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DESIGN OF TEST FOR SIMULATING URBAN AREA BURNS

Final Report

Contract No. N0022866C0882

OCD Work Unit 1132B

June, 1966

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IIT Research Institute

NRDL-TRC-56

IITRI Project
No. M6147

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IIT RESEARCH INSTITUTE
Technology Center
Chicago, Illinois

DESIGN OF TEST FOR SIMULATING URBAN AREA BURNS

Final Report

by

F. Salzberg

June, 1966

Prepared for
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PREFACE

This is the final report on Contract No. N0022866C0882, T. O. 65-200 (63), OCD. No. 1132B (IITRI Project No. M6147), "Design of Tests for Simulating Urban Area Burns". The objective of the program is to design tests which will provide guidelines for the Operation Flambeau experiments. The program has been sponsored by the Department of the Army, Office of the Secretary of the Army, Office of Civil Defense through the U.S. Naval Radiological Defense Laboratory with Dr. M. Gibbons as the project monitor.

IIT Research Institute personnel who contributed to the project include W. J. Christian, H. J. Nielsen, F. Salzberg, and T. E. Waterman.

Respectfully submitted,
IIT Research Institute

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Heat and Mass Transfer

ABSTRACT

A study was performed to determine the requirements for simulating urban area burns by means of crib fires or other synthetic type fires. Particular attention was given to the mass fire problem to be investigated during Operation Flambeau.

A review of the literature revealed only a limited amount of pertinent information. Existing data pertain primarily to fires unaffected by interactions with other fires or by fire-induced changes in the environment. Wood-crib fires were found to be the most extensively used for studying building burns, but reported experimental results are not sufficient for relating behaviors of crib and building fires, particularly in the environment of a mass fire. An experimental program for obtaining this information has been outlined.

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I. INTRODUCTION

The objective of the program is to outline methods for learning 1) how buildings burn in a mass fire environment (including consideration of the effects of wind and the effects of deficiency or impeded access of oxygen); 2) how processes (such as the coalescence of individual plumes and the generation of fire whirls) within the mass fire depend on the ignition pattern and on the ambient wind. Both tasks should be done by means of scaled down experiments either in the laboratory or in connection with the Operation Flambeau.

One of the difficulties encountered in the description of the behavior of building fires in the environment of a mass fire is the lack of understanding of the physical processes involved. This is true whether the mass fire is stationary (the fire storm) or whether it moves under influence of wind (the conflagration). Since both fires are of main interest when they occur in an urban area, their simulation under actual conditions is not feasible.

A possible means to resolve this problem is first to study the phenomena of mass fires by using some fuels other than actual structures. Then, through relationships between the burning characteristics of the fuel used and those of real structures, the knowledge gained could be applied to situations encountered in urban areas. Besides obvious economic advantages, this approach provides, in addition, possibilities for controlled fuel reproducibility and extensive instrumentation. Because it offers such advantages, wood has been extensively used as fuel in fire research studies.

Wood cribs have been employed to represent various physical situations. Placed in the enclosure, cribs were considered as the room content; freely burning without confinement, cribs were viewed as a burning building; when placed in an array, cribs represented buildings.

Although such physical interpretations have been given to crib fires, the main emphasis of the investigation has been placed on gaining better understanding of free burning fires. This was done with relatively little concern for whether or not the cribs truly represented the physical cases investigated. This lack of concern could be justified as long as the studies were of a basic nature or could be subsequently verified by full-scale experiments. The situation is different, however, for large scale experiments such as those to be conducted during the Operation Flambeau, because verification is not possible and economic considerations limit the number of experiments. For this reason, simulation of building fires in Operation Flambeau is essential for gaining an understanding of mass fires in urban areas.

This study is directed toward defining the information needed for relating building and crib fires. Consideration is first given to the burning behavior of crib fires. Following this, available information pertaining to the building fires is analyzed in order to determine possible relationship to the crib fires. Finally, a program is outlined which will provide the necessary data for simulating the burning behavior of structures in a mass fire by means of wooden cribs. Such knowledge is necessary for planning the large scale fires to be conducted during the Operation Flambeau.

II. STUDIES OF CRIB FIRES

In the past, crib fires have been extensively used to study the burning rates of fuels and their relationship to the flame heights for various ventilation conditions. More recent studies have dealt with the fire propagation along and within the crib beds, and with the coalescence of crib fires. Results of these studies are discussed below.

A. Burning Rate

1. Effect of Ventilation

Depending on the available air supply a crib fire may be either ventilation or fuel surface controlled. Burning rates for ventilation controlled fires have been studied by various investigators. These studies involved cribs in enclosures containing various size openings.

Thomas[1] used his own and Kowagoe's[2] data to describe the burning rate of a ventilation-controlled crib fire by the following expression:

$$R \text{ (lb./min.)} = 0.678\ A\sqrt{H} \qquad (1)$$

where H is the height (ft) and A is the area (ft^2) of the opening. Waterman, Labes[3], et al. have shown that the constant 0.678 given by Thomas is too low, and recommended instead the value 1.5. Since the ventilation controlled fire has been considered on numerous occasions, the equation

$$R \text{ (lb./min.)} = 1.5\ A\sqrt{H} \qquad (2)$$

can be considered, at this time, as sufficiently accurate.

For fuel-surface controlled fires the maximum burning rate can be expressed by:

$$R \text{ (lb./min.)} = 0.09\ A_s \qquad (3)$$

where A_s is the fuel surface area (ft^2). Although Eq. 3 predicted reasonably well the burning rates obtained with both crib and structural fires[3], additional verification is still necessary.

2. Flame Height

Several investigators [4, 5] attempted to establish the relationship between the burning rate of unconfined crib fires and the flame height. Since the height of flames, whether from a burning structure or a crib, indicates the burning behavior, it is of interest to this study. Thomas[5] correlated his own and the data of others in terms of dimensionless parameters. This correlation including Waterman's data[3] obtained with 6 x 6 ft crib fires, is shown in Figure 1. As pointed out by Thomas some of the Gross[4] experiments, included in Figure 1, may have been in the laminar regime and all data pertaining to flame heights less than two feet should be disregarded. Even under these conditions, the discrepancy between Waterman's results and those of other investigators is quite evident in Figure 1. Waterman attributes this discrepancy to the difference in stick spacings. The six-inch spacing he used was large compared to spacings in other experiments, and apparently resulted in more fuel consumption within the crib itself with consequent reduction in the flame heights.

3. Effect of Fuel Spacing

As indicated above, the spacing of fuel in a crib fire may affect its burning rate. No investigations seem to be reported in the literature specifically treating this problem for fully involved crib fires. Waterman et al.[3] considered this subject in a limited way in connection with burning-rate studies. Their findings, plotted in Figure 2, show the relationship between burning rate and fuel surface for two fuel spacings. Although the experiments were not extensive enough to permit definite conclusions,

