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IITRI

FIRE SPREAD IN HIGH DENSITY HIGH-RISE BUILDINGS

Final Report

Contract DAHC-20-70-C-2086
OCD Work Unit 2638F

February 1971

IIT Research Institute
10 West 35th Street
Chicago, Illinois 60616

SUMMARY OF FINAL REPORT

FIRE SPREAD IN HIGH DENSITY HIGH-RISE BUILDINGS

by

A. N. Takata

February 1971

For

Office of Civil Defense
Office of the Secretary of the Army
Washington, D.C. 20310

Contract DAHC-20-70-C-0286
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OCD REVIEW NOTICE

This report has been reviewed in the Office of Civil Defense and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Office of Civil Defense.

SUMMARY

I. INTRODUCTION

The fact that high-rise areas present special fire problems has been increasingly apparent to the fire community and has been reflected by an increasing number of programs to deal with various aspects of the problem. This particular program is concerned with developing a computer code to evaluate the initiation and development of fire within buildings in dense high-rise areas as a result of a nuclear burst. Specific concern is given as to how the fires progress from floor to floor, the rate of heat generation from high-rise areas and various hazards to individuals in the streets. Order of magnitude calculations were made using estimated values of several parameters to gain an overall appreciation of the severity of the fires and possible consequence to human beings. Four major tasks are involved in this program:

- Survey of Chicago's Central Business District (Loop)
- Development of analytical means for evaluating the overall development of fire
- Development of a computer code to evaluate the effects of fire in high-rise areas
- Estimation of the possible effects of fires in Chicago's Loop following a nuclear detonation

II. SURVEY

In order to better appreciate the vulnerability of major high-rise areas to fire, a brief survey was conducted of Chicago's Loop to obtain information describing the buildings and arrangement of the buildings from a standpoint of fire initiation and spread. Information was obtained describing the following:

- Distribution of buildings according to type, size and height
- Separations between buildings
- Number of windows per floor
- Fraction of window panes covered by window coverings
- Building density
- Vertical separations between windows

Most of the buildings were less than 10 stories.

Examination of the interiors of several buildings indicated that modern high-rise office buildings are among the least susceptible buildings to fire and probably will not support sustained fire unless seriously altered by blast. Whether or not such buildings present a fire threat depends primarily on the consequences of the blast on the amount and availability of fuels as well as how the blast affects incipient fires. Of particular importance is how the blast affects the large quantities of fuels in filing cabinets.

The interiors of modern high-rise buildings are very similar except for the fact that some buildings contain residential units while others do not. For the buildings examined, the residential units were confined to a few floors rather than being scattered throughout the building. Except for such variations, modern high-rise office buildings are very uniform in their susceptibility to fire either on a room by room or a floor by floor basis. The most serious threat to individuals in such buildings is smoke produced by small fires within the building or from external fires.

In contrast, the survey indicated that older buildings are much more variable both in their construction, and in their usage and content. Each of the buildings surveyed would be particularly susceptible to fire in a nuclear emergency because of the lack of water. Without water, it is doubtful that unattended fires could be contained because of the construction of the buildings and the presence of substantial quantities of readily available fuels. Particularly large quantities of fuels were noted in a number of merchandising enterprises scattered throughout these buildings.

Such areas as the Loop exibit large variations in the types, and sizes and heights of buildings and require a much more comprehensive data and analysis than has been afforded residential areas.

III. RESULTS

Aside from the procurement of survey data and information, the principal products of this program are:

- a computer routine that is designed to evaluate the initiation and spread of fire within buildings in dense high-rise areas as a result of a nuclear burst, and
- preliminary calculations of the probable fire effects of a given nuclear burst

The major difference between this code and previous codes is primarily in the greater detail used to account for large variations of building types and sizes and heights. Particular care was taken to determine the probable floor locations of the initial fires within buildings, and to account for the possible spread of fire from burning debris blown into the streets. Provisions were also made for vertical and horizontal spread of fire within buildings and for the spread of fire between buildings by radiation on a floor by floor basis.

Data required by the code aside from that used to describe the types, sizes, heights, and arrangement of the buildings include a description of windows and a specification of the times for fire to spread horizontally as well as between floors. Also needed is a specification of the amount of available fuel per unit area of floor allowing for the effects of blast. Times at which fires spread between buildings are calculated in terms of the number and locations of fires within buildings.

Order of magnitude calculations were conducted to gain an appreciation of the initiation and development of fire in a major central business district following a nuclear burst and of its possible consequences. The most noteworthy results are:

- The substantial shielding of the fireball by remotely located buildings
- The large concentration of fire starts in the upper floors as contrasted with the almost negligible number of fire starts on the ground floors
- The importance of radiant fire spread caused by exposures to large buildings
- The rather low radiant intensities received along the base of buildings from building fires during the first hour. Movement in the streets during this period would be contingent on the severity of debris fires
- The very intense radiant intensities in the streets between 1 and 2 hrs. Personnel in the streets during this period would experience intense pain and would, if exposed for appreciable periods, succumb to heat stroke
- The fact that the induced wind velocities are well below those noted in fire storms.

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FOREWORD

This final report summarizes studies under Contract No. DAHC-20-70-C-0286 OCD Work Unit No. 2538F (IITRI Project J6195), "Fire Spread in High Density High-Rise Buildings." The program was sponsored by the Office of Civil Defense, Office of the Secretary of the Army, Department of the Army, Washington, D. C. 20310. The contract was initiated on 14 Nov. 1969; work accomplished between that date and 14 Nov. 1970 is reported herein.

Respectfully submitted,
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Approved:

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ABSTRACT

This program has the objective of developing a computer routine to determine the initiation and spread of fire in high density high-rise areas following a nuclear detonation, and its effects on the street environment. The result of this endeavor is a computer code that evaluates the probable number and floor locations of fires, the rate of heat generation from such built-up areas, the radiant intensities in the streets, and the induced winds as functions of time.

Provisions were made to keep the code sufficiently flexible to allow for improved data and information as they become available. Also, provisions were made to simplify the problem of incorporating the routine in a more general code for an entire urban area. Preliminary calculations were conducted to gain an appreciation of how the fires develop in time, the threats to personnel in the streets and the possibility of a fire storm.

