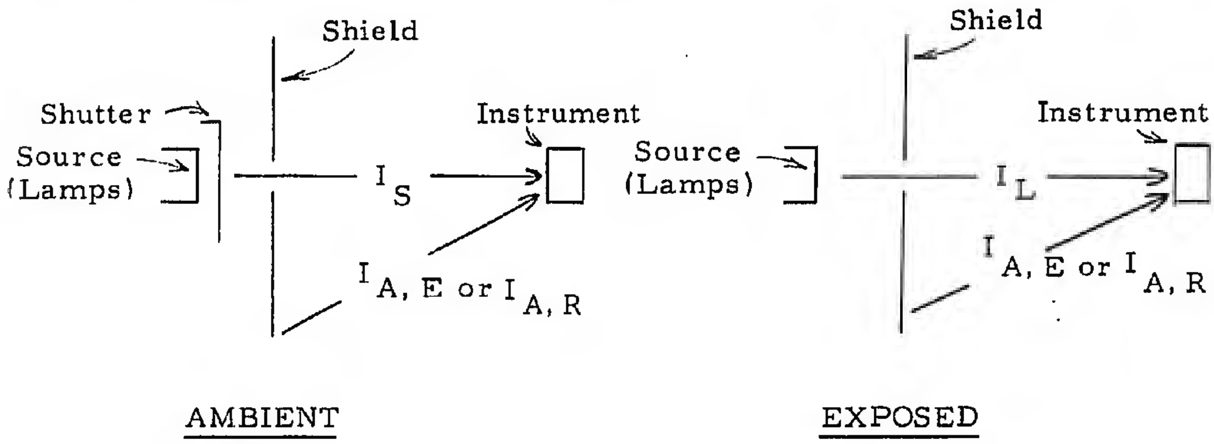


Radiometer assembly

Fig. G-2 PHOTOGRAPHS OF THE RADIOMETER

(0.002 in. thick) to achieve rapid response to changes in flux intensity. The exposed disk is blackened on the side viewing the radiant source and highly polished on the reverse side. The shielded disk which serves as the reference is highly polished on both sides to minimize temperature changes due to radiation received from the sink and cover plate. A copper block is used as the sink to minimize temperature changes so that the unexposed sides of the disks see an essentially constant temperature. Each disk is supported by a chromel leg of the thermocouple wire (0.005-in. diameter) which is lead through a ceramic tube to a terminal block on the unexposed side of the radiometer for connection to the recording instrument. An alumel wire connects the two disks completing the differential thermocouple circuit. Radiation shields are used on the exposed radiometer face to reduce the temperature attained by the inner cover plate during long exposures to a source. Heating of this cover plate will result in a temperature increase of the reference disk, causing the millivolt reading to decrease with time. A window of mica, approximately 0.001 in. thick, is used to prevent convective cooling of the exposed disk by wind in the field. Mica was chosen since it has low absorption of radiation in the infrared region.

The instrument was calibrated for radiant flux levels up to 0.04 cal/cm^{2}sec by comparison with the reading from an Epply thermopile, using a device similar to an optical bench for alignment and a bank of eight quartz lamps with reflector as a source. A shield with a 2 in. x 2 in. opening was placed in front of the lamps to reduce the source size to within the field of view of both instruments. Changes in shield temperature over long time periods will still affect each instrument differently due to their dissimilar viewing angles. To account for this effect, calibration was accomplished by exposing both instruments to the shielded source with and without a shutter across the shield opening as shown below.



With the shutter in place, fluxes measured are:

$$I_E = I_{A,E} + I_S \qquad \text{(G-1)}$$

and

$$I_R = I_{A,R} + I_S \qquad \text{(G-2)}$$

With the shutter open:

$$I_E^* = I_{A,E} + I_L \qquad \text{(G-3)}$$

and

$$I_R^* = I_{A,R} + I_L \qquad \text{(G-4)}$$

The subscripts R, E, A,L and S refer to the radiometer, Epply cell, ambient,lamps and shutter respectively. As noted above, $I_{A,E} \neq I_{A,R}$ due to the variation in the angle of vision of each instrument.

By subtraction:

$$I_E^* - I_E = I_L - I_S = I_R^* - I_R \qquad \text{(G-5)}$$

which relates the flux differences measured by each instrument.

For higher flux intensities, beyond the range of the Epply thermopile, the shield was removed and a ten-to-one chopper was placed in front of the radiometer, readings being taken with and without the chopper in use. Comparison of the readings permitted the radiometer to act as its own calibration standard for the high range. The calibration device is shown in Fig. G-3 with the chopper in place.

It was found necessary to correct for the radiation from the chopper itself, since it reached temperatures sufficient to cause an appreciable reading. The chopper was close to the radiometer so that, for a ten-to-one chopper, the radiometer saw the flux from the source (I_S) one-tenth of the time, and from the chopper (I_c) nine-tenths of the time. Thus, the total flux impingent on the radiometer was:

$$I_i = \frac{1}{10} I_S + \frac{9}{10} I_C \qquad \text{(G-6)}$$

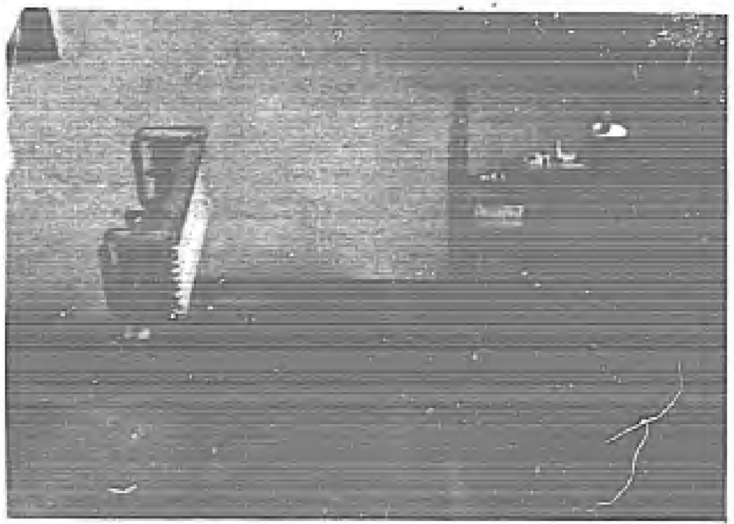
Since the radiometer measures the flux above a reference, it is more convenient to consider

$$\Delta I_i = I_i - I_o = \frac{1}{10} (I_S - I_o) + \frac{9}{10} (I_C - I_o) = \frac{1}{10} \Delta I_S + \frac{9}{10} \Delta I_C$$

or

$$\Delta I_S = 10 \Delta I_i - 9 \Delta I_C \qquad \text{(G-7)}$$

The terms ΔI_i and ΔI_C are determined from the radiometer readings, which fall in an already calibrated range. A typical calibration curve is



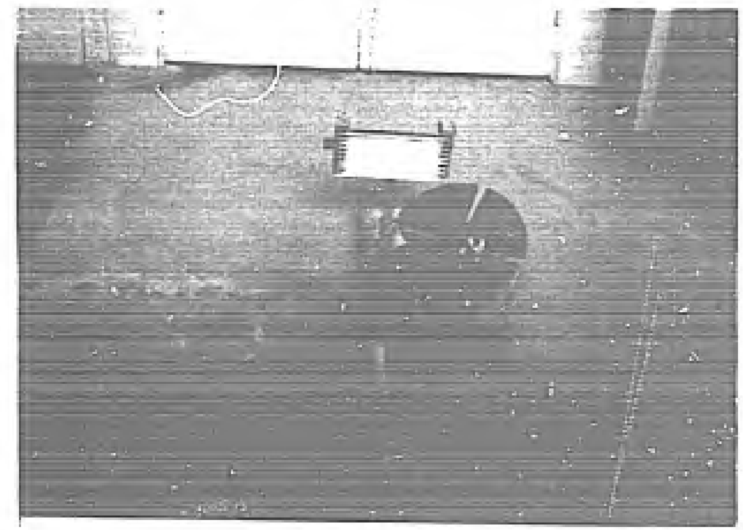


Fig. G-3 RADIOMETER CALIBRATION STAND WITH CHOPPER IN PLACE shown in Fig. G-4. A comparison of various radiometers with the curve for a perfectly black receiver absorbing and emitting energy on one side only is shown in Fig. G-5.

An approximate analysis of the instrument may be obtained by considering only radiant heat transfer from the exposed disk. Consider a flux I_i of which ϵI_i is absorbed. If the sink temperature, T_R, is the same as the reference disk temperature, and T is the temperature of the exposed disk, then $\sigma F (T^4 - T^4_R)$ is the net radiant interchange between the back side of the exposed disk and the sink. F is defined as:

$$F \approx \frac{1}{\frac{1}{\epsilon_{disk}} + \left(\frac{1 - \epsilon_{Sink}}{\epsilon_{Sink}}\right)\frac{A_{disk}}{A_{Sink}}} \qquad \text{(G-8)}$$

considering the geometric angle factor from the disk to the sink as one. The terms ϵ and A are the emissivity and area respectively. A heat balance for the disk yields:

$$I_i = \sigma T^4 + \frac{\sigma F}{\epsilon} (T^4 - T_R^4) \qquad \text{(G-9)}$$

It is noticed that when $T \rightarrow T_R$, $I_i \rightarrow \sigma T_R^4$, the reference flux associated with a zero millivolt reading. Calculations of $I_i - \sigma T_R^4$ check the experimental calibration curve, if $F/\epsilon \approx 3$, up to flux levels of 0.08 cal/cm^{2}sec. Above this point, the calculated values are higher than the calibration values, indicating possible cooling of the disk due to internal convection.