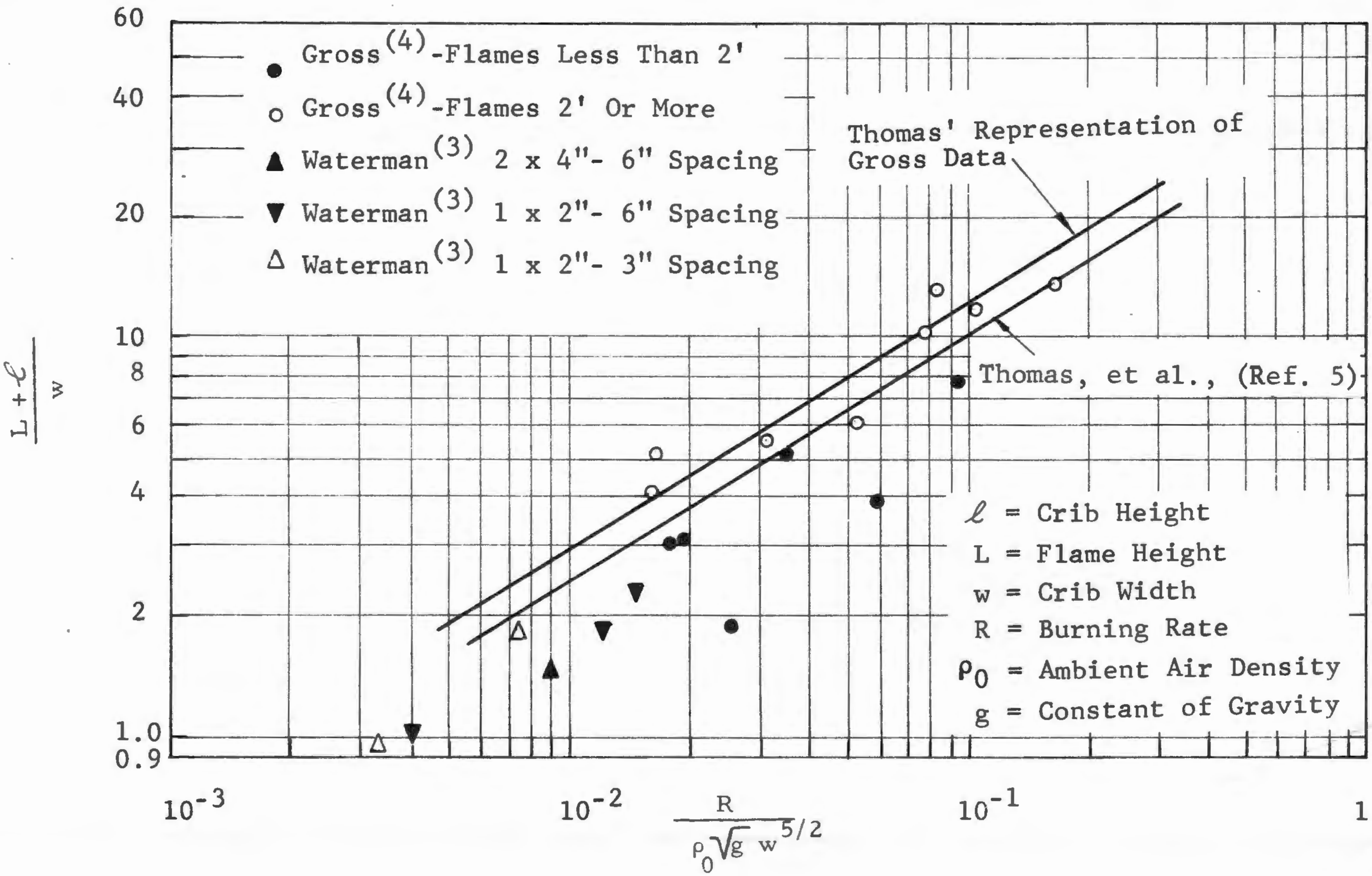


Fig. 1 EFFECT OF BURNING RATES ON FLAME HEIGHT FROM FREE BURNING FIRES

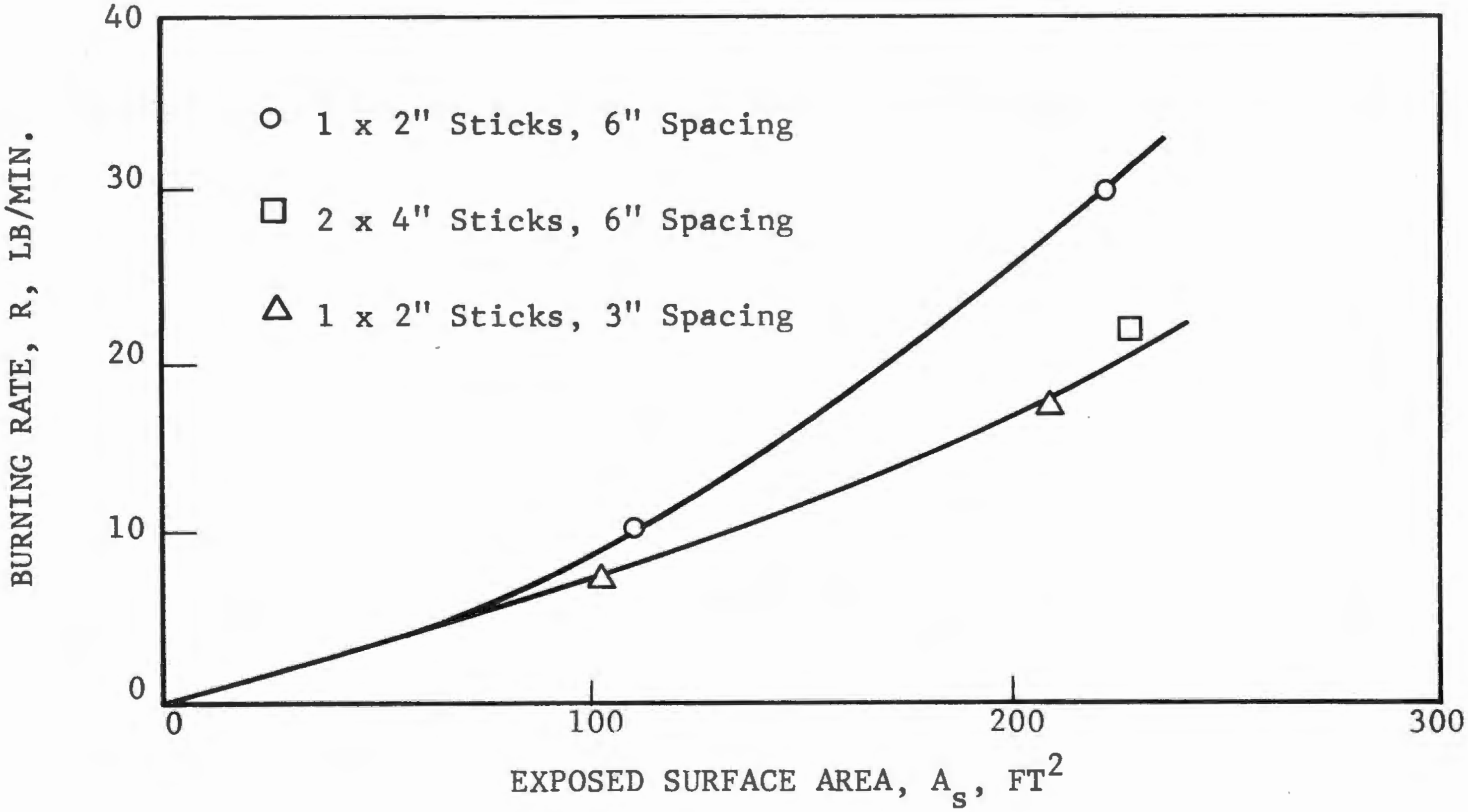


Fig. 2 EFFECT OF WOOD SURFACE AREA ON BURNING RATE OF 6 x 6 FT CRIBS

qualitatively the data indicate an increase of burning rate with increasing void size. It can be expected that this increase will reach a limiting value corresponding to the optimum combination of air supply and conservation of heat.

An indication of the effect of fuel geometry on burning rates of unordered fuels is given by the experiments of Strasser and Grumer(6). The experiments involved measurements of burning rates of cubical fuel elements randomly filled in cylindrical baskets ranging from 30 to 100 cm in diameter. Burning rate is plotted in Figure 3, as a function of fuel surface area and size of the fuel elements. As can be seen, the 2 x 2 x 2 cm cubical fuel gave the highest, the 4 x 4 x 4 cm the lowest, and the 9 x 9 x 9 cm an intermediate burning rate. The reason for this behavior is not apparent. Also, for the data plotted in Figure 3, the Reynolds numbers, calculated by the method suggested by Thomas(5) are between 547 and 3509. This indicates that the burning may have been in laminar regime which introduces additional uncertainties in interpretion of the data.