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I. INTRODUCTION

This program is concerned with evaluating the initiation of fire produced by a nuclear detonation near high-rise buildings located in areas of high building density, and with the subsequent spread of fire. High density high-rise areas contain buildings of different sizes, heights and usages, and are much more difficult to analyze than the more uniform buildings in residential areas. This difficulty applies to predicting both the number and location of the initial ignitions, and the subsequent spread of fire. For these reasons, a more comprehensive computer model than that previously used is required to predict the initiation and spread of fire in such areas. Also, a more comprehensive data base is needed to describe the built-up areas.

The objective of this program is to develop computer routines that may be used to predict both the ignition and spread of fire in high density high-rise areas, and to estimate the hazards to personnel. The Chicago Loop area has been chosen for this study. Specifically the program is to develop information for:

- Internal and external spread of fire within and between buildings.
- Rate of heat generation as a function of time.
- Radiant heat flux in the street as a function of time.
- Level of casualties of the population at risk.

This information is to be achieved by first-order analyses using previous analyses such as that associated with power-density predictions (Ref. 1), or modified versions of the same. Estimates are to be used in lieu of experimental data. The program will be subdivided into these major tasks:

- Select and survey a single modern high-rise office building.

- Formulate a computerized model of ignition and spread of fire within and between buildings in high density high-rise areas.

- Predict the development of fire, and street environment for a given attack condition.

- Estimate level of population casualties in the streets.

Specific work and services as indicated in the scope of work are:

1. Evaluate the dynamic fire spread in high density high-rise buildings in urban areas following a nuclear attack and develop and apply a computer fire spread model. The model shall allow for the more likely ignition situations created by the fireball as well as ignitions caused by burning buildings. The model shall be capable of predicting the number of rooms on fire on each floor, the rate of heat generation from the buildings, the sizes of the flames above the roof and in various numbers of windows, and the radiant flux in the streets surrounding the buildings.

2. Conduct an analysis: (i) to predict fire spread within high-rise buildings in both vertical and horizontal directions; (ii) to predict the duration fires in buildings and an indication of the times required for fire spread between buildings; and (iii) to estimate the rate of heat generation by burning buildings per unit area of ground (power density), the indraft velocities, and the casualties of population at risk. The above analysis shall be programmed for computer solutions.

3. Apply the fire spread model in high-density high-rise buildings to downtown Chicago under attack conditions to be prescribed by the Government. The model shall be used to predict the fire spread, rate of heat generation, and thermal flux associated with a selected high-rise building.

4. Prepare a report documenting the evaluation procedures and the predictions. Particular attention shall be given to the future needs of integrating the results with existing fire-spread analyses for an entire urban area, for the inclusion of Office of Civil Defense initiated countermeasures to contain or suppress the fires, and calculation of the potential hazards to individuals in high-rise buildings, shelters, and surrounding streets.

II. SURVEY OF BUILDINGS IN HIGH DENSITY HIGH-RISE AREAS

Two types of surveys were conducted during this program. The first involved an overall view of the types, sizes and arrangement of the buildings in Chicago's Loop while the second involved a survey of the Prudential Building on the eastern border of the Loop facing Lake Michigan. A discussion of the results of each of these surveys follows.

A. Overall Description of Area

Data describing the general makeup of Chicago's Loop from the standpoint of fire was obtained by sampling a total of 74 buildings. Specific information sought for the computation of the initiation and spread of fire following a nuclear detonation included:

- Distribution of building heights
- Distribution of building separations
- Building occupancy
- Number of windows per floor
- Vertical separation between windows
- Fraction of windows covered by blinds, drapery or other window coverings.

Data for the sizes of windows were obtained from Ref. 2.

Because of substantial differences in the buildings and street widths in different parts of the Loop, particular care was exercised in selecting a random sample of buildings in different parts of the Loop. Over half of the buildings sampled are used either as offices or shops and most of the recently constructed buildings are high-rise office buildings.

Results of the surveys for the number of windows per floor, and the heights and separations between buildings are illustrated in Figs. 1, 2 and 3, respectively.