When using the radiometer to measure the radiation from a fire, the flux associated with the reading represents the net radiation increase from the fire above that of the background. The total radiation from the fire would be obtained by adding an equivalent to the contribution from the

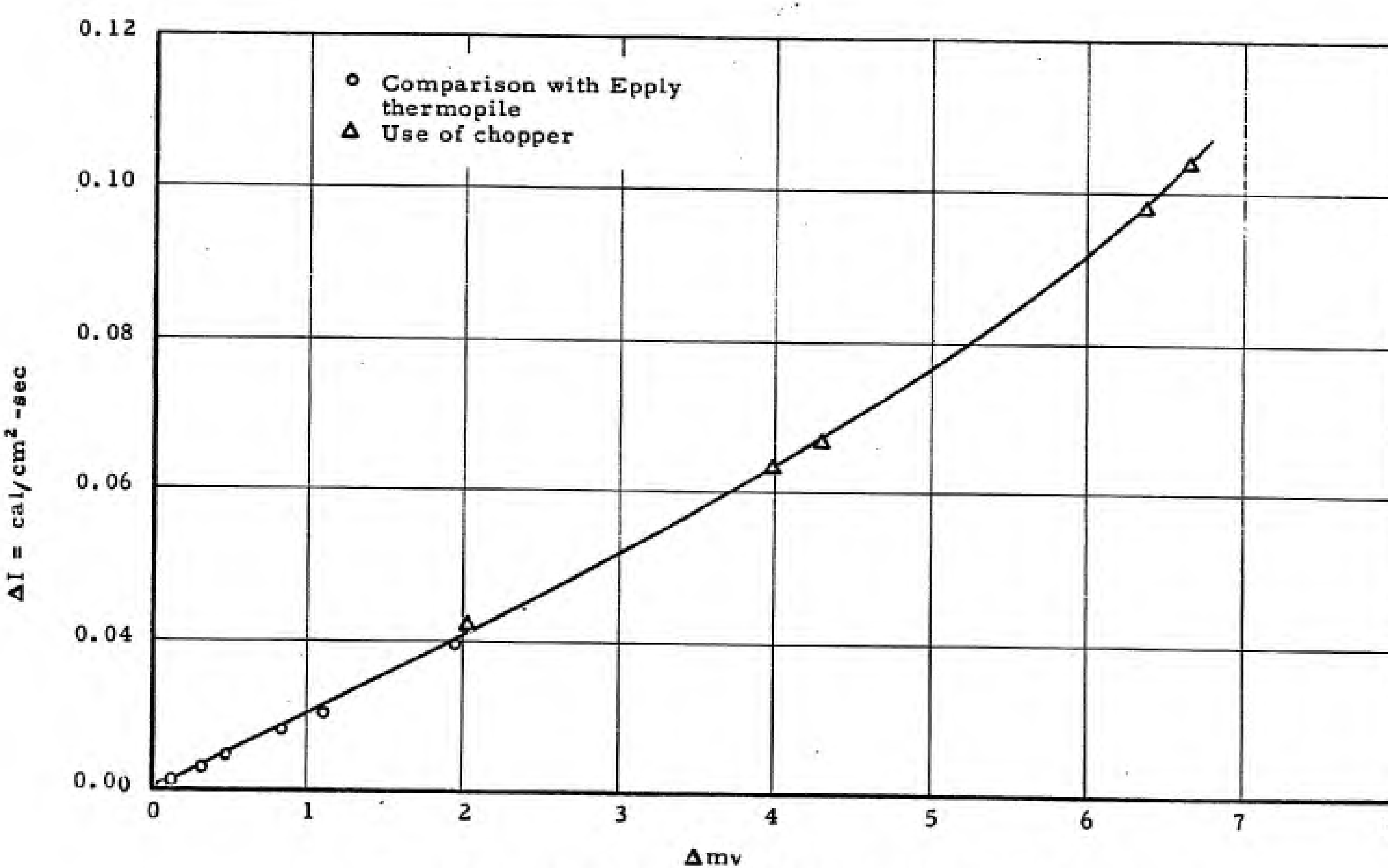


Fig. G-4 TYPICAL RADIOMETER CALIBRATION CURVE

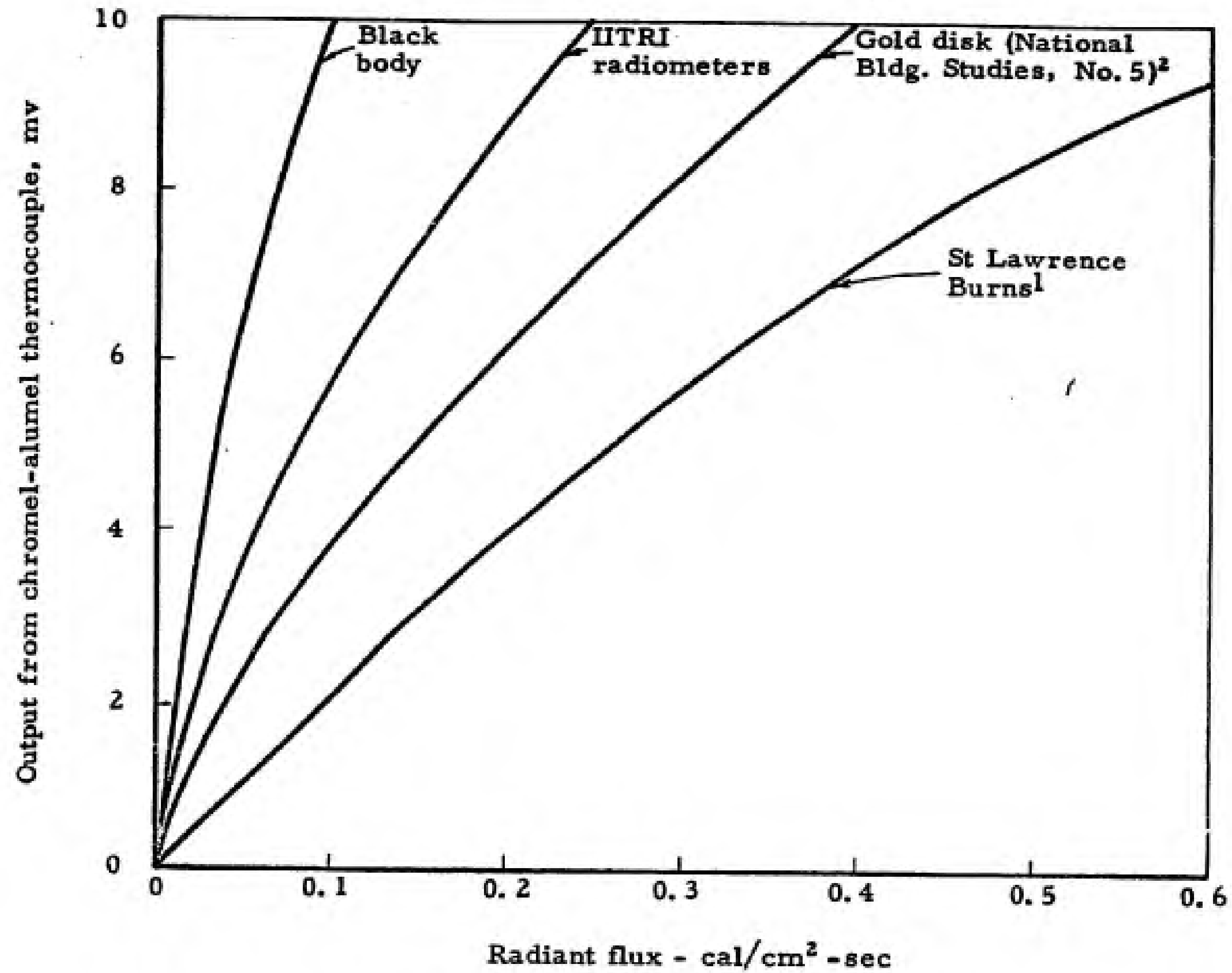


FIG. G-5 COMPARISON OF RADIATION MEASURING DEVICES portion of background no longer visible to the radiometer. Fortunately, this correction amounts to less than 0.5 percent for typical background temperatures (70°F) and may be neglected.

III. AIR VELOCITY

The hot-wire anemometer is commonly used for measuring low air speeds and its sensing element normally consists of a very fine exposed wire which is heated by an electric current. The temperature of this wire and consequently its electric resistance depends on the rate of cooling caused by air flowing over it, and, therefore, it can be calibrated for measuring air speed. A modified instrument is described by Simmons[3] who used a twin-bore silica tube with a resistance-heated element in one hole and a temperature measuring thermocouple in the other. At a sacrifice in response time he was able to achieve greater accuracy and a more stable calibration. Such an instrument, however cannot be used in the vicinity of a fire because varying thermal radiation from the flame may overshadow the convective heat transfer due to air flow.

This difficulty was overcome by Fire Research investigators[4], who used two identical tubes and connected the thermocouples in opposition so that the emf signal is a function of the temperature difference between them. If only one tube is slightly heated electrically, the output of the differential thermocouple should depend only on the heating current and on the rate of cooling due to the air flow. The effect of radiant heating from a high temperature source, such as flames, is essentially the same for both tubes and the difference of the heat balances from each tube yields the relation:

$$T - T_R = \frac{I^2R}{hA} - \frac{\sigma\epsilon}{h}(T^4 - T_R^{\ 4}) \qquad \text{(G-10)}$$

where T and T_R are the temperatures of the hot and reference tube respectively, I is the constant current through the hot tube, R the heating wire resistance, ϵ the emissivity, and h the convection coefficient. When there is no radiation, the relation reduces to:

$$T - T_R = I^2 R/hA \qquad \text{(G-11)}$$

In the calibration region, $T - T_R$ is almost directly proportional to the millivolt output of the differential thermocouple. The instrument is based on changes of h, with velocity in the forced convection region. For small temperature differences:

$$T^4 - T_R^4 \approx (T - T_R)\, 4T^3_m, \text{ where } T_R < T_m < T \qquad \text{(G-12)}$$

Then:

$$T - T_R \approx \frac{I^2 R/hA}{1 + \frac{\sigma\epsilon}{h} 4\,T^3_m} \qquad \text{(G-13)}$$

indicating that radiation will not affect the calibration if $\frac{\sigma\epsilon}{h} 4\,T^3_m$ is much smaller than one. For room temperatures, $4\,\sigma\,T^3_m$ is on the order of 1 Btu/hr-ft^{2}R. Then it is desired to have ϵ/h much smaller than one. For $\epsilon = 0.1$ and h = 10 Btu/hr-ft^2 - R, $\epsilon/h = 0.01$, and the error due to radiation is only one percent.