4. Burning in Vitiated Atmospheres

The reports describing the behavior of the fire storms(7), as well as the currently conducted large scale experiments, strongly indicate that the mass fire environment is oxygen deficient. Thus the burning rates of fuels in

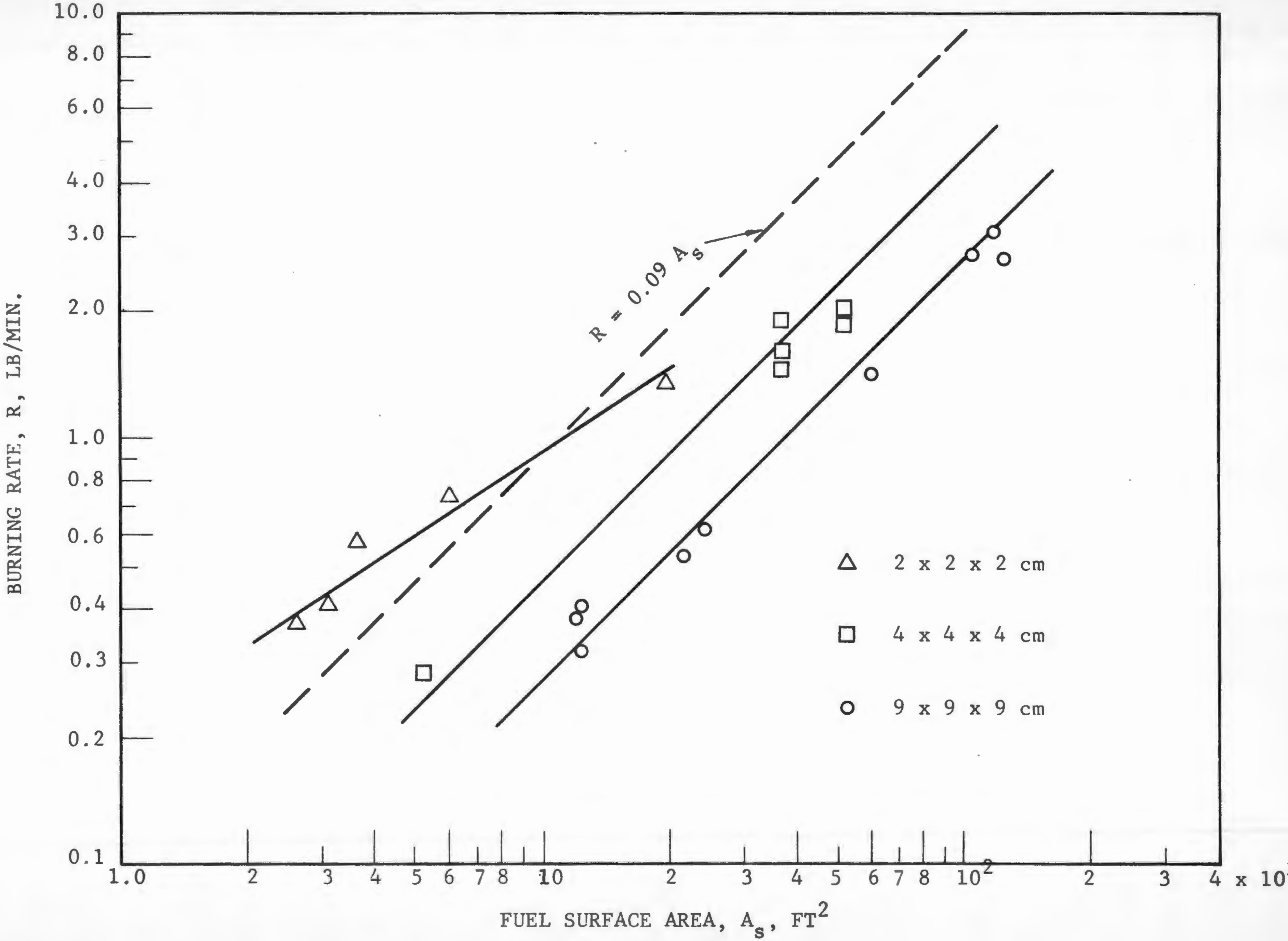


Fig. 3 BURNING RATES OF UNORDERED CRIBS AS A FUNCTION OF FUEL SURFACE AREA

vitiated atmospheres are of considerable interest for this study. Unfortunately, this subject has been considered in only a very few instances. Experiments conducted by the Joint Fire Research Organization[8] have shown that flame height and burning rate of wood fires both decreased with decreasing oxygen concentration, and at 14 per cent or less of oxygen the fires were extinguished.

5. Effect of Moisture Content

The effect of moisture content of the fuel on the burning rate of fully-developed crib fires was investigated by the Joint Fire Research Organization[9]. In these experiments 1 x 3 ft cribs, 1/3 to 1/2 ft high were used. The sticks had square cross sections from 1/2 to 1 inch on the side with spacing between centers from 1-1/2 to 4 inches. Moisture content of the sticks ranged from 13 to 30 per cent of the dry wood. The cribs were ignited evenly over the entire area.

Within the range of moisture content reported, little change was observed in the burning rates. As a matter of fact the rate of burning and the average flame height, derived from photographs, have been found to agree with the results for sticks and cribs of various sizes with a fixed moisture content of 11 per cent. It can be expected, however, that with large moisture content the water vapor evolved will dilute the decomposition products and cause a decrease of the burning rate.

6. Heat Transfer

Whether or not a crib fire is sustained depends on the heat received from the flames above. Therefore, it can be expected that this feed-back heating affects the burning rates. Although no information pertaining directly to this subject has been uncovered, related experiments, involving the exposure of wood strips to various levels of radiation(10), give some indication regarding the effect of heating on the burning rates. For an irradiance level of 5 cal $cm^{-2}sec^{-1}$ fire penetrated two inches of wood in about half the time required at 1 cal $cm^{-2}sec^{-1}$. A reduction of irradiance level to 0.5 cal $cm^{-2}sec^{-1}$ increased the penetration time by over 50 per cent of that corresponding to 1 cal $cm^{-2}sec^{-1}$. Since in the mass fire the irradiance may reach 8 cal $cm^{-2}sec^{-1}$, the knowledge of crib burning rates as a function of environment temperature, i.e. external heating, is of considerable interest.

7. Wind Effects

The burning rate of a crib fire in a wind may change due to 1) better mixing of the fuel with air, and 2) an increase in the convective heat transfer through the fuel bed. These effects have been investigated experimentally using four lengths of cribs 3-ft wide and 4-inches high[11]. The results, shown in Figure 4, indicate that, for the sizes of crib used, the effect of wind on burning rate per unit area of the fuel surface is small. However, as can be seen from Figure 5, the intensity of radiation ahead of the burning 2 ft wide crib increases considerably with the increasing wind speed. This increase is larger than could be expected by the increased deflection of the flames.

B. Flame Coalescence

By definition, a mass fire in an urban area refers to the conditions when fires from individually burning structures merge and produce one large convective column. In the past the formation of a mass fire has been attributed to the large heat release in either an unstable or rotating atmosphere. The question which of the latter conditions is of importance is not resolved. Swirling flows were indeed observed in experimental and actual mass fires; however, it remains to be determined whether these were causes or results of mass fires.

To resolve some of these questions experiments were performed using gaseous liquid and solid fuels. Studies[9] with town gas burners have shown that the radiation intensity from flames on two burners is greater than the sum of the intensities of flames produced by individual