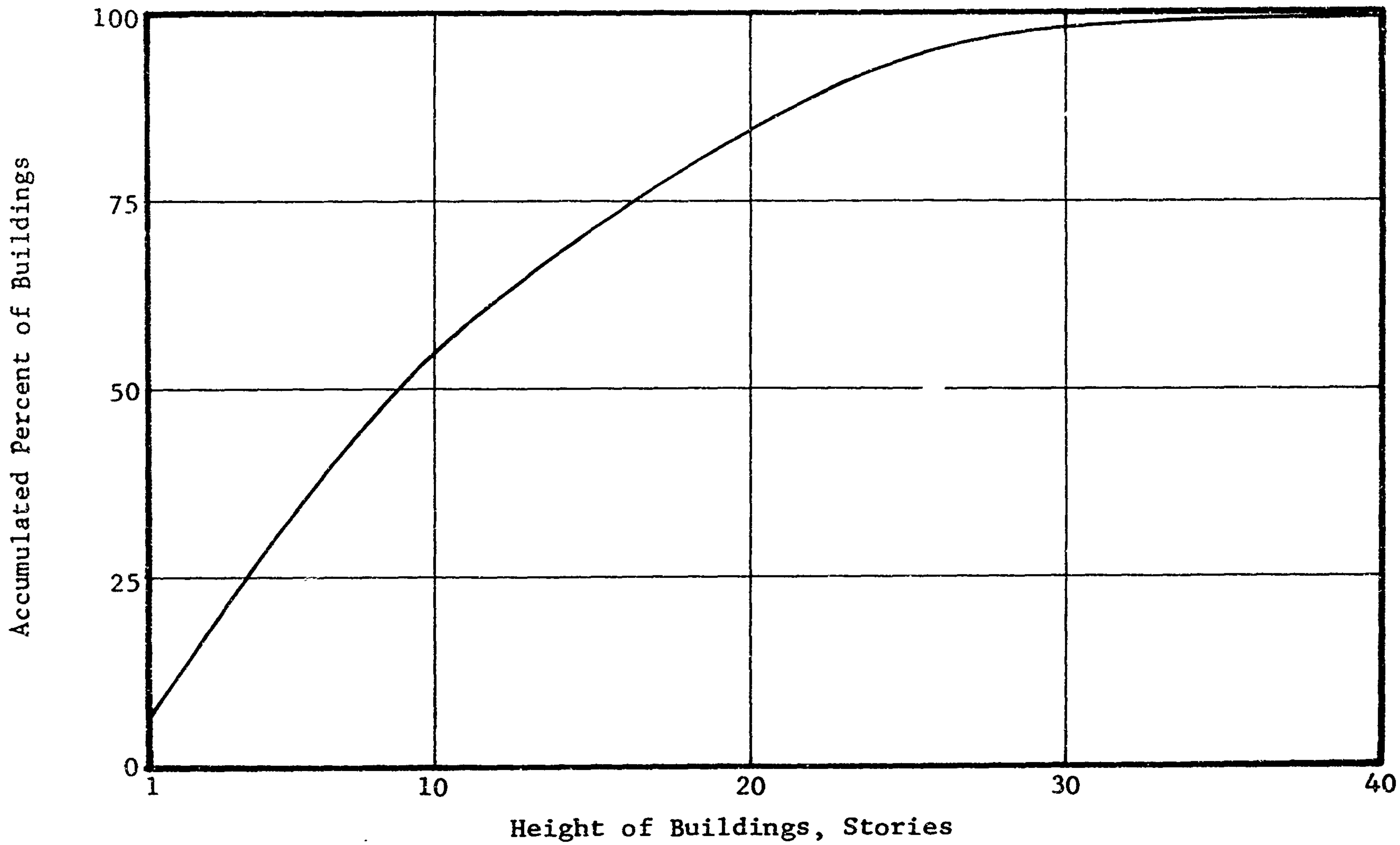

Fig.1 HEIGHT OF BUILDINGS IN CHICAGO'S LOOP

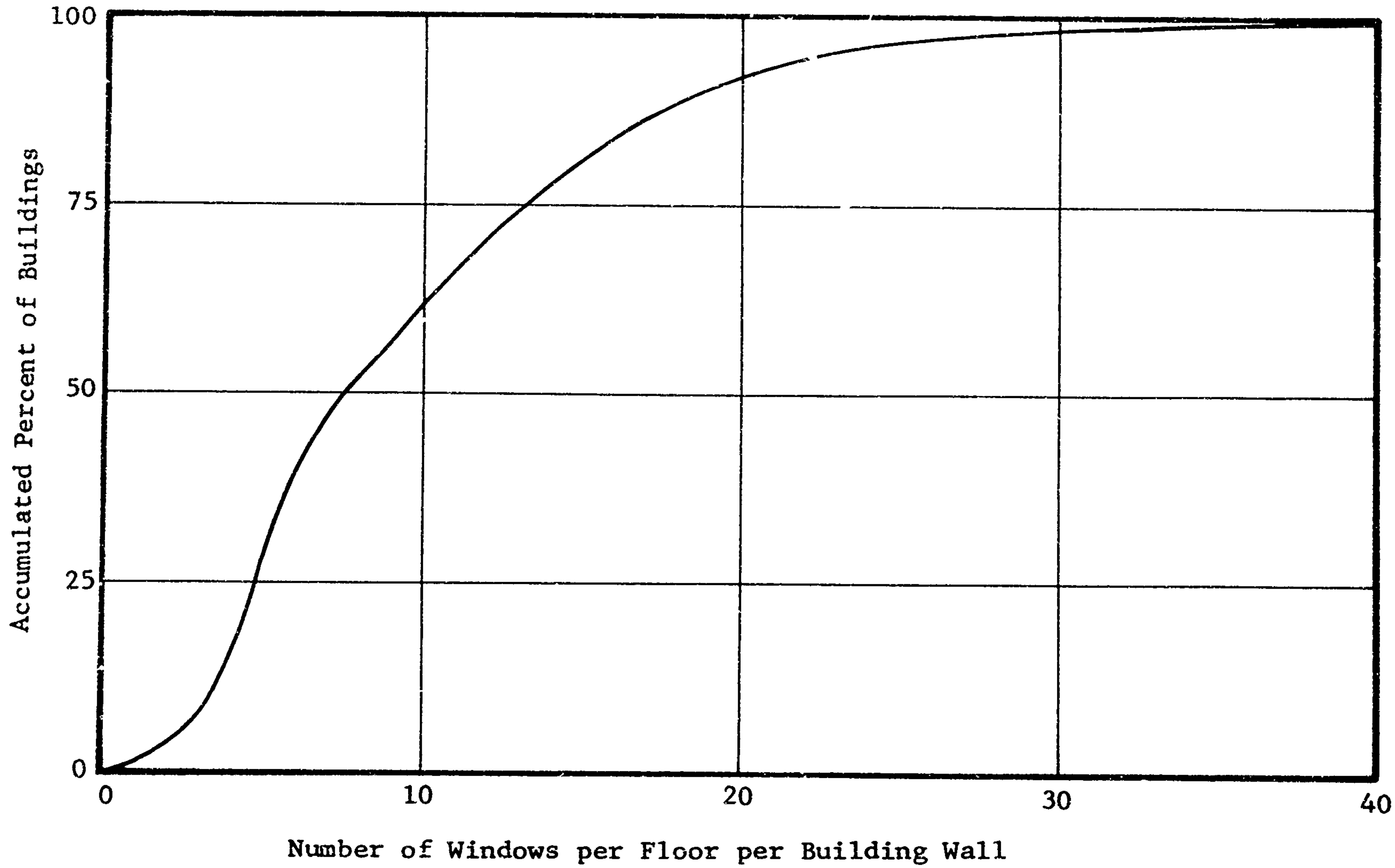

Fig. 2 NUMBER OF WINDOWS ASSOCIATED WITH BUILDINGS IN CHICAGO'S LOOP

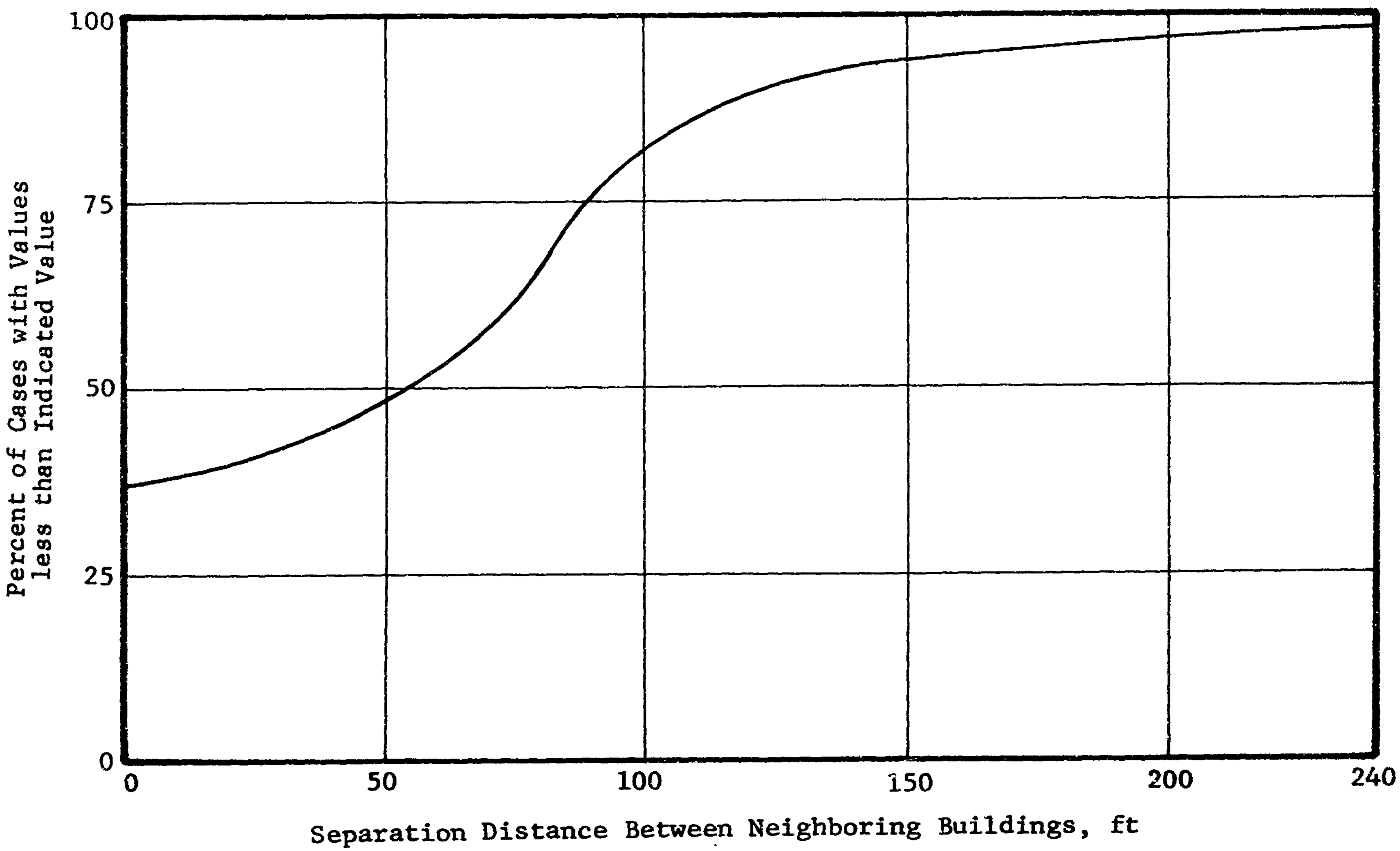

Fig. 3 SEPARATION DISTANCE BETWEEN BUILDINGS IN CHICAGO'S LOOP

Notice that approximately one-third of the buildings have five or less windows per floor per wall; one-third of the buildings have six to 11 windows per floor per wall, and one-third of the buildings have 12 or more windows per floor per wall. Usually, fewer numbers of windows are associated with the shorter buildings rather than with tall buildings. This is partly due to the fact that many of the short buildings are used for commerical purposes and involve large display windows.

Figure 2 shows that the median height of the buildings is nine stories. One-third of the buildings are less than five stories; one-third of the buildings range from six to 12 stories and one-third of the buildings exceed 12 stories. A surprising percentage of one-and two-story buildings were found in the Loop, namely, 6 and 7 percent, respectively. Most of these buildings were small stores or restaurants.

Figure 3 describes the separation distance between adjacent walls of buildings. In 37 percent of the cases the buildings have no separation. The fact that only 13 percent of the separations range from 1 to 55 ft serves to illustrate that most separations are a result of streets.

Since the vertical spread of fire between windows is a distinct possibility with vertical separations less than about 3 or 4 ft, a total of 43 buildings were examined to determine how the vertical distance between windows varies from building to building. A summary of the results is shown in Fig. 4. Notice that about one-half of the cases have separations between 3 and 4 ft while the remainder are distributed approximately equally above and below this range of distances.

Finally, a survey of 54 buildings was conducted to determine the kinds and heights of buildings in the Chicago Loop. The results are shown in Table 1. Office buildings tend to be more modern and taller than those used for other purposes. Mercantile and hotel buildings are usually older and much more vulnerable