Differential hot-tube anemometers based on the above design were constructed for the fire experiments and are illustrated in Fig. G-6 and G-7. The tubes of each unit were 0.042 in. OD stainless steel, and the

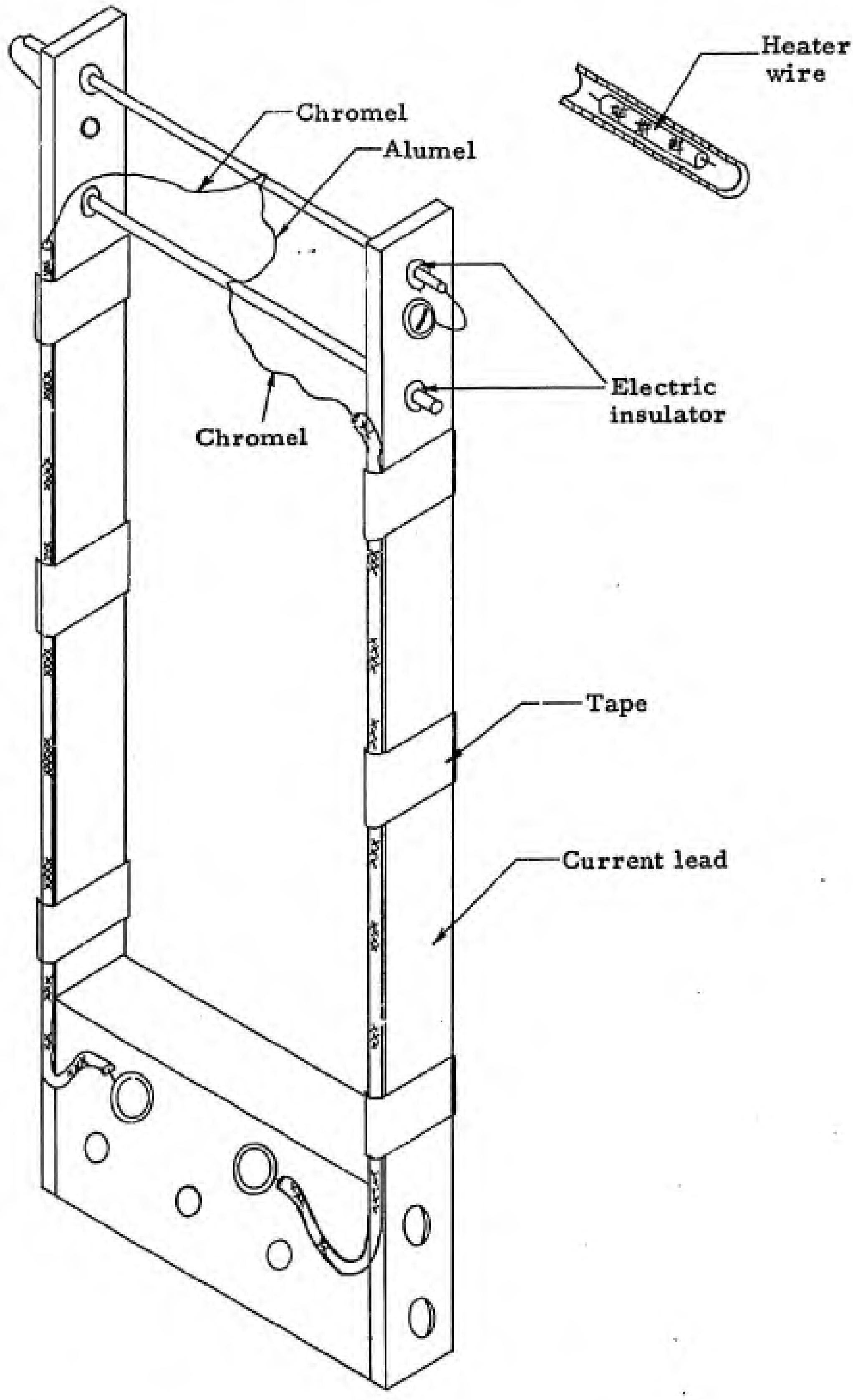


FIG. G-6 HOT-TUBE ANEMOMETER

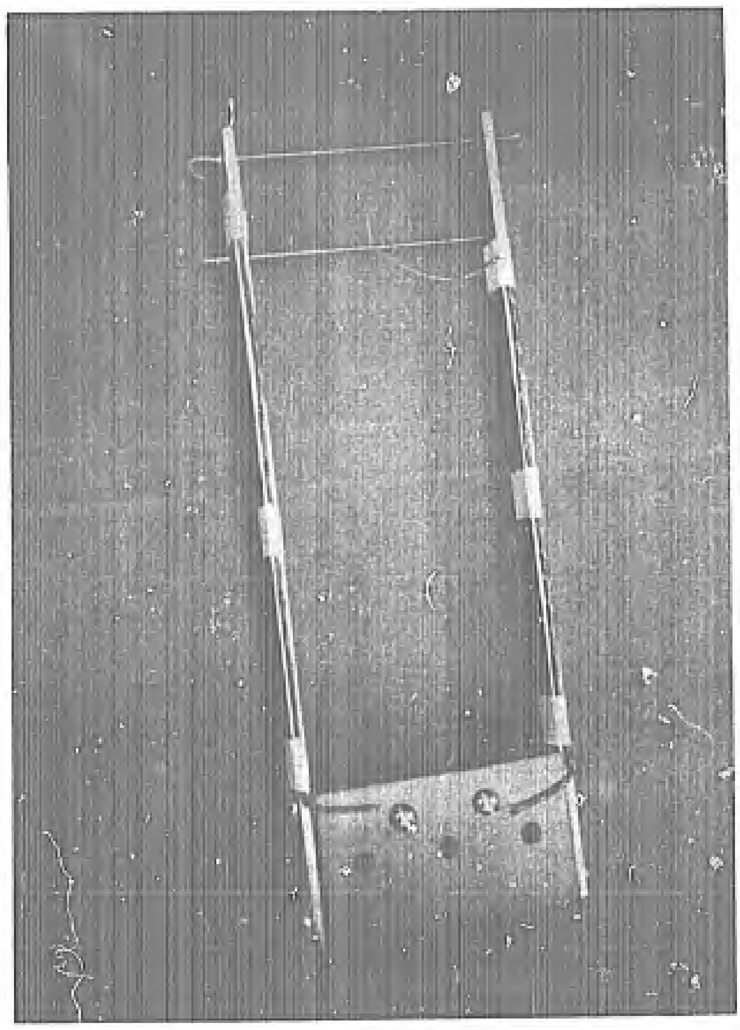


Fig. G-7 PHOTOGRAPH OF HOT TUBE ANEMOMETER externally-connected differential thermocouple was made of 36 gage (0.005 in. dia.) chromel-alumel wires. One of the tubes contained an insulated 30-gage (0.010 in. dia.) constantan wire as a heating element, the supports serving as electric current leads. Heating of the resistance wire was recorded by monitoring the voltage drop. These hot-tube anemometers are of simpler construction than those described in Ref. 4 and offer certain advantages. The use of a single hole metallic tube, instead of twin bore ceramic, assures uniform temperature around the circumference of the tube, and thermocouples welded to the tube wall yield a more rapid response time. Gold plating and polishing the tubes reduces their emissivity with a subsequent reduction in error due to radiation from the fire.

Calibration of the anemometers was accomplished by rotating them in an enclosure as shown in Fig. G-8. Power and thermocouple leads were brought to a series of annular mercury pools where the signals could be picked up by wipers, rotating with the anemometer. This rotation was accomplished by use of a constant speed motor with an adjustable drive. Wind velocity is determined by timing the rotational speed. A typical calibration curve is shown in Fig. G-9.