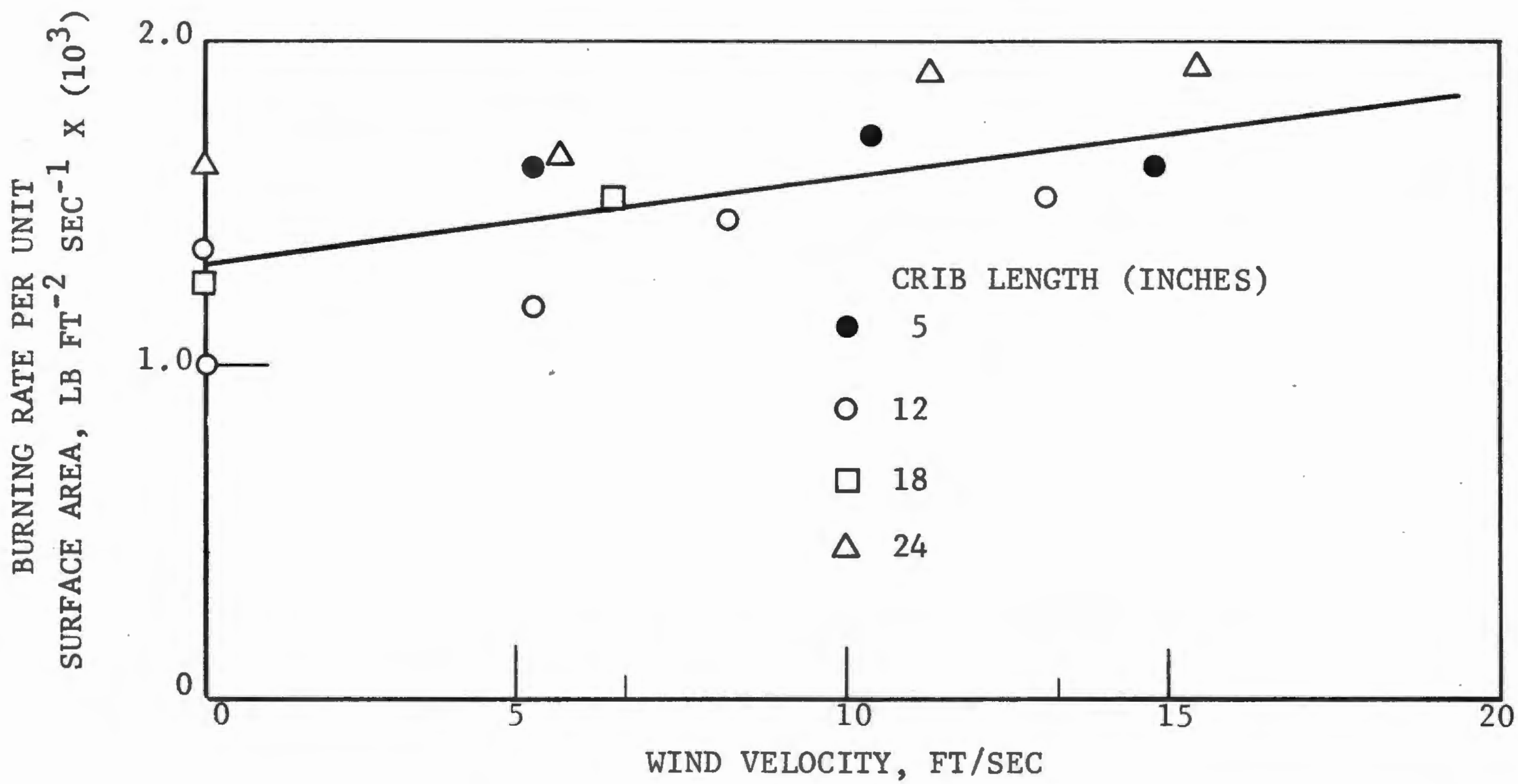


Fig. 4 EFFECT OF WIND ON BURNING RATES

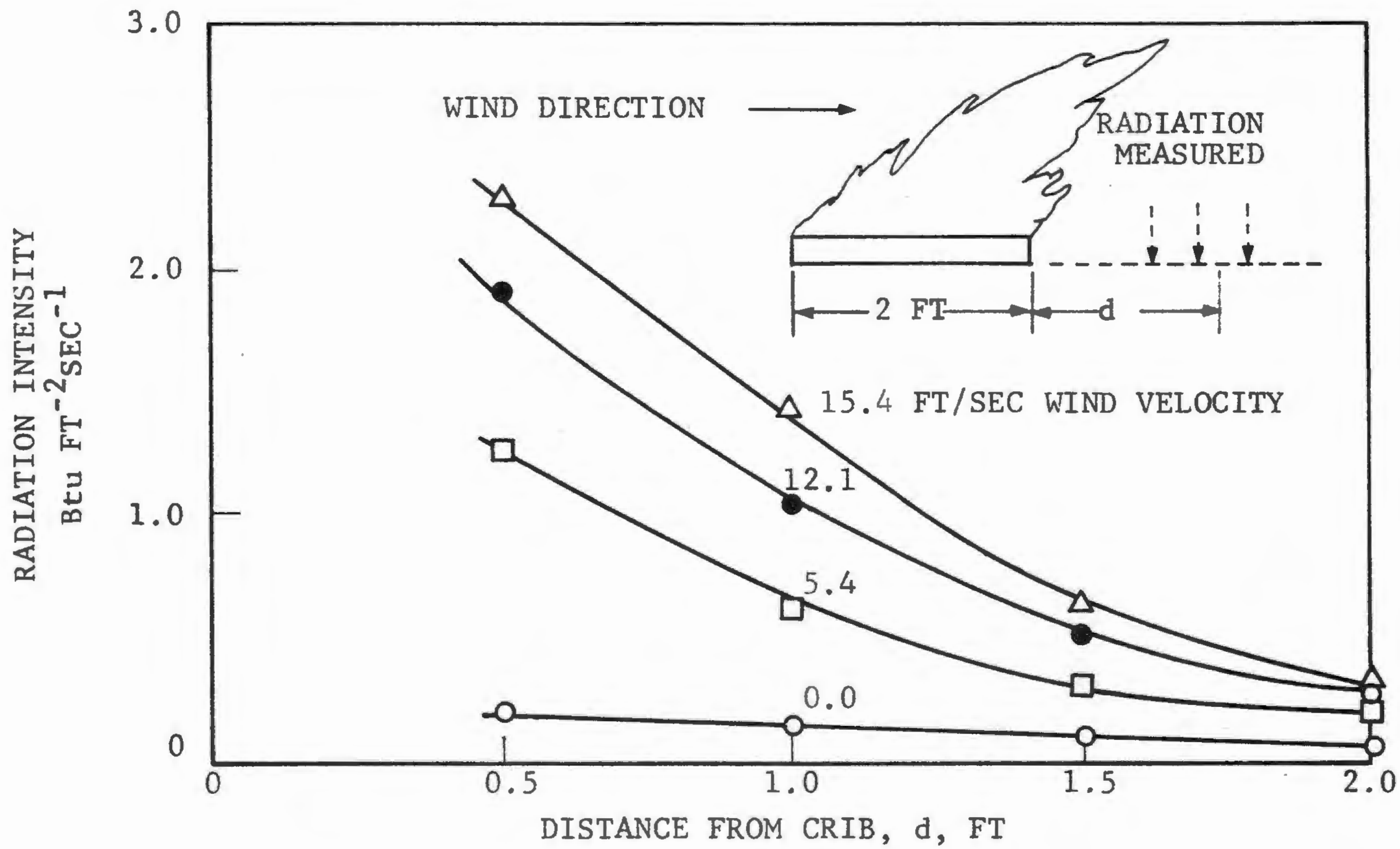


Fig. 5 EFFECT OF WIND ON RADIATION

burners. (See Figure 6). The observed flame heights were also greater. This increase in the radiation intensity and flame heights appears to be less pronounced in the case of wood crib fires. As a matter of fact, Waterman et al.[3] have found that the coalescence effects primarily the burning rates of wood crib fires. The effect is clearly demonstrated in Figure 7 showing the burning-rate data obtained by Waterman et al.[3]. As can be observed, the burning rate first increases as the space between cribs increases until the transition point is reached after which the burning rate decreases rapidly. This may be explained in the following manner. Air is rapidly drawn down the channels between cribs, as long as the fires remain coalesced, and the amount of air increases with increasing spacing. 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 is no abrupt change in radiation between cribs. As some resistance to the normal convective air flow to individual cribs remains due to the proximity of the adjacent fires, the burning rates may be reduced to a value below that corresponding to very large crib spacings. Figure 7 also shows that the transition point for coalescence (peak of each curve) occurs at larger ratios of crib spacing to crib dimension when either the