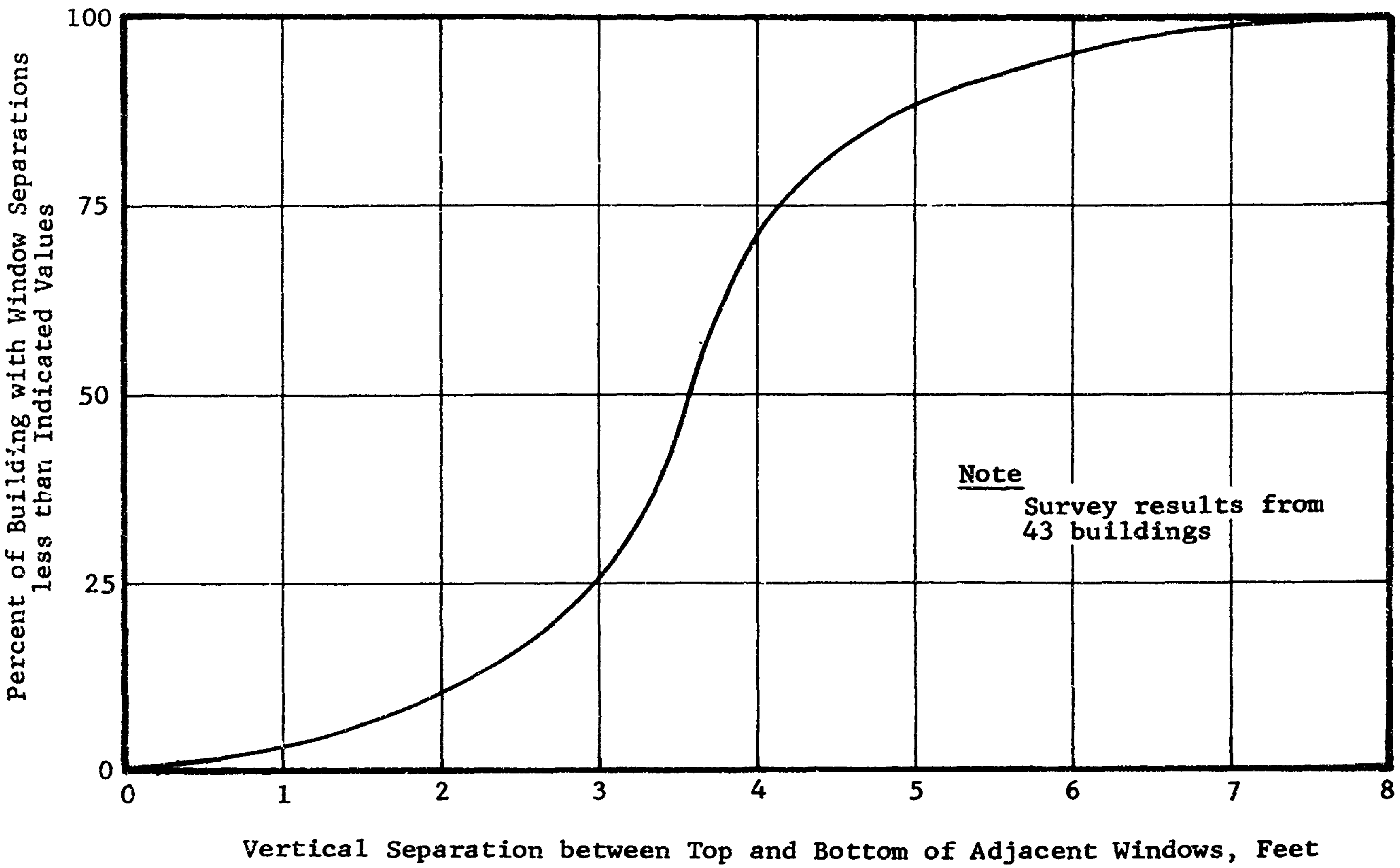

Fig. 4 DESCRIPTION OF VERTICAL SEPARATIONS BETWEEN ADJACENT WINDOWS

TABLE 1

UTILITY AND HEIGHTS OF 54 BUILDINGS RANDOMLY SELECTED IN CHICAGO'S LOOP

Type of Building	Percentage of Buildings	Range of Building Heights, Stories	Average Height, Stories
Office	28	4 to 57	18
Mercantile	28	1 to 12	4
Residential	15	1 to 7	3
Hotel	9	7 to 24	16
Vacant	7	5 to 13	8
Garage	6	3 to 10	5
Theatre	6	2 to 5	4
College	2	16	16

to fire initiation and spread. In contrast to modern office buildings, the threat of fire spread in most other types of buildings is serious. This is particularly true of some of the older buildings that contain large numbers of merchandising enterprises scattered throughout the building. Fortunately, most of the more vulnerable buildings are small. This will not only minimize the possibility of their ignition by the fireball but also minimize their threat to surrounding structures.

B. High-Rise Buildings

High-rise buildings are becoming more prevalent in cities and present a number of problems in the event of fire. Within the central business district, most of the high-rise buildings are used for offices while those on the periphery and beyond are usually residential. Mixed usage is not uncommon especially outside the central business district.

For this study, the Prudential Building was chosen since it is a modern high-rise office building and is used solely as office space by several business establishments. The building contains no residential or merchandising units.

The Prudential Building is a reinforced concrete building that was constructed in 1955. It consists of 42 stories including an observation deck, and five basement levels that are used to maintain, heat and air-condition the building. In addition to four elevators that service floors one through eight, there are eight express elevators that run between the main floor and floors above the eighth floor. Also there are four stairwells in the building, all closed by metal fire-resistant doors and provided with fire hoses at each landing. The only vertical openings, aside from those for heating and air-conditioning ducts, are provided for escalators that run between the first and fifth floors and between the 40th floor and the observation deck on top of the building. The escalator openings at the lower floors are not considered serious sources of fire spread because of the very limited quantities of fuels on these floors and the fact that the openings are offset from each other on consecutive floors. Also, each floor is highly compartmentalized and not conducive to the spread of fire.

While the building contains a variety of furnishings and utilizes a number of materials on the floors and walls, no serious concentrations or arrangements of fuels were found that would constitute a serious threat of fire spread in their normal configuration. The largest quantities of fuel consisted of paper in filing cabinets. Except for isolated situations, the exposed fuels are generally insufficient to develop an intense sustained fire. What the fire situation would be like if the content of filing cabinets are scattered about by the blast remains to be seen.

An examination of the exterior of the building indicated there is an average of forty 3-ft by 5-ft windows per floor per wall. A description of the degree to which these windows are covered by drapery, blinds, etc., is shown in Fig. 5. Included in the figure, for purposes of comparison, are the results of a daytime survey of the central business district of Detroit, Michigan in 1968 (Ref. 2). In each case it may be observed that over half of the windows are completely covered and, hence, will shield interior fuel items from the fireball's radiation unless the window coverings are blown out by an earlier detonation.

While a number of small incipient fires may be started within the building, none of the fires should spread appreciably beyond the initially ignited rooms unless the blast seriously rearranges the fuels and/or integrity of the building. Smoke generated by internal fires may present a serious problem (Ref. 3) to occupants of the building as may heat and smoke generated by fires involving combustible debris blown into the streets. The fact that there are no structures on the lakeward side of the Prudential Building will cause indrafts from the