As one might suspect, the calibration curve is quite sensitive to input current to the heated tube. A 100% error was indicated in the wind velocity from a 15 percent change of heater current. For this reason, the input current must be carefully monitored and controlled. To accomplish this and to minimize the number of controls required, panels were constructed which operated any number of anemometers up to 10 per panel. The anemometers were connected in series through the panel and thus each received exactly the same current flow. A schematic diagram of a panel is shown in Fig. G-10. Power was adjusted by means of a variable

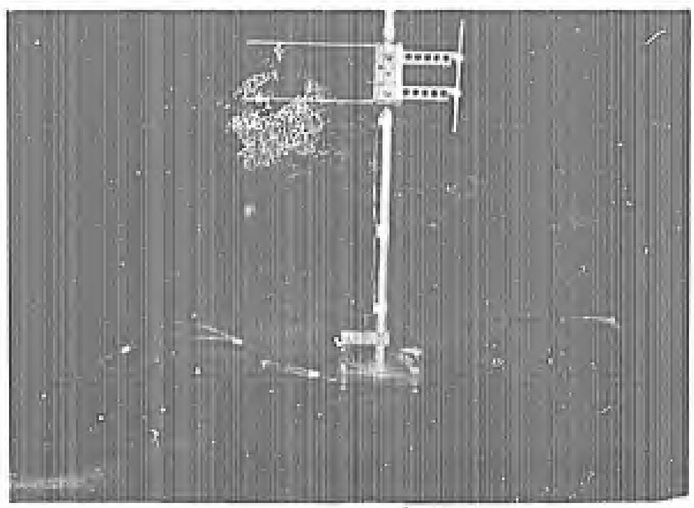


Fig. G-8 ANEMOMETER CALIBRATION

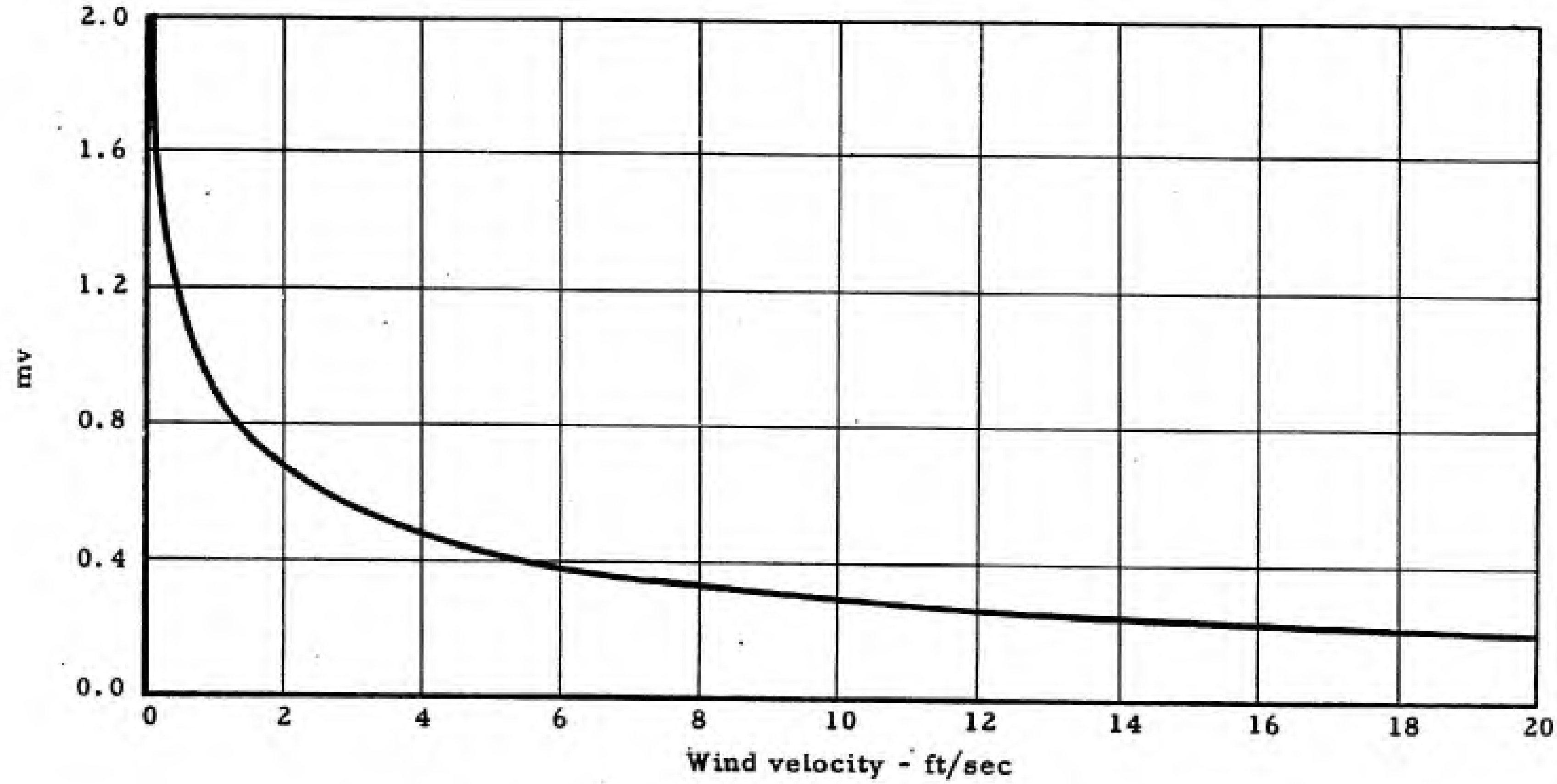


Fig. G-9 <u>TYPICAL ANEMOMETER CALIBRATION CURVE</u>

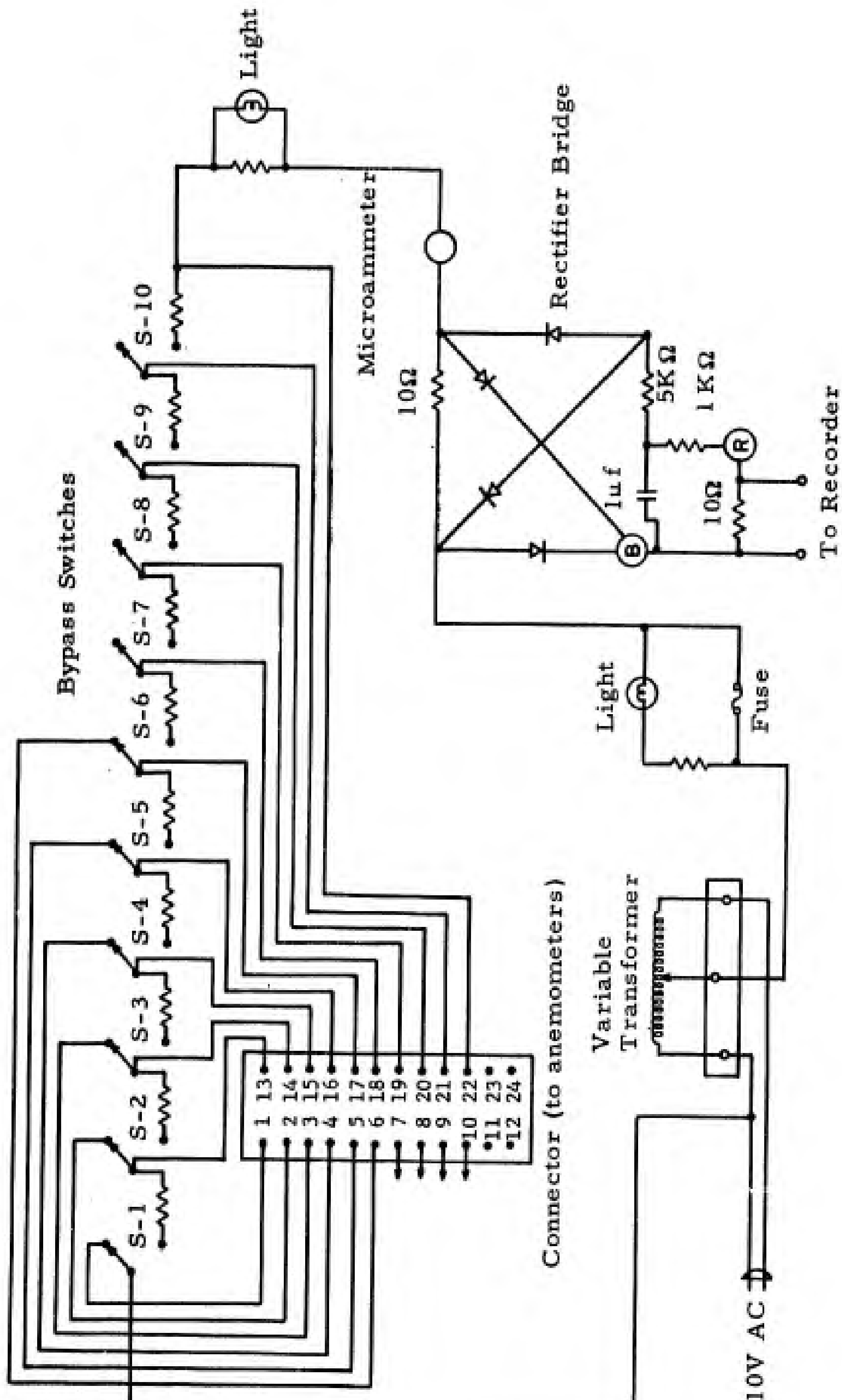


FIG. G-10 ANEMOMETER CONTROL PANEL

transformer and the approximate current level read from a microammeter. To establish a precise, reproducible setting, a resistor was placed in series with the anemometers and, through a rectifier bridge, a D. C. millivoltage monitored. The conversion to a D. C. signal permitted the monitoring voltage to be read on the same recorder that read the differential thermocouple output of the anemometer.

During the instrumentation development, several other methods were considered for measuring air velocity. They include various smoke generating devices and the use of bubbles. Of these, smoke generation was retained for use at very high radiation levels and to confirm air velocity vectors. A brief discussion of methods investigated is presented below.