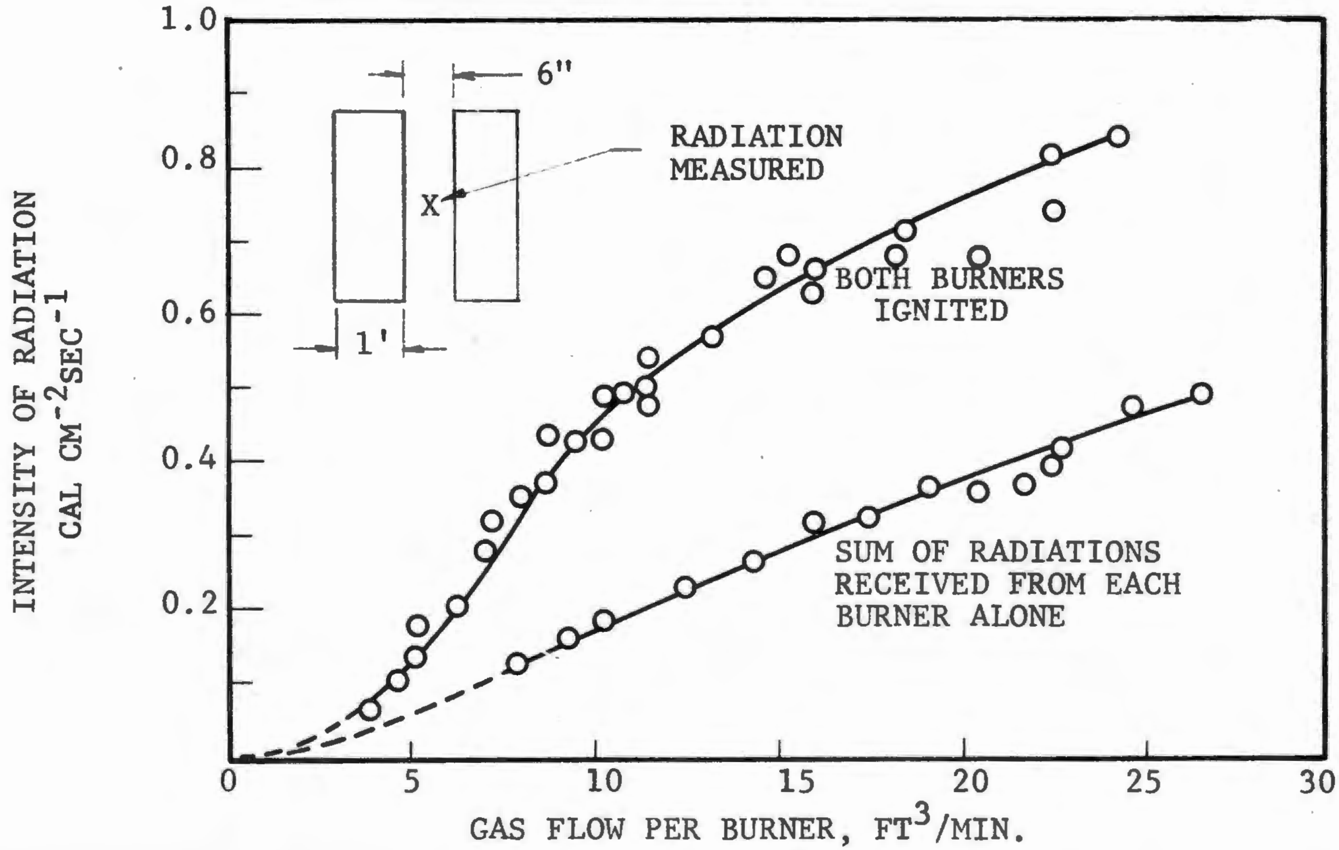


Fig. 6 RADIATION FROM TWO GAS BURNERS

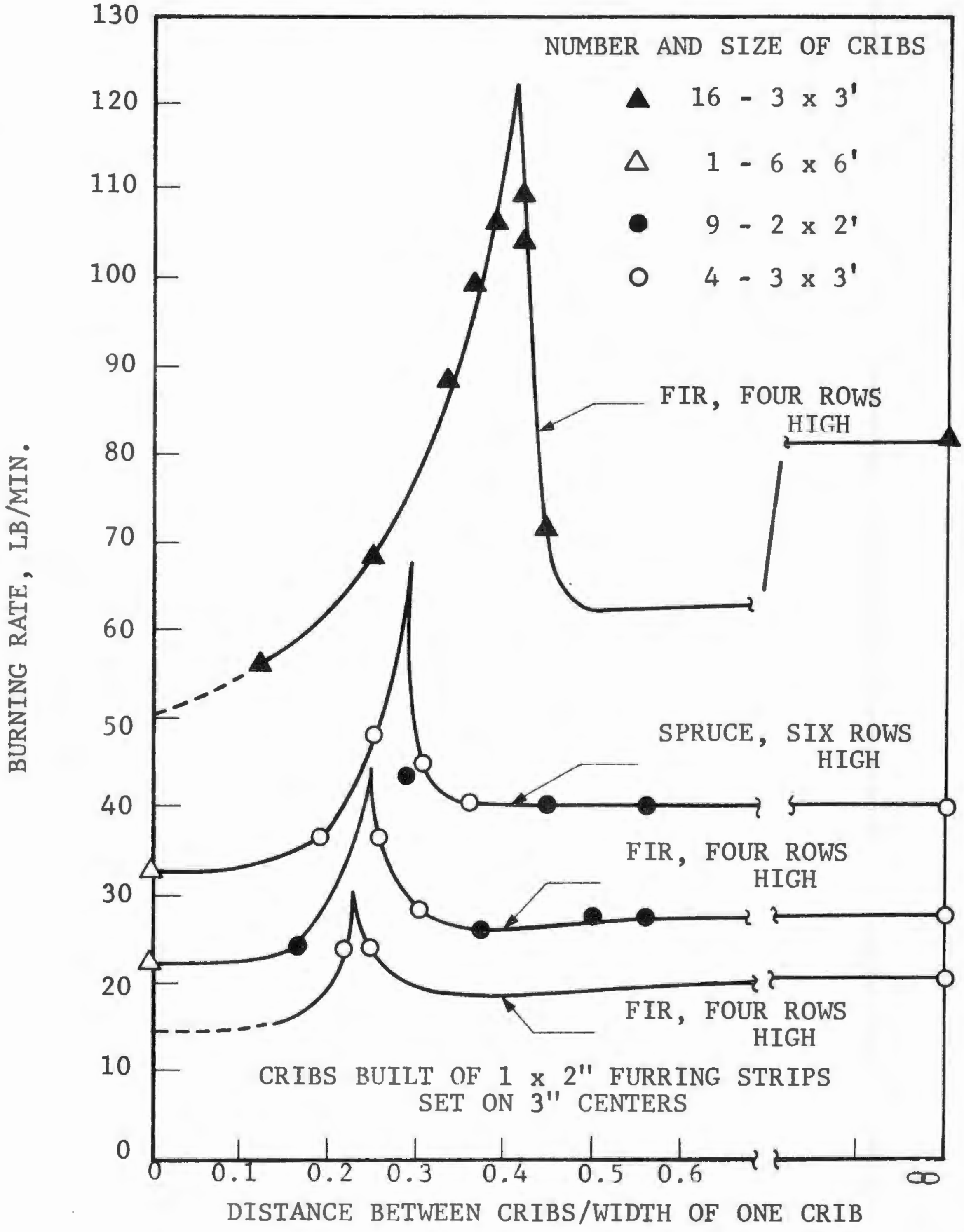


Fig. 7 BURNING RATE AS A FUNCTION OF THE DISTANCE BETWEEN CRIBS

total number of cribs is increased or the single-crib burning rate is increased (crib height increases or wood type changes).

III. BURNING BEHAVIOR OF STRUCTURES

A. General Remarks

A structural fire can be characterized by several parameters such as: burning rate, flame pattern (area, temperature and emittance), combustion products (amounts and types), and smoke. Since all these quantities are interrelated and time dependent, their exact duplication by synthetic means, such as wooden cribs, is probably impossible to achieve. Such duplication is not necessary for the problem of mass fires where the energy-release rate and total energy released are of main interest. These correspond to the burning rate of the structure and the fire area involved. In turn, both of these quantities are functions of the building contents (fire load), type of construction, the internal layout, size and number of external openings, and local meteorological conditions. Furthermore, the fire buildup, i.e., the fire area at any particular time, will also depend on the location of initial ignition. Upper floor ignition, probably more prevalent after a nuclear burst, will result in a slower fire buildup than ignition on lower floors. As the fire penetrates barriers within the structure and develops new channels for gas flows, the burning may change. Thus, even when the simulation of structural fire is limited to burning rate and fire area, it still requires consideration of many time-dependent parameters. It is worthwhile to examine the state of existing knowledge of the burning characteristics of real structures.

B. Spread of Fire Within Structures

As indicated above, the rate and the total amount of thermal energy released by a burning structure depend considerably on the manner in which fire spreads through the structure. Both are functions of the burning rate.

1. Burning Rate

Burning of a material located within a structure can be described as either fuel-surface or ventilation controlled. It must be noted that these two categories represent only the extremes in burning rate. In real situations there is a gradual change from one extreme to the other. Existing knowledge of free burning fires has not advanced to a state where these intermediate burning rates can be described.