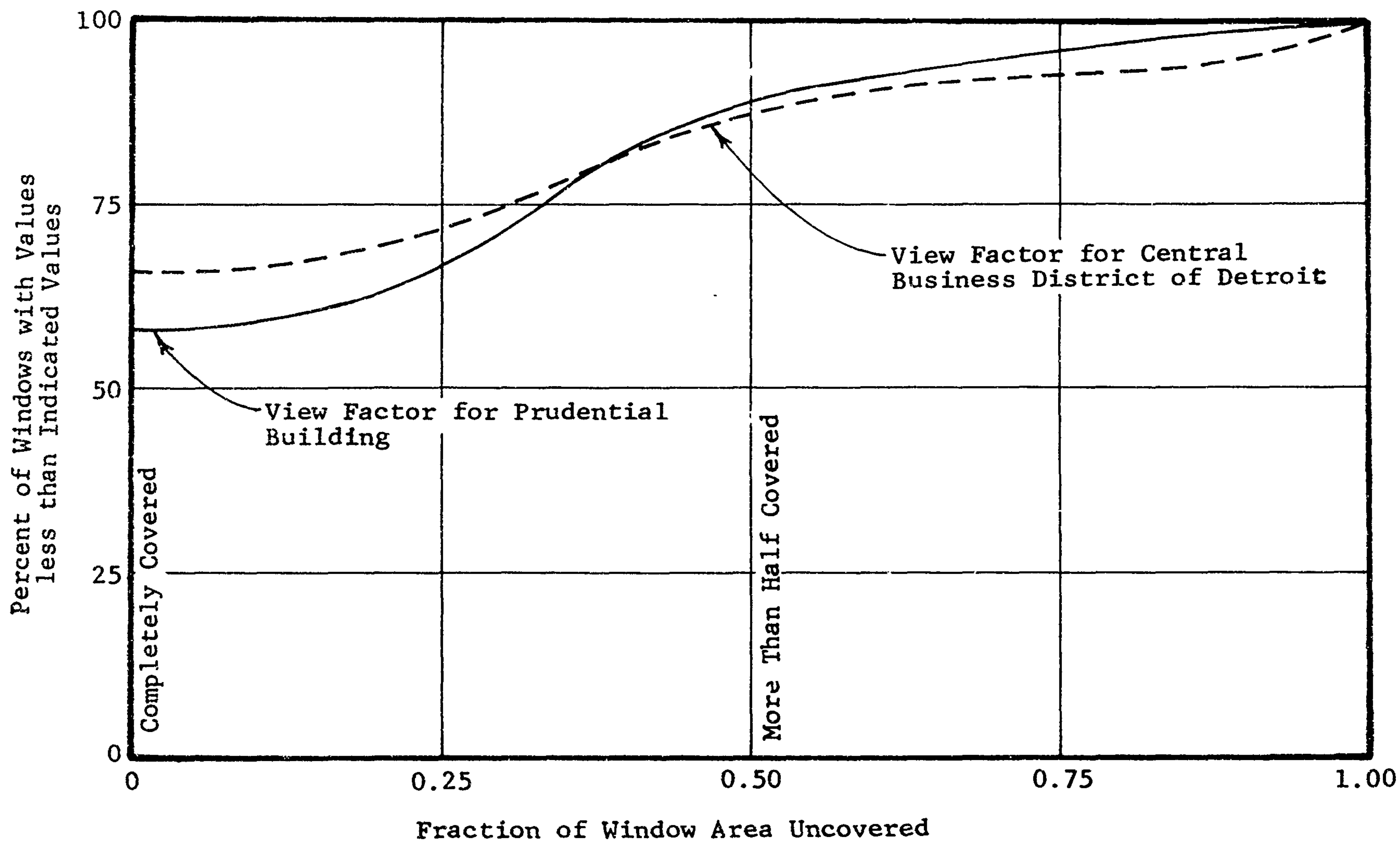

Fig. 5 PERCENT OF WINDOW AREA UNCOVERED (DAYTIME HOURS)

lake that will not only minimize the environmental air temperatures but also the effects of fires on the west side of the building.

Aside from internally developed smoke, the greatest threat to occupants of high-rise office buildings is fire either in neighboring buildings or in combustible debris blown into the streets by the blast. Also of concern is the effect of fires on the environment in the streets. To ascertain the fire threat, a computer code was developed that predicts the fire situation on various floors of buildings as a function of time, as well as the effect of the fires on the street environment. The remainder of this report is concerned with a discussion of means to predict the number and location of initial ignitions and the subsequent spread of fire.

III. ANALYSIS

In modeling any phenomenon, one must compromise between a highly detailed approach which frequently is impractical, and a less accurate approach which is more tractable. In addition, one must consider the adequacy of existing knowledge, the cost and effort required to supplement this knowledge, and the operational options available to OCD. Finally one must consider the capabilities and needs of potential users of the model.

Our approach here is to develop a statistically oriented model that appraises the fire situation from a probabilistic rather than deterministic point of view considering the total ensemble of buildings in the central business district. Such an approach presents an overall view of the fire situation as a function of time without the need for enormous quantities of detailed data. Also it defines the fire environment within which individual buildings are situated as well as the probable fire conditions within buildings.

One of the major problems in modeling complex arrays of disimilar buildings in central business districts, involves the selection of representative categories of buildings with which to represent individual buildings. Here, we will consider two types of buildings, namely those within which fire will not spread, and those within which fire will spread. The first category of buildings generally involves buildings of fire-resistive construction with limited quantities of available fuels and is characteristic of modern office buildings. The second category of buildings is exemplified by typical department stores. Secondly, buildings will be described in terms of their heights and in terms of their number of windows.

Another major problem in the modeling of building fires caused by a nuclear detonation is the prediction of:

- the effects of blast on the initial ignitions, and
- the effects of structural damage and rearrangement of fuels on fire spread.

Determinations of the actual blast wave, building damage and their effects on fire are difficult tasks that have been under study with various degrees of success for several years. Predictions of the blast wave in heavily built-up areas represents a particularly difficult task since the presence of buildings or other obstructions will modify the magnitude and form of the free field blast wave and the induced winds. At present, the state of knowledge in this area is limited in the sense that only isolated buildings can be treated apart from interactions of the blast with other buildings. Furthermore, the effects of blast on fire spread are not defined at the present time. For this reason, means for evaluating the fire spread were kept as general as possible to allow incorporation of results of blast-fire interaction studies as they are developed.

While much of the remaining discussion revolves about undamaged buildings, provisions have been made to account for blast effects by adjusting the number and locations of the initial ignitions, the rates of fire spread, window openings, fuel loads, etc. The effect of debris fires in the streets on building fires is accounted for by considering that certain percentages of the ground floors of buildings are ignited by the debris fires at specified times.

A. Fire Starts

A very important aspect of the prediction of nuclear-induced fire in a high density high-rise area, is the determination of the number of ignitions caused by exposure to the fireball. Equally important are the locations of these ignitions within the buildings. Except for the possible consequences of blast, ignitions on the middle to upper floors are less hazardous than fires on the lower floors because fires on the upper floors represent less of a threat to surrounding buildings. Also there are greater quantities of fuel on the lower floors and fire and smoke move upward more readily than downward.