Smoke generation can be accomplished by dropping oil or various chemicals on a heated surface or by oxidation of titanium tetrachloride vapors in air. In general the resulting smokes were not very dense and coherent and created fumes that were quite irritating and corrosive. The most satisfactory system consisted of the blending of two air streams, one containing hydrochloric acid vapors and the other containing ammonium hydroxide vapors. The resulting ammonium chloride smoke photographed quite well although discrete puffs were not easily obtained. Thus, the primary use of the smoke was for the determination of air flow direction. Figure G-11 shows the unit in operation. A small vibrator type aquarium pump was found to deliver sufficient air to supply several units. Air flow control was achieved by the use of adjustable pinch clamps on the tubing supplying the acid and ammonia bubblers. Passing through the bubblers, each air stream picked up sufficient vapor to produce the smoke cloud at

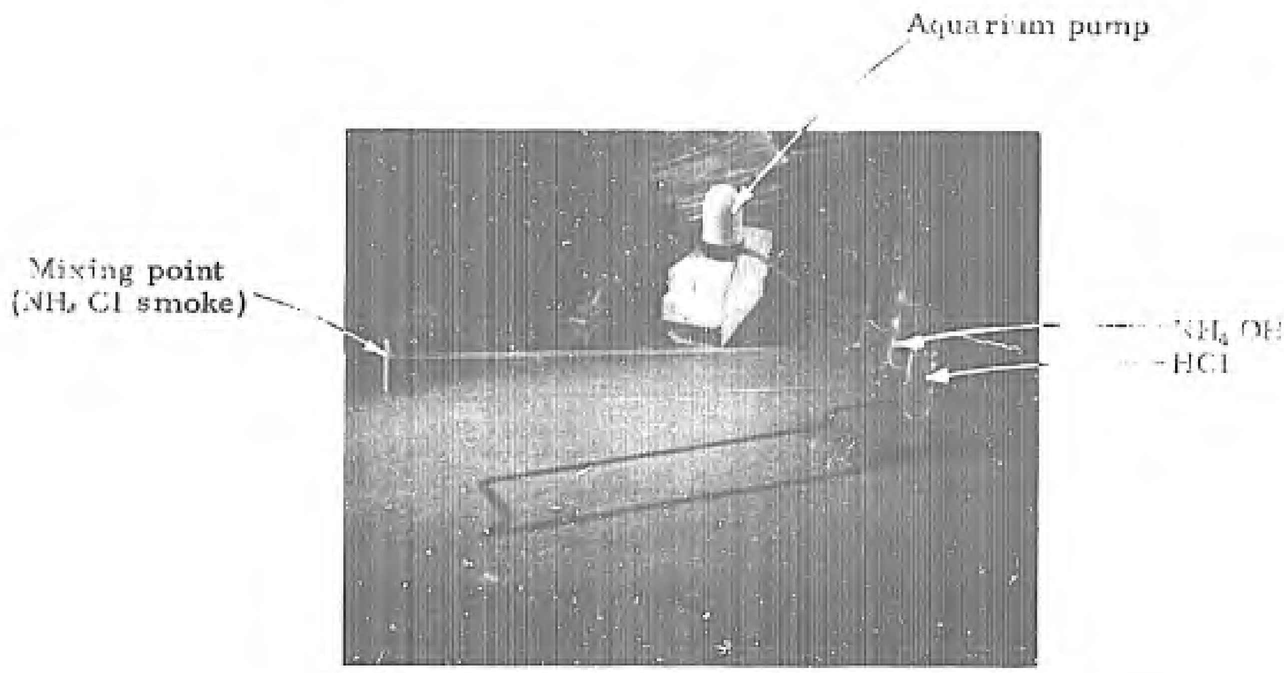


Fig. G-11 AMMONIUM CHLORIDE SMOKE GENERATOR the point of mixing. By extending the mixing point several feet from the bubblers and shielding them from the fire with metal foil, boiling of the liquids was overcome.

Modifications of the HC smoke candle used in chemical warfare were also tried. The standard formulation burned satisfactorily in fairly large volumes but was found unreliable when small quantities were involved. The addition of 5 percent potassium chlorate improved the behavior, however, the mixture proved quite hygroscopic. At this point, "magic smoke," sold by novelty shops, was found to be quite satisfactory and further investigation of special formulations was halted.

Soap bubbles made from commercial soap solutions, as sold at the toy counters and variety stores, were quite long lasting if about 10 percent glycerine were added. They also proved quite resistant to radiation exposure. However, the bubble density proved difficult to control, being very much a function of the small amount of excess liquid invariably attached to the bubble base. Several blowing techniques using various mixtures of helium, acytelene, illuminating gas and air were investigated, all without success. The investigation was therefore terminated.

IV. TEMPERATURE

When a temperature sensor is placed in a hot gas stream, the indicated temperature will normally be considerably different from the true temperature of the gas. The steady state temperature indicated by such a sensor is the result of a heat balance between the heat absorbed by the sensor and the heat lost from it. Heat is gained by the sensor as a result of gas radiation and convection, while the loss from the sensor is primarily by radiation to the cold surrounding environment. An accurate calculation of the true gas temperature from the indicated temperature in such a heat balance is impossible in practice because it involves prior knowledge of such factors as the emissivity of the sensor and of the flames, convective heat transfer coefficient, and temperature of the surroundings visible to the sensor. In order to avoid this difficulty, precautions are taken in order to make the indicated temperature be the true gas temperature. Such precautions usually involve shielding of the sensing element so that it will see surfaces at its own temperature. Radiation shields alone, however, are not sufficient because they tend to reduce the rate of gas flow over the sensing element and convective heat transfer to it, and therefore, the velocity of the gas over the sensor must be induced by artificial means.

The temperature sensor developed for the open fire tests consisted of a thermocouple which was surrounded by several radiation shields over which the gas velocity is increased by aspiration. The radiation shield is shown in Fig. G-12. It consists of seven small-diameter tubes pressed into a circumscribing tube of 3/4 inch diameter. The thermocouple junction is placed in the middle of the center tube and the lead wires are carried to the outside. This shield assembly is tack-welded to a standard 1/2 inch pipe tee which is in turn connected to a length of pipe with an aspirating blower at the far end. The rig for obtaining a temperature traverse across a fire is shown in Fig. G-13. This consists of a series of such shielded thermocouples arranged along a vertical line and spaced approximately one foot apart. The entire assembly is mounted on caster wheels so that a temperature traverse across the fire may be obtained in steps. Provision is made for use of this assembly in larger fires by increasing the spacing between the temperature sensors.