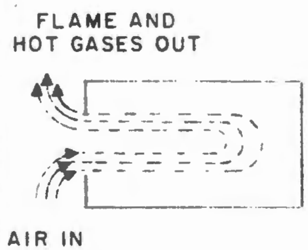
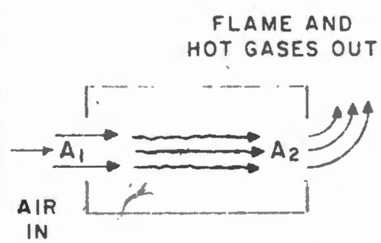
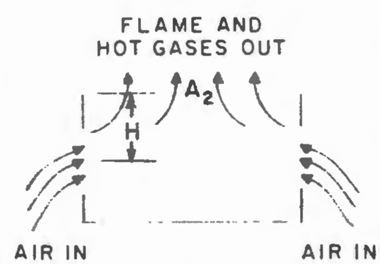
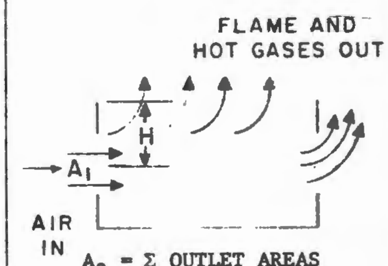
Whether the burning is fuel-surface or ventilation controlled depends on the amount of air (oxygen) reaching the fuel surface. When a sufficient quantity of air is supplied, the fuel surface is the controlling factor and the burning rate (R) can be approximately expressed by Eq. 3 given in the previous section:

$$R = 0.09\ A_s \qquad (3)$$

where R is in lb./min. and A_s is the area of the fuel surface in ft^2. In structures, the fuel-surface controlled burning can be expected to occur during initial buildup of fires following the ignition by the weapon or immediately after structural failures provide additional air channels.

In cases where sufficient air is not available at the fuel surface, the burning is ventilation controlled. Equations for ventilation-controlled burning for various air and fire gas flows are summarized in Tables 1 and 2.

It must be noted that the burning rate given by Eq. 1 corresponds to conditions of unrestricted air supply and must always exceed the burning rates given in Tables 1 and 2. In order to determine which mode of burning is prevalent in structures, calculations have been performed using Eq. 3 and the expressions given in Tables 1 and 2. As input parameters typical structures(12) described in Table 3 were used. For the fuel surface area, values shown in Table 4 were employed. These values had been obtained during a survey of shelter buildings(13).

ROOF INTACT		ROOF COLLAPSED	
NO WIND	WITH WIND	NO WIND	WITH WIND
FLOW PATTERN	FLOW PATTERN	FLOW PATTERN	FLOW PATTERN
	 WIND VELOCITY = V_w	 $A_1 = \Sigma$ INLET AREAS	 $A_2 = \Sigma$ OUTLET AREAS WIND VELOCITY = V_w
EQUATION a	EQUATION b	EQUATION c	EQUATION d
$R = 1.5\, A_w \sqrt{H_w}$	$R = 0.51 A_1 \sqrt{\dfrac{V_w^2}{1 + 5.42\left(\dfrac{A_1}{A_2}\right)^2}}$	$R = 0.51 A_1 \sqrt{\dfrac{48H}{1 + 5.42\left(\dfrac{A_1}{A_2}\right)^2}}$	$R = 0.51 A_1 \sqrt{\dfrac{48H + V_w^2}{1 + 5.42\left(\dfrac{A_1}{A_2}\right)^2}}$
NOTES 1 AND 2 *	NOTES 1 AND 2 *	NOTES 3 AND 4 *	NOTES 3 AND 4 *

* SEE NOTES ON PAGE 22

Table 1 BURNING RATE EQUATIONS FOR SINGLE LEVEL FIRES

NOTES FOR TABLE 1

1. Equation (a) applies with or without wind, until values obtained by Equation (b) exceed those of Equation (a). Effects of low wind velocities may be neglected.

2. Equation (b) also applies to individual compartments and individual floor levels of multi-level structures, with each level isolated as to ventilation.

3. Equation (c) applies with or without wind, until values obtained by Equation (d) exceed those of Equation (c). Effects of low wind velocities may be neglected.

4. Equation (d) also applies when only the top level of a multi-level structure is burning and the roof has collapsed.

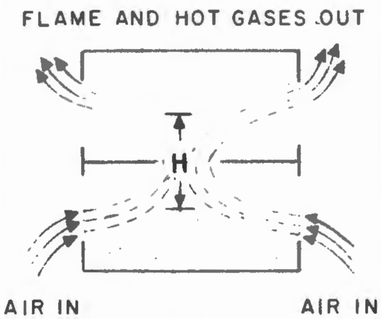
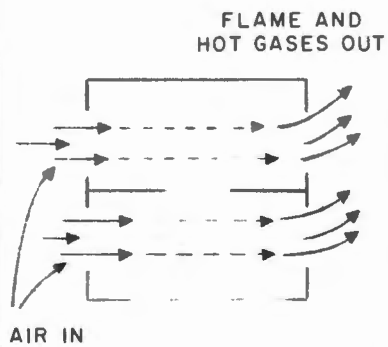
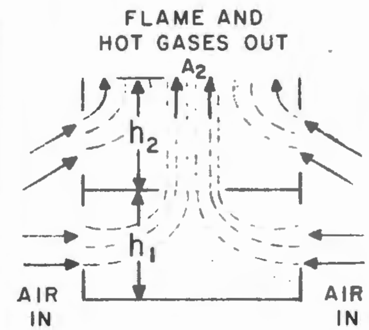
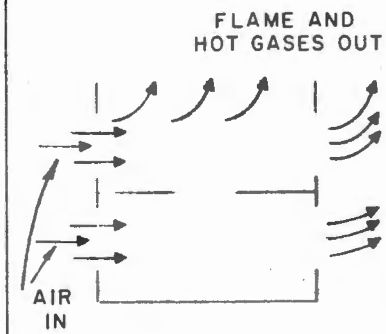
ROOF INTACT		ROOF COLLAPSED	
NO WIND	WITH WIND	NO WIND	WITH WIND
FLOW PATTERN	FLOW PATTERN	FLOW PATTERN	FLOW PATTERN
			
$A_1 = \sum$ INLET AREAS $A_2 = \sum$ OUTLET AREAS	WIND VELOCITY = V_w	$A_1 = \sum$ INLET AREAS	WIND VELOCITY = V_w
EQUATION e	EQUATION	EQUATION	EQUATION
$R = 0.51 A_1 \sqrt{\dfrac{48H}{1 + 5.42\left(\dfrac{A_1}{A_2}\right)^2}}$	SAME AS EQ. b $A_1 = \sum$ INLET AREAS $A_2 = \sum$ OUTLET AREAS	SAME AS EQ. e	SAME AS EQ. d
		$H_{EFFECTIVE} = \dfrac{\left(\dfrac{h_1 + h_2}{2}\right)\sum \text{INLET AREA FIRST LEVEL} + \left(\dfrac{h_2}{2}\right)\sum \text{INLET AREA SECOND LEVEL}}{\sum \text{INLET AREA FIRST LEVEL} + \sum \text{INLET AREA SECOND LEVEL}}$	

Table 2 BURNING RATE EQUATIONS FOR MULTIPLE-LEVEL FIRES

Table 3 TYPICAL STRUCTURES

							WINDOW AREA/STORY						
							FRONT/REAR*			SIDES			TOTAL FIRE LOAD
LAND USE	OCCUPANCY	CONST. TYPE	NO. OF STORIES	FT/ STORY	WIDTH	DEPTH	%	NO.	SIZE	%	NO.	SIZE	LBS/FT^2
Principal Business District (Downtown)	Mercantile	Br	3	12	50	65	24+	8	3 x 6	0	-	-	21
Principal Business District (Downtown)	Offices	Br	3	12	50	55	30+	6	4 x 7-1/2	27	12	4 x 7-1/2	20
Industrial	Mfg/Whse	Br	2	12-1/2	75	125	27	4	12-1/2 x 5	0	-	-	35
Industrial	Mercantile	Br	1 2	15	50	85	4+	3 3	2-1/2 x 4	0	-	-	25 22
Commercial (Principal Business District or Suburban)	Flat	Br WF	3	10	40	50	22	6	3 x 5	9	6	3 x 5	15 21
Suburban Commercial	Mercantile	Br	1 2	15	50	75	4+	3 3	2-1/2 x 4	0	-	-	25 22
All Except Multi-Family Residential	Dwelling	WF	2	9	25	30	20-1st 13-2nd	3 2	3 x 5	17	6	3 x 5	24
Multi-Family Residential	Apartment	Con.	5	10	50	75	29	8	3 x 6	29	24	3 x 6	10
Multi-Family Residential or Industrial	Flat	Br WF	3	10	25	50	18	3	3 x 5	9	6	3 x 5	17 23
Multi-Family Residential	Dwelling	WF	2	9	25	50	20-1st 13-2nd	3 2	3 x 5	13	8	3 x 5	27
Multi-Family Residential	Mercantile	Br	1 2	15	50	65	4+	3 3	2-1/2 x 4	0	-	-	25 22
Single-Family or Blighted Residential	Flat	WF	2	10	25	50	18	3	3 x 5	9	6	3 x 5	23
Blighted Residential	Mercantile	Br	2	15	50	40	4+	3	2-1/2 x 4	0	-	-	22