In order to predict the numbers and initial locations of ignitions in various buildings in a high-rise area, an analysis was developed to account for the shielding of thermal radiation from the fireball by buildings other than the adjacent building in the direction of the fireball. This provision is important in high-rise areas because of the variety of building heights and the relatively small separations between buildings. The analysis is an extension of that presented in Ref. 2 and differs from previous analyses in that it allows for shielding of the fireball's thermal radiation by the two nearest buildings in the direction of the fireball instead of only one.

The result of this effort is a computer code that computes the radiant intensities within various parts of rooms considering the likelihood of various window openings, numbers of windows, and heights and separations of the two closest buildings in the direction of the fireball. The first step in the evaluation is to determine the radiant intensities at various room locations by summing the radiation from each of 94 elements of the fireball that may be sensed by each incremental area of the room. This is followed by an evaluation of the likelihood that the given room location is occupied by fuels with critical energies equal to or greater than the incident radiant energies. Consideration is given only to those fuels which would cause the complete involvement of the room in fire. The result is the probability that a sustained fire will be started in that area of the room. By performing a similar analysis, over other parts of the room one arrives at the probability that the room is ignited.

For a specific building, one may perform the above computations using specific data for the window openings, heights and separations of neighboring buildings, and a specification of the arrangement of fuels within each room. For an overall picture of the ignitions throughout the area, consideration is given to all combinations of factors affecting the transmission of radiation into rooms.

Among the predictions are the probabilities of ignition of various floors, and the expected number of ignitions on each floor. Predictions are also given for the total number of ignitions expected in buildings of various heights as well as the fraction of the buildings with at least one fire capable of spreading appreciably within the building.

B. Fire Spread

Spread of fire within and between buildings can occur in a variety of ways and involves a number of complex phenomena many of which are known only qualitatively. Within buildings, fires can spread:

- by the successive kindling of adjacent fuels,
- by building up concentrations of combustible gases that flashover,
- by burning through partitions,
- by the movement of flames and/or burning materials from window to window, and
- by burning material falling through collapsed floors or into open windows.

Fire spread between buildings also involves a variety of phenomena and can occur as a result of:

- thermal radiation from flames emanating from the buildings,
- firebrands,
- burning debris sucked out of buildings by the blast, and
- burning debris from collapsed buildings.

Further complications are introduced by the effects of the blast, ambient winds and fire-induced winds. Our approach throughout this study is to provide a methodology that will include all phenomena for which there is data and which can be extended to include other known phenomena for which there is little or no significant data.

The result of this effort is a computer routine that predicts the subsequent spread of fire within and between buildings. Fire spread by firebrands is not included because of the uncertain nature of the generation of firebrands from high-rise buildings and because of uncertainties in the local wind patterns in such areas. Provisions are made for predicting the spread of fire as a function of time by a statistical approach allowing for:

- upward and downward spread of fire in buildings, and
- fire spread between buildings by radiation from flames as a function of the size and location of fires within the various buildings.

The technique for predicting the spread of fire between buildings represents a major improvement over methods used previously (Refs. 1 and 2) in that the fire spread is computed on a time-dependent basis as a function of the changing fire conditions. Earlier methods involved an arbitrary assignment of the probabilities of ultimate spread over the period of intense fire in the various buildings.

For the study of fire spread, consideration was given to two types of buildings, namely those that are capable of appreciable internal spread and those that are not. Fuels within vulnerable buildings are considered to have the same composition and spacial distributions as fuels found in residential buildings. Future surveys should be concerned with additional building surveys to allow for the inclusion of additional categories of building occupancies.

Prediction of the spread of fire within nonresidential buildings has always presented a problem because of the lack of comprehensive data either from fire departments or from experimental studies. For the case of fire departments, the data are meager because most fires do not spread very far before engagement by the fire department. On the other hand, while a number of experimental fires have been studied, the results barely begin to cover the variety of building types, sizes and interiors, as well as types, quantities and arrangements of fuels, and ways in which fires are started.

A large percentage of the data is for fires in residential buildings and indicates that the fire area A increases in an exponential relationship with time (Ref. 4):

$$A = A_o \cdot \exp(t/m) \qquad (1)$$

where A represents the floor area engaged in fire at time t, m is a constant that is determined experimentally, and A_o represents the initial fire area at t = 0. This equation only applies to buildings within which fires will spread. For such buildings, time is usually measured from the initial flashover of a room and A_o is set equal to the area of the room that has flashed over.

Three other types of fire spread are included in the model, namely, upward and downward spread between floors and the spread of fire from fires in neighboring buildings as a result of thermal radiation. Fire spread between floors is considered to take place after a given interval of time following the first flashover of a room on the floor. Different intervals of time are used for the upward and downward spread of fire.

Fire spread between buildings is treated by evaluating the probabilities associated with the exposure of each floor to various radiant intensities from probable fires in surrounding buildings at successive intervals of time. Any increase in the incident radiant intensity is accounted for by increasing the probabilities of fire on the given floors. After a fire spreads over all floors of a building, the building is not considered further as a spreader of fire to other buildings by radiation.

C. Radiant Fluxes from Burning Buildings

Radiation emitted by flames from burning buildings is particularly serious in high density high-rise areas because of large densities of windows. The radiant intensity is important for three reasons, namely,

- o fire spread between buildings,
- o effects on personnel in the streets, and
- o effects on air temperature.

In the computer code, the radiant intensities are calculated following the technique discussed in Ref. 1 in which the standard configuration-factor method is used to evaluate the radiant intensities in terms of the separation distance, and the temperature, emissivity, area and location of the flames. These evaluations are made both as a function of time and as a function of the probable location of fires on various floors. Means have been developed for calculating the radiant intensities incident on the walls of buildings as a function of height, and the average radiant exposures of personnel proceeding along the center or sides of streets.