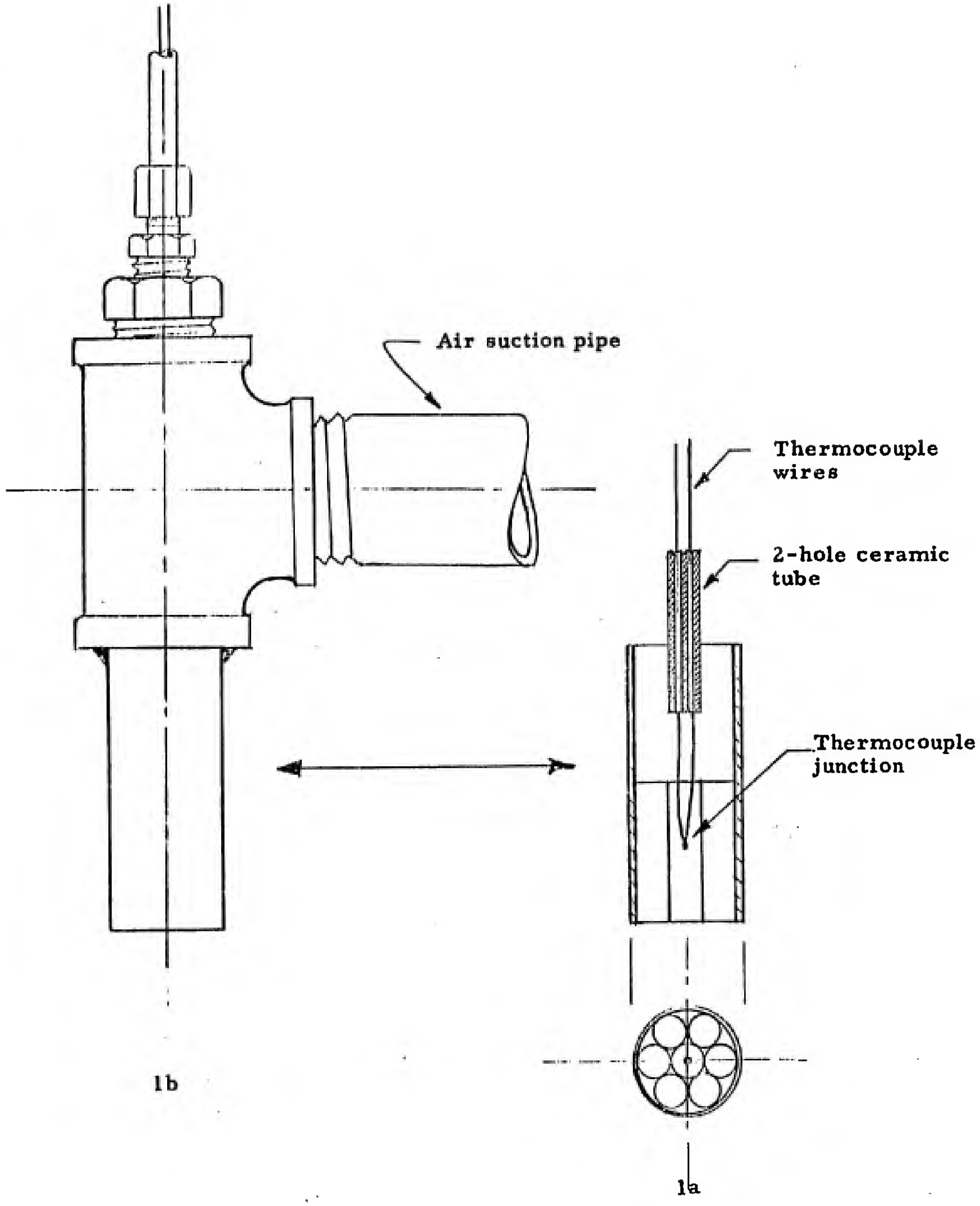


FIG. G-12 SHIELDED THERMOCOUPLE ASSEMBLY

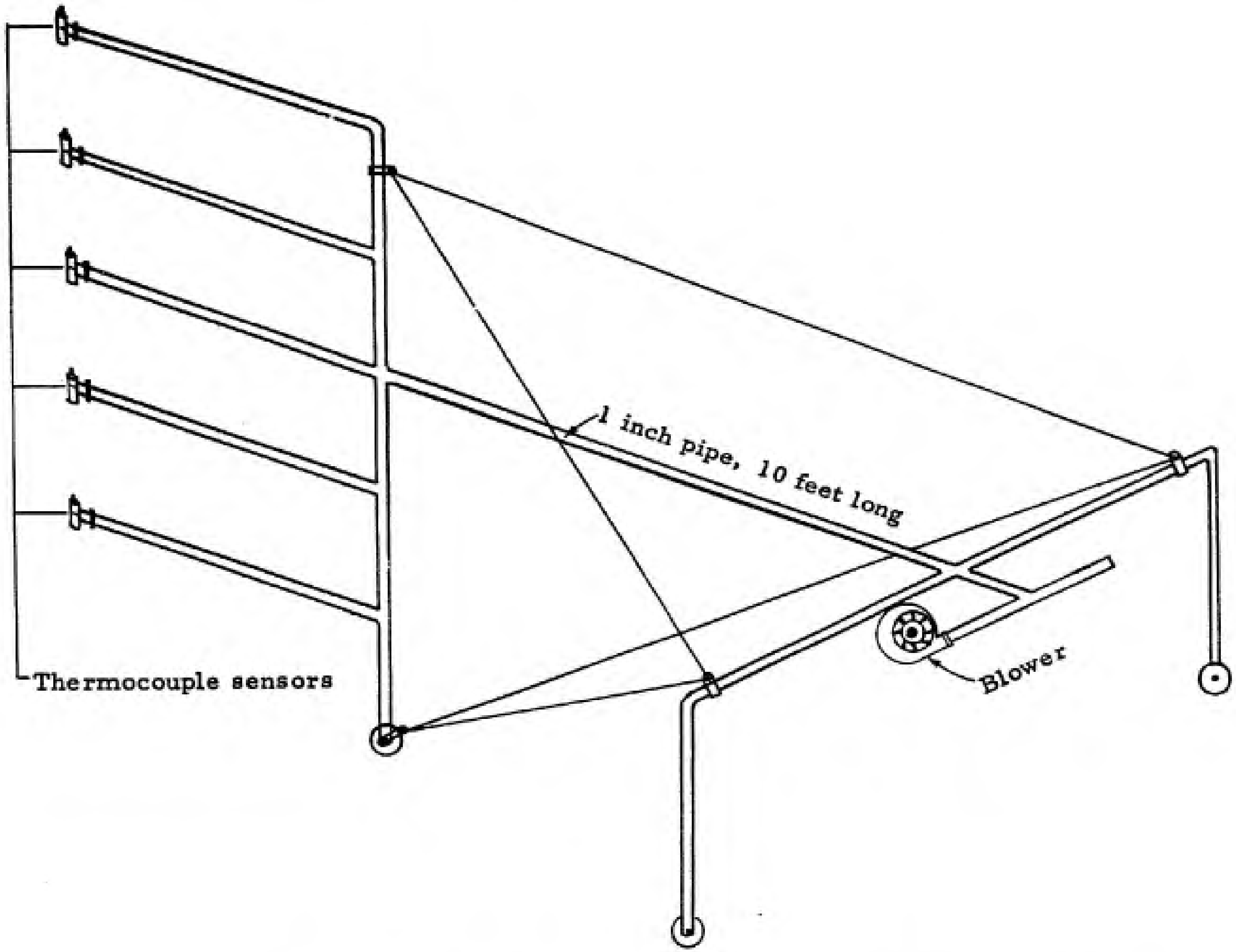


FIG. G-13 RIG FOR MEASURING FLAME TEMPERATURES

A test of such a thermocouple assembly was made for the purpose of establishing the minimum required rate of gas flow over the sensor. The test was conducted using a pot-burner of approximately 10 inches diameter and operating on city gas. Such a test would tend to give results which are on the safe side because the gas flame is considerably cleaner than that expected from the experimental fires, and consequently more transparent to radiative heat loss from the sensor. It was to be expected that as the rate of gas flow over the sensing element is increased, the temperature would rise to an asymptotic value which is the true gas temperature. The results of this test are shown graphically in Fig. G-14. This figure shows the variation of the signal from a chromel-alumel thermocouple (in millivolts) as a function of the relative gas flow over the sensor. The rate of gas aspiration was altered by changing the voltage at which the blower was operating by means of a variable transformer, and subsequently these voltage readings were translated to relative gas velocities by means of a velometer. (The velocity of the gas flow is termed "relative" because the velometer has to be used in a manner which did not indicate the true velocity in feet per minute.)

In the model and full-scale room burns, bare thermocouples were used as the enclosure surfaces approximated the effective flame temperature within a short period of time. To reduce the amount of thermocouple wire required for the full scale burns, thermocouples were lead to a series of insulated containers at the exterior walls of the structure. These containers were packed with a crushed ice-water mixture and served as constant temperature baths for the reference junction. Rather than providing separate electrical insulating containers for each thermocouple

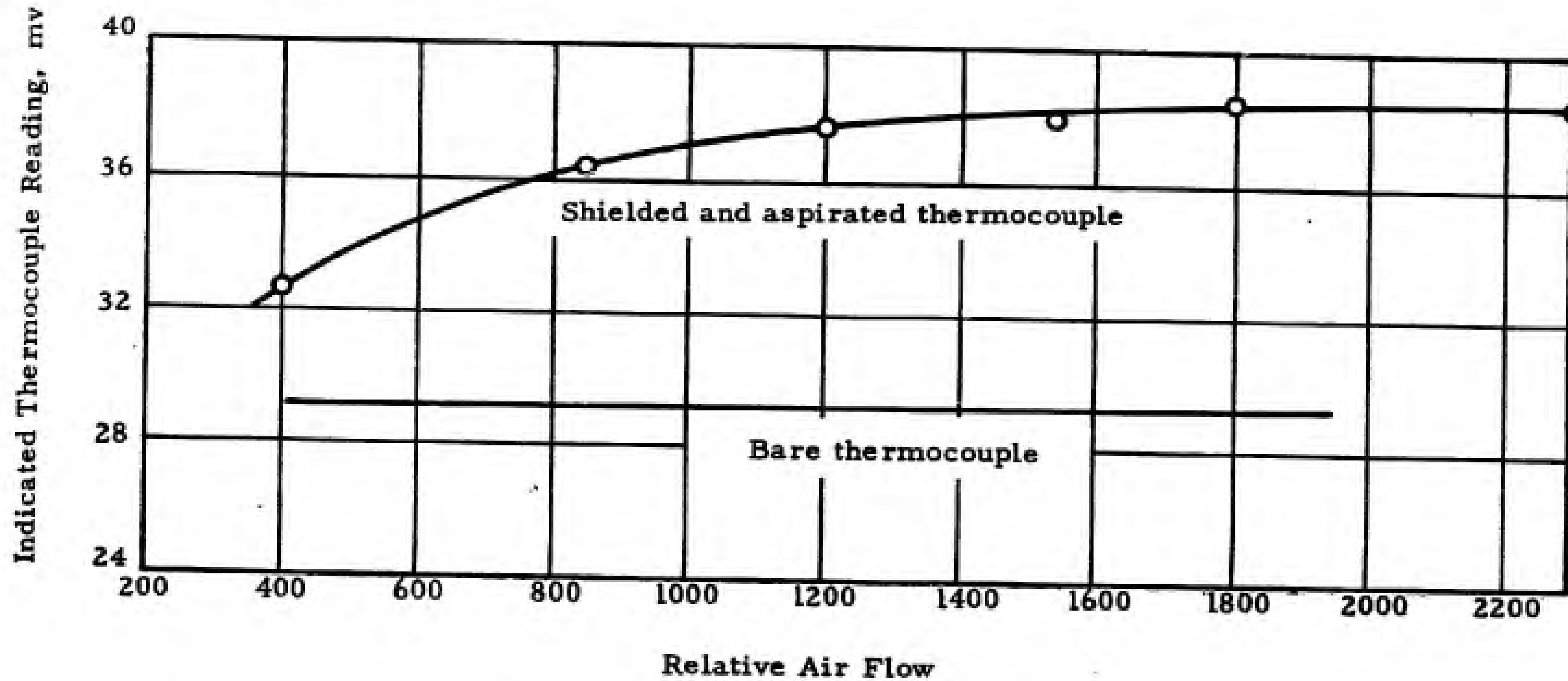


Fig. G-14 VARIATION OF INDICATED TEMPERATURE WITH RELATIVE GAS FLOW cold junction, the connector strips were placed in plastic bags and submerged directly in the bath. Telephone cable (22 conductors/cable) provided a simple extension wire to carry the signal to the recording instruments.

V. BURNING RATE

Burning rates of interest included both solid and liquid fuels. For this reason a means of measuring each was devised and is described below.