+ Except for 50' x 7-1/2' Show Window on First Floor Front

* FRONT/REAR refers to windows parallel to the street and alley, respectively

Table 4. Ratio of Fuel Surface to Floor Area for Various Occupancies

Occupancy	Fuel Surface Area / Floor Area
Residential	3
Commercial - Department Store	4
Office - Modern	1
Office - Old	2
Manufacturing	3
Warehouse	
Below Average Fire Load	2.5
Average Fire Load (15-25 lb/ft^2)	4
Above Average Fire Load	5
Publishing Houses	3
Theaters	3
Schools	2
Libraries	5
Hospitals	1.5

The results of the calculations show that the burning rates of structural fires in an urban area are predominantly fuel-surface controlled. This conclusion is based on the assumption of unrestricted availability of air external to the structure. In a mass fire environment this may not necessarily be true, and the air may also be oxygen deficient. For actual structures, no information is available dealing with this phenomenon. Similarly, no reports exist concerning the burning behavior of actual structures under the influence of the radiation environment of a mass fire. As has been pointed out in the previous section dealing with crib fires, both factors may affect the burning rate of a structure.

2. Burning Rate and Duration of Peak Fire in Typical Structures

As mentioned, the formation and behavior of a mass fire depend also on the total amount of the released energy. Based on data given in Tables 3 and 4, the total amounts of fuel per story, the burning rates, and the durations of peak fires were calculated for typical structures. In the calculation of the duration of the peak fire, the assumption was made that only one half of the total fuel is available during the most intense (peak) burning. Of the other half, some is consumed during the fire build-up and some remains in the form of the charcoal at the end of the fire.

This assumption has been verified in the past by other investigators[14,15].

The results of the calculations are shown in Table 5. For residential occupancies the average fire load per story and the duration of the peak fire are 30,000 lb and 37 minutes, respectively. Except for fire resistive structures, the average burning rate for the residential occupancies was calculated to be 376 lb/min.

In actual fires, as already indicated, the amount of energy released depends on the rate the fire spreads through the structure. However, past experiments[3] with full scale structures have shown that the peak fire in newly involved floors can be assumed to occur at about the time when the fire intensity of previously burning floors begins to decrease. This assumption considerably simplifies the representation of building fires and permits direct use of the typical values listed in Table 5. Thus, for a single-story ignition of a multi-story structure the duration of peak fire will be equal to the appropriate multiple of the single-story duration. The burning rate will correspond, however, to that of a single story. On the other hand, ignition on all floors of a multi-story structure will result in a burning rate equal to the appropriate multiple of the single-story burning rate, and a duration equal to that for a single-

TABLE 5. FUEL LOAD AND BURNING TIMES OF TYPICAL STRUCTURES

Land Use	Occupancy	Stories	Fuel Load/Story lbs.	Burning Rate lbs/min.	Duration of Peak Fire in a Story (min)
Principal Business District (Downtown)	Mercantile	3 Br	68,250	1170	29
Principal Business District (Downtown)	Offices	3 Br	22,000 *	248	44
Industrial	Mfg/Whse	2 Br	328,125	3375	49
Industrial	Mercantile	1 Br	106,250	1530	35
		2 Br	93,500	1530	31
Commercial (Principal Business District or Suburban)	Flat	3 Br	30,000	540	28
		3 WF	42,000	540	39
Suburban Commercial	Mercantile	1 Br	93,750	1350	35
		2 Br	82,500	1350	31
All Except Multi-Family Residential	Dwelling	2 WF	18,000	203	44
Multi-Family Residential	Apartment	5 Conc.	37,500	1013	19
Multi-Family Residential or Industrial	Flat	3 Br	21,250	338	31
		3 WF	28,750	338	43
Multi-Family Residential	Dwelling	3 WF	33,750	338	50
Multi-Family Residential	Mercantile	1 Br	81,250	1170	35
		2 Br	71,500	1170	31
Single-Family or Blighted Residential	Flat	2 WF	28,750	338	43
Blighted Residential	Mercantile	2 Br	44,000	720	31

* Based on 40% of effective combustible content assumed to be located in filing cabinets

story. In general, it seems reasonable to assume that in the area where a mass fire will develop, at least two upper stories of the multi-story structure will be ignited by the thermal pulse from a nuclear detonation.

As stated above, the duration of the peak fire refers here to the period during which 50 per cent of fuel is consumed by the fire. This period is usually different (longer) than the violent burning defined as the time during which the radiation emitted by the fire exceeds 50 per cent of the maximum irradiance received by a radiometer located externally to the burning structure[16]. Since the behavior of a mass fire depends on the total heat flux, the duration of peak fire based on the rate of fuel consumption is of main interest for the investigations discussed in this report.

IV. SUMMARY AND CONCLUSIONS

The review of the literature pertaining to the burning behaviors of structural and wood crib fires revealed that both have been treated only in a very limited manner. In addition, many experiments involved models of such small scale that the applicability of the results to full scale cases is very doubtful. This has been found to be true on several occasions when the available laboratory data have been compared with large scale experiments. For this reason the conclusion presented must be considered as tentative. The following interim information is given for burning behavior of structures and cribs assuming no external heating and normal level of oxygen in the atmosphere.

A. Structural Fires

1. Maximum burning rates of structural fires are fuel-surface controlled (See Eq. 3, p. 4).

2. For residential occupancies the average fire load per story and duration of peak fire are 30,000 lb and 37 min., respectively.

3. Except for the fire resistive structures, the average burning rate of residential structures is 376 lb/min.

4. In a multilevel structures, stories ignited by the thermal pulse burn with maximum intensity simultaneously. Other stories ignited by fire spread within the structure burn consecutively.

B. Crib Fires

1. Maximum burning rate (R) of a crib, when controlled by the fuel surface (A_s), is given by the following equation:

$$R \text{ (lb/min.)} = 0.09\ A_s\ (\text{ft}^2) \qquad (1)$$

2. During the peak fire, half of the crib fuel is consumed.

3. Coalescence of crib fires considerably affects the average maximum burning rate.

4. Crib fires coalesce and burn with maximum intensity when(3):

$$\frac{\text{Distance between cribs}}{\text{Width of one crib}} = 0.069\ (nR_s)^{0.4} \qquad (4)$$

where n is the number of cribs and R_s is the burning rate of the individual crib.

5. Peak burning rate of a coalesced crib fire is(3):

$$R_{peak} = 1.56\ (n \cdot R_s) \qquad (5)$$

where n and R_s are as before the total number of cribs and the burning rate of an individual crib, respectively.

C. Simulation of Urban-Area Mass Fires

At the present time, sufficient information is not available to permit simulation of urban area mass fires by means of crib or other types of fires. Limited studies with crib fires revealed that coalescence drastically increase the burning rates. A similar situation can be expected in the mass fire environment existing in an urban area. Proper simulation of this environment in terms of fuel other than actual structures requires systematic studies of the entire problem. Only through such studies will it be possible to develop relationships between mass fires in urban areas, and those in other fuel types. In the following, a program of systematic studies is described.

V. SUGGESTED EXPERIMENTAL STUDIES

The objective of the suggested experiments is to provide the necessary background information for Operation Flambeau. In particular, the experiments should result in: 1) representation of building fires by means of crib fires and 2) guidance for the performance and instrumentation of large scale fires. These objectives require systematic investigations of the various processes and parameters governing the behavior of free burning fires. In the following, experiments are proposed involving both laboratory and field fires, with particular emphasis on burning rates, since these are most affected by the coalescence of individual fires.