D. Induced Winds

Winds induced into an area of intense fire can alter a fire situation appreciably and are one measure of the severity and consequences of mass fire. An appreciation of the possible radial wind velocities at the perimeter of the fire may be gained by use of the following scaling relationships between the velocity v, the rate of heat generation q and the fire area A (Ref. 5):

$$\frac{v_1}{v_2} = \left[\frac{q_1}{q_2}\right]^{1/3} \left[\frac{A_1}{A_2}\right]^{1/6} \qquad (2)$$

Substitution of following data for v_2, A_2 and q_2 (Ref. 6) from the Flambeau Fire Tests,

$$v_2 = 20 \text{ ft/sec},$$

$$A_2 = 1050^2 \text{ ft}^2, \text{ and} \tag{3}$$

$$q_2 = 30 \text{ B/(ft}^2\text{sec)},$$

yields

$$v_1 = 6.11 \cdot (q_1^2 A_1)^{1/6}. \tag{4}$$

Here the units are in feet, seconds and Btus. If one uses miles and hours instead of feet and seconds, then Eq. (4) becomes

$$v_1 = 0.00161 \cdot (q_1^2 A_1)^{1/6} \tag{5}$$

The above correlations pertain to the radial velocity developed by the fire. A tangential or swirl velocity component is also developed in large fires but an appreciable period of time is required for their full development. In steady state conditions the magnitude of the tangential velocity exceeds the radial velocity when the Thermal Rossby Number as defined below falls beneath 8×10^{-4}

$$\text{Thermal Rossby Number} = \frac{h^4 \Omega^2}{R^3 g \frac{\Delta T}{T_\infty}} \tag{6}$$

where

g = acceleration corresponding to gravity

h = height to which plume ascends

R = radius of fire

Ω = rotation of system. Earths rotation = 5×10^{-5} radians per sec

For a fire on the order of the one that occurred at Hamburg, Germany in World War II the tangential wind reaches about 60 percent of its steady state value in a period of two hours.

IV. RESULTS

The result of this endeavor is a computer routine that computes the effects of fire in high density high-rise area as a consequence of a specified nuclear burst. This routine has been made as general as possible so as to allow for revisions and upgrading to accommodate new developments in the knowledge of fire and its effects. Also provisions have been made to simplify incorporation of the routine into more generalized computer codes for treating whole cities.

Among the principal quantities predicted by the code are the following:

- Probable number and location of fires started by fireball on various floors
- Spread of fire within and between buildings as function of floor
- Radiant intensities in street
- Rate of heat generation from builtup area
- Induced wind velocities at periphery of fire area

Provision are included for accounting for the effects of blast and of debris fires in the streets as data become available.

In order to obtain an appreciation of the gross effects of fire on the central business district of a major city, several parameters were estimated and used to approximate the effects of fire initiated within the business district by a 5 MT ground burst located 5 miles away. This is the same attack condition that was used for the OCD study of Detroit (Ref. 2).

Two types of evaluations were made. The first consisted of a determination of the probable number and floor locations of fires started by the fireball. The second estimated how these fires would spread within and between buildings and how the fires affect the street environment. Values of parameters used in the computations are presented in Table 2, and in Figs. 1, 2, 3 and 5. Data for the types and arrangements of fuel within rooms and windows, and the transmissivity of the atmosphere are given in Refs. 2 and 7. Parameters shown in Table 2 with asterisks are highly dependent on blast effects and represent crude estimates used to gain an overall appreciation of fire. Only half of the fuel is considered to participate in vigorous burning. Two cases are treated to account for the possibility of debris fires in the street, one in which the debris fires do not endanger buildings and one in which debris fires spread to the ground floors.

TABLE 2

DATA USED IN COMPUTATIONS

Fraction of buildings in which fires will spread extensively	0.5*
Ratio of maximum flame area to wall area	0.3*
Flame temperature	1600°F
Time for fire to spread downward to next floor	75 min*
Time to spread fire upward to next floor	45 min*
Time to burnout of floor	75 min
Average width of building	84 ft
Average heat release of fuels	8000 Btu/lb
Average fuel load per unit area of floor area	25 lb/ft^{2}*
Building density**	0.36
Size of high density high-rise area	0.7(mile)^{2}

*Estimated values.

**Fraction of ground area covered by buildings.

A. Blast Effects

For many buildings, one can accurately treat the effects of the 5 MT blast on isolated structures in a free field environment of 4.5 psi. Such evaluations are however, valuable in gaining an appreciation of the effects of blast on densely built-up areas even though many of the buildings have common walls.

Isolated one- and two-story residences, are not expected to survive at this weapon range since they begin to fail at overpressures of 1 to 2 psi. Owing to the high velocity winds that accompany the blast wave, buildings damaged by overpressure will be further damaged (leveled, dismembered and translated) by these winds. At 4.5 psi field free pressures associated with the 5 MT burst, building members will be broken up into debris and translated large distances from the original site.

As far as multistory buildings are concerned the situation at this range is somewhat different and depends on the type of building in question. Two types of buildings are discussed here.

- Reinforced Concrete Frame Building with Curtain Walls - Large Apertures

At this range, frame and concrete floors will remain standing while walls will fail in the neighborhood of 3 psi. Resulting debris is not expected to travel very far at the 4.5 psi level. Fifty percent of the contents of buildings (including partitions) are expected to be swept out, and deposited in the streets.

- Steel Frame with Concrete Block Filler Walls and Open Web Joist Floors - Small Apertures

In addition to concrete block, this type of building is usually covered with a layer of brick which adds little additional strength even though the filler walls tend to arch. At this range and weapon size, the walls are expected to fail, although the resulting debris is not expected to travel far. Floors are expected to fail and break up and the resultant debris to be deposited locally. While it is difficult and at the same time dangerous to generalize from a single building to a group of buildings as to their behavior in a nuclear environment, it is apparent that the 5 MT detonation will inflict considerable blast damage to the Loop. Unfortunately, the present state of knowledge in blast effects and in fire is not adequate for a complete quantitative description of the consequences of blast on the initial fires and on the subsequent fire spread.

B. Initial Fires

In this section we will discuss the thermal effects of the fireball on those buildings which will sustain and spread fire internally. Many high-rise buildings that are used exclusively as offices will not support large fires and do not fit into this category. Buildings used as temporary or permanent residences or for merchandising purposes are typical of the buildings under consideration. For purposes of calculation, we will assume that roughly half of the buildings in high density high-rise business areas will sustain serious fires.

Figures 6 through 8 present the anticipated effects of the fireball on buildings with fuels similar to those found in residences. Because of the lack of comprehensive statistics describing the variety of buildings and building usages as well as the effects of blast, most of the following results represent first-order approximations and are presented primarily to develop an overall picture of the consequences of a nuclear detonation.

Figure 6 describes the probabilities that different floors are ignited as a function of the number of windows per floor. The ignitions, of course, occur on the side or sides of the building facing the fireball. The fact that most ignitions are on the upper floors is due to the shielding of the lower floors by the taller buildings, and is most pronounced for the surface detonation considered. Unless these fires are appreciably reduced in number by the blast -- either by blowing the ignited items out or onto the street -- there will be a severe fire