For solids and small amounts of liquid a direct weighing device was developed. It consisted of a commercially available unit similar to a household bathroom scale which was modified to permit remote recording by replacing the dial by a low torque potentiometer. Figure G-15 shows the photographs of one of the scales with cover removed. Application of a load to the knife edges through the cover plate causes movement of the slide plate (see top photograph), which in turn rotates the axis of the potentiometer. The rotation of the axis changes the measured portion of the voltage impressed on the potentiometer by the circuit arrangement shown in Fig. G-16. The design of the circuit allows connection of 10 scales in series using bypass switches (S-1 to S-10, Fig. G-16). The current flow from a storage battery is adjusted by a potentiometer (R-1, Fig. G-16) and measured by a microammeter (A-1, Fig. G-16) having a range of 0 to 50 μa. In use, both the total impressed voltage to each scale as well as the portion spanned by the slide contact of the potentiometer were measured. Overheating of any individual scale was thus noted immediately as a variation in total voltage drop through its potentiometer. The result of a typical calibration is shown in Fig. G-17. As each scale had a usable capacity of about 200 lb, the loading of cribs or model rooms was usually distributed over four or more units. For extremely high loads, the scale capacity was doubled by placing the load on the center

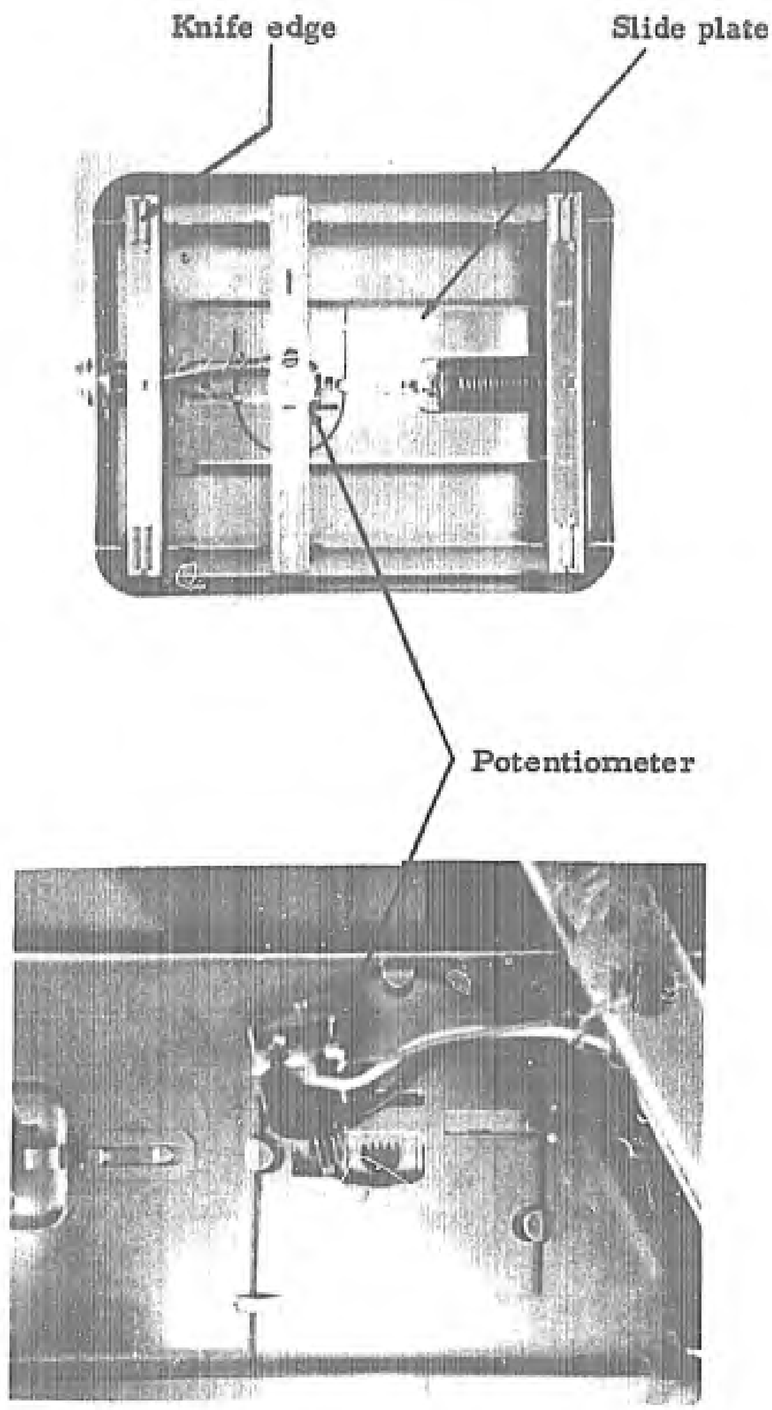


Fig. G-15 PHOTOGRAPH OF SCALES FOR MEASURING BURNING RATES

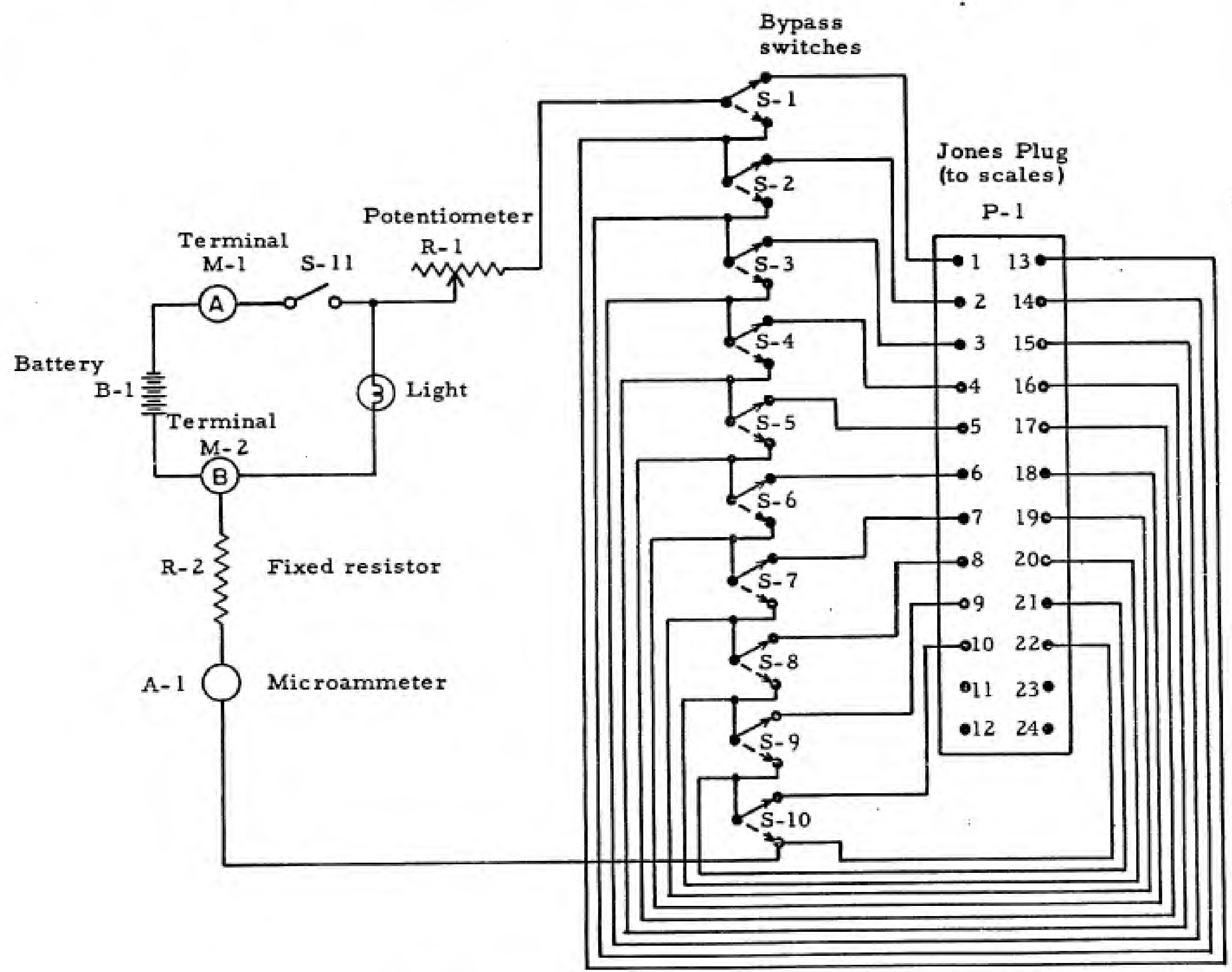


FIG. G-16 SCALE CONTROL SYSTEM

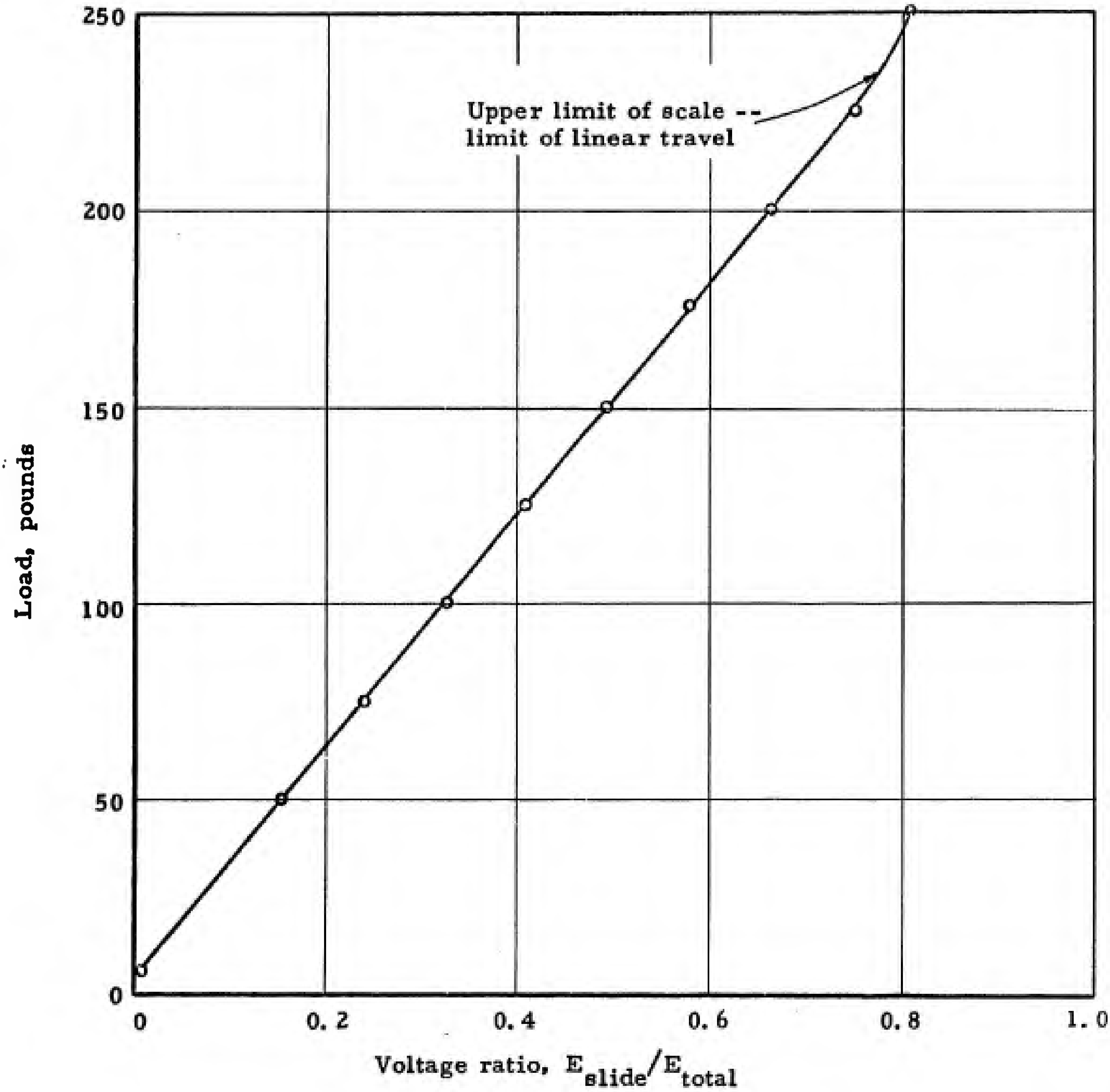


FIG. G-17 TYPICAL SCALE CALIBRATION CURVE of a lever, one end of which is supported by a scale.

The scales were used in two manners for liquid fuel fires. In the first case, a tray of fuel was placed on the scale and weighed directly. In later fires, it was desired to maintain a constant fuel depth in the tray and so a constant head supply tank was connected to each tray. This consisted of a commercial chicken feeder which was connected to the fuel tray by a combination of copper and tygon tubing (Fig. G-18). As the level of fuel in the tray dropped, the level in the feeder decreased to below the reservoir rim at which time more fuel was released to the feeder. By placing the feeder assembly on a scale, its delivery to the burning tray to maintain constant fuel level was measured.

Direct weighing was impractical for the large scale field fire using liquid fuels. For these fires a float was placed in the fuel tray and its motion translated by a simple lever to a pointer and scale placed nearby (Fig. G-19). The lever arm magnified the change in fuel level by about 4 to 1. The movement of the pointer was recorded photographically.

VI. GAS ANALYSIS

Gas samplings of burning structures were analyzed for O_2 and CO. As the concentrations of interest were those occuring prior to flashover (human escape) the measuring devices spanned 0 - 21% O_2 and 0 - 5% CO.

The oxygen analyzer was a continuous unit (Hays Corporation, model 631) using the paramagnetic properties of oxygen. In operation, the unit supplies the gas sample by diffusion to each of two resistors forming legs of a Wheatstone bridge. By placing a magnetic field through one of the resistor chambers, cool oxygen rich gas is drawn to this resistor. Once heated, the oxygen loses its magnetic properties and is forced out of