With the exception of full scale building fires, experiments are listed in their order of importance. The full scale building fires should be conducted whenever suitable structures become available.

A. Laboratory Experiments

Laboratory experiments are essential for resolving many of the complex problems pertaining to free burning fires. The possible close control of the environment, fuel types, and use of extensive instrumentation are some of the advantages provided by the laboratory experiments. For this reason, most of the suggested studies pertain to laboratory investigations. These involve single crib fires, multiple crib fires, and model structures.

1. Single Crib Fires

As indicated above, burning rates are of particular interest to the proposed experiments. Parameters to be considered are:

a. Crib size
b. Crib height
c. Wood geometry
d. Wood spacing
e. Wood type
f. Wood moisture
g. Wind
h. External heating
i. Availability of oxygen

All parameters listed should be considered with both ordered and unordered fuel arrays.

To conduct the experiments, the cribs should be placed on a weighing platform. For large cribs, the platform may consist of several sections providing means for determining the local burning rates. Cribs should be ignited over the entire area by wetting the first layer of wood with liquid fuel. With multiple crib fires, the air flow pattern to the fuel is also of interest. For this reason, some experiments should involve cribs with their sides covered by non-combustible material. The crib should rest on a perforated platform elevated above the ground level. In this manner, the amount of oxygen supplied to the fire could be controlled and its effect on burning rates measured.

For studying the effect of wind on the burning rates, the crib should be placed in a low velocity wind tunnel. A test section with 12 x 12 ft width and 20 ft length would be adequate. For visual observation, glass wired windows may be provided along the wind tunnel walls. Velocities up to about 40 mph should be used. The same tunnel may also be used in fires with model structures.

In all experiments, where appropriate, the data collected should include weight loss, temperature, gas velocities, flow pattern and velocity of entrained air, heat flux, gas composition and pressure. Each experiment should also be recorded photographically to provide information on flame height, inclination, and area.

2. Coalescence of Crib Fires

The purpose of the coalescence studies would be to resolve many of the fundamental problems pertaining to mass fires. Some of the questions to be answered are: What is the mechanism causing the increase in the burning rates of coalesced fires? What arrangement of cribs can produce a coalesced and/or rotating fire? How does this affect the burning rate, heating of other fuels? etc.

To provide answers to these various problems, experiments should be performed with crib fires with varying number, spacing, and arrangement of cribs. The selection of the typical cribs for these experiments should be based on knowledge gained from experiments with the single-crib fires.

Types of data collected and the experimental procedures should be similar to those used with single crib fires. Included should be measurements of radiant heat and convective fluxes within the fire area. This information is of considerable significance since it will indicate whether the increase of burning rates by coalescence is due to the better conservation of heat or higher entrained air velocity. As in the case of single cribs, the velocity of the entrained air should be studied with cribs whose sides are covered by non-combustible material, with the cribs resting on a perforated platform raised above the floor.

The question of the significance of vortex motion in mass fires is of particular interest. In the past the identifying features of the fire storm have been taken to be 1) the non-spreading front and 2) extremely high induced air velocities. Theoretical calculations have shown that these velocities probably cannot be reached without vortex motion in the convection column. This is well confirmed by the communication received from Commissioner Brunswig[17] of Hamburg's Fire Department, who seems to be one of the few to witness and record the actual fire storm. Of particular interest are the following remarks made by Commissioner Brunswig pertaining to the well publicized Hamburg fire storm:

"The fire storm did not have a center such as exists in a hurricane. In the fire area involved there were zones of different fire intensities depending on the construction type of buildings, their density, contents, and also on the characteristic of the area, such as long streetways ending in open spaces.....

"In the fire area the wind was unstable. I estimate that in the vicinity of the fire station the wind had the velocity of the hurricane (wind strength 12 on the Beaufort scale)..... Also the direction of the wind was continuously fluctuating. I would like to characterize the main firestorm area as consisting essentially of whirls. Similar whirlwinds moved through the streets and ignited all available combustibles, including people. We have eyewitness to this effect.....

"The distance over which the fire spread cannot be given. However, distances of 50 meters presented no obstacles for spread of fire.....

"Regarding the flame heights, no information is available since the vision was obscured by the thick smoke over the areas involved. I have observed that the flames issuing from the windows opposite the fire station were almost horizontal, as in a soldering torch, and ignited the window frames of the fire-station which was 30 meters away.....

"People died on the streets because either they wandered into the fire-whirl or were engulfed by one, or were killed by hot air. On the streets the lack of oxygen or carbon monoxide poisoning should have not been the cause of death. Such cases happened in basements, in particular in the vicinity of the burning coal"......

The remarks made by Commissioner Brunswig clearly indicate the need for careful study of the formation of fire-whirls and the effect of wind on burning rate and the flame pattern outside the windows of burning structures.

Investigations of whirls may be accomplished by using various crib arrangements and channelling the air flow to the fire by means of carefully positioned non-combustible walls. Considerable preliminary effort will be required in connection with the fire whirls since the phenomenon is not well understood.

3. Wind Effect on Building Fires

Preliminary experiments(3) with 1/2 scale room fires have shown that the wind can influence both the burning rate and the flame pattern outside windows. Both factors probably affect the behavior of mass fires. For this reason, experiments should be performed with 1/2-scale rooms burning in the low velocity wind tunnel discussed above.

All rooms should be furnished with scaled-down wooden furniture. Two-room assemblies, on the same level, may be used to determine whether or not a high velocity wind can prevent communication of fire from a burning room to one located upwind. Studies should also be made of the possible radiative fire spread between 1/2-scale structures for various wind direction. This information may provide some clues regarding the stationary behavior of the fire storm.

Burning rates should be studied using single and two story 1/2 scale structures. In the latter case, experiments would have to be conducted in a larger tunnel, or outside the tunnel with the wind produced by aircraft engines or some other means. Both single and two story structures should be oriented at various angles to the wind direction to determine the effect of air-fuel mixing on the burning rates. The burning rates may be determined by continuously monitoring the weight loss of structures during the experiments.

B. Full Scale Experiments

1. Building Fires

Experience indicates that whenever possible, the data obtained with laboratory-scale models should be verified by full scale fires. Such an opportunity often presents itself when structures are destined for destruction for various reasons. Of interest are the fire spread within the structures, and as before, the burning rates and flame patterns outside windows, both as functions of the prevailing wind.

Two levels of effort can be used to obtain the data desired. One would involve the use of trained research engineers using extensive instrumentation. Some types of information require such an approach. However, valuable data could also be provided by the Fire Services, who frequently conduct building burns. For this purpose, some guidance must be provided regarding the procedures and nature of data to be collected. This requires the development of a set of instructions, perhaps a "building-burn manual" for use by Fire Service personnel.

2. Crib Fires

It is not possible at this time to finalize field experiments with crib fires such as those to be conducted during Operation Flambeau. These will depend on the results of above proposed laboratory investigations. However, some preliminary experiments with large scale fires will be required in order to verify and extend the laboratory findings.

In general, the preliminary large-scale field experiments should be similar to those conducted in the laboratory but will include large numbers of individual fires. This would permit studies of some phenomena not easily measurable in laboratory size fires. One such phenomenon is the effect of the ignition pattern on the fire behavior. Of interest would be the number and distribution of individual crib fires required to produce a mass fire. The ignition pattern may also affect the severity of the mass fire. As indicated by Commissioner Brunswig, during Hamburg's fire storm the areas involved burned with different intensities.

Another parameter which needs to be considered in connection with large scale field experiments is the completeness of combustion. The high altitudes reached by smoke from actual fire storms and recent crib experiments conducted by the Forest Service clearly indicate that in the mass fire the combustion is incomplete. Hence, in order to determine the actual amount of heat energy released, the burning rates measured must be supplemented by the information pertaining to the completeness of combustion. Since the released heat energy is the key parameter in theoretical analysis of mass fires, this information is of considerable importance. It could be obtained by gas sampling of combustion products within the convective column. The sampling may require modifications of existing instruments.

The preliminary field fires would also be useful for development of procedures for data collection. Of particular benefit would be extension of the measurements within the convective column to heights of few hundred feet. This information would be valuable for checking theoretical analyses of the convective column.

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