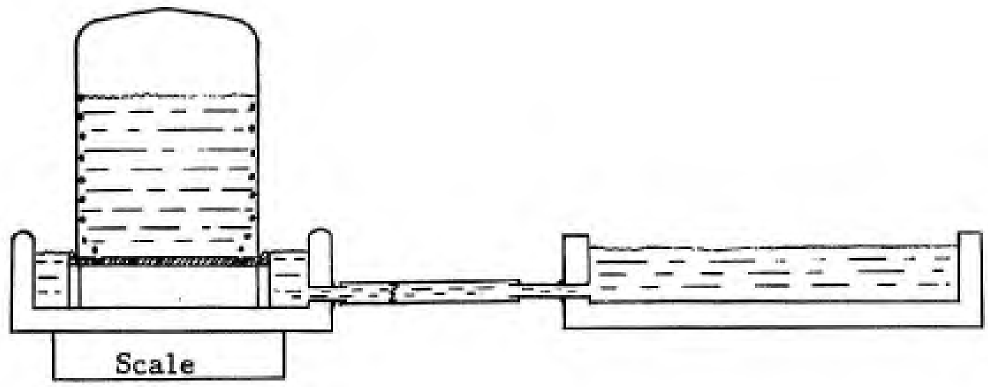


Fig. G-18. BURNING RATE DETERMINATION FOR CONSTANT FUEL DEPTH FIRES

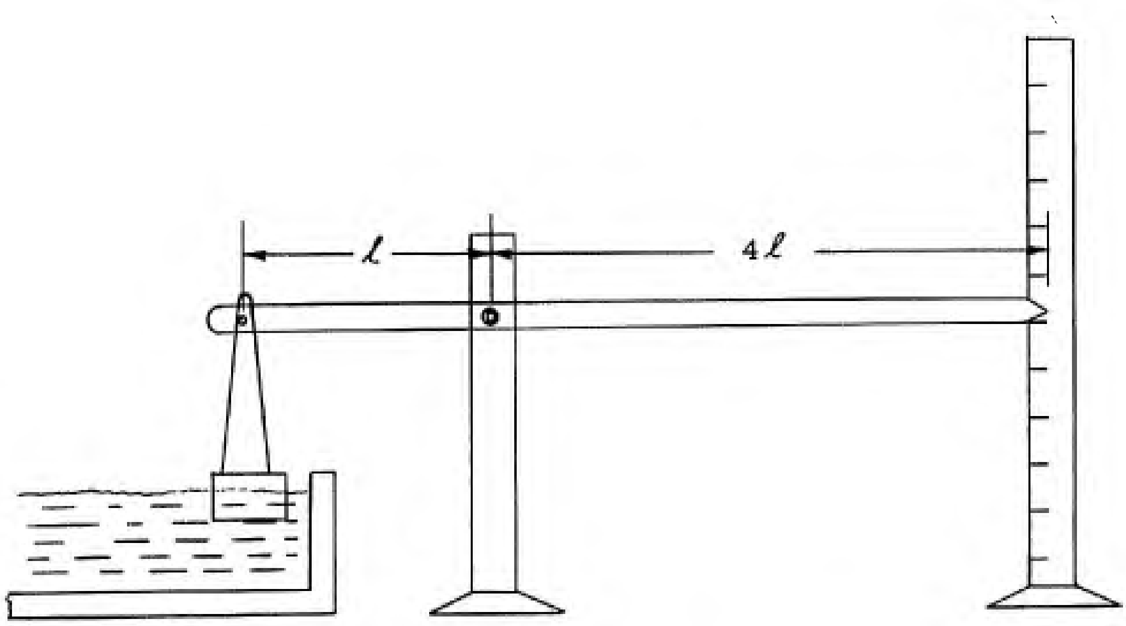


Fig. G-19. FUEL DEPTH INDICATOR FOR LARGE LIQUID FUEL FIRES the way by cooler, more magnetic oxygen rich gas diffusing into the chamber. The additional cooling of the resistor in the magnetic field results in a resistance change which is noted in the bridge circuit and may be recorded.

Carbon monoxide concentrations were measured with a combustibles analyzer (Hays Corporation, model 646). The principle of operation is the catalytic combustion of the gas sample on a heated filament. As the filament also has a high temperature coefficient of resistance, the combustion causes a measureable change in resistance which is related to the amount of combustible present. A Wheatstone bridge circuit is again used to produce a signal suitable for recording.

Each of the above analyzers is nominally designed to continuously monitor a single gas stream. Through a series of solenoid operated valves controlled by a timed step-switch, their capability was extended to cover the sequential sampling of up to 10 separate streams.

VII. FLAME HEIGHT AND AREA

Stop motion photography (50 or 100 frames/min) was used throughout the experimental program. Flame heights and areas were read from the film by projection on appropriately scaled grids. Kocachrome II film was found sufficiently fast (ASA 25 daylight, 40 tungsten) to permit exposures at 1/50 sec. with a variable shutter 16 mm camera (Bolex Rex H-16). The availability of films for subsequent re-examination of the behavior of various fires was very valuable. The inclusion of a clock in all pictures permitted rapid correlation of film records with the other measured parameters. Through the stop motion photography, each fire history was condensed to about 10 percent of its actual time permitting rapid review and emphasizing changes in flame patterns.

REFERENCES

1. McGuire, J. H., and H. Wraight, "Radiometer for Field Use", Journal of Scientific Instruments, Vol. 37, April 1960, pp. 128 - 130.

2. Davey, N. and L. A. Ashton, "Investigation on Building Fires - Part V. Fire Tests on Structural Elements", National Building Studies Research Paper No. 12, Her Majesty's Stationery Office, London, 1953.

3. Simmons, L. F. G., "A Shielded Hot-Wire Anemometer for Low Speeds", Journal of Scientific Instruments, Vol. 26, No. 12, 1949, pp. 407 - 11.

4. "Fire Research-1956", Department of Scientific and Industrial Research and Fire Offices' Committee, Her Majesty's Stationery Office, London, 1957.

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13. ABSTRACT

Experiments were performed to provide necessary data for the prediction of fire damage to urban areas exposed to a nuclear burst. The investigations dealt with: flame heights and burning rates of well-ventilated fires, fire spread within structures - model room experiments, fire spread from interior kindling fuels, fire spread from exterior kindling fuels, full-scale building fires and coalescence of convective columns from free burning fires. Detailed description of the employed instrumentation is given. The derived correlations as well as the actual data are included in the report.

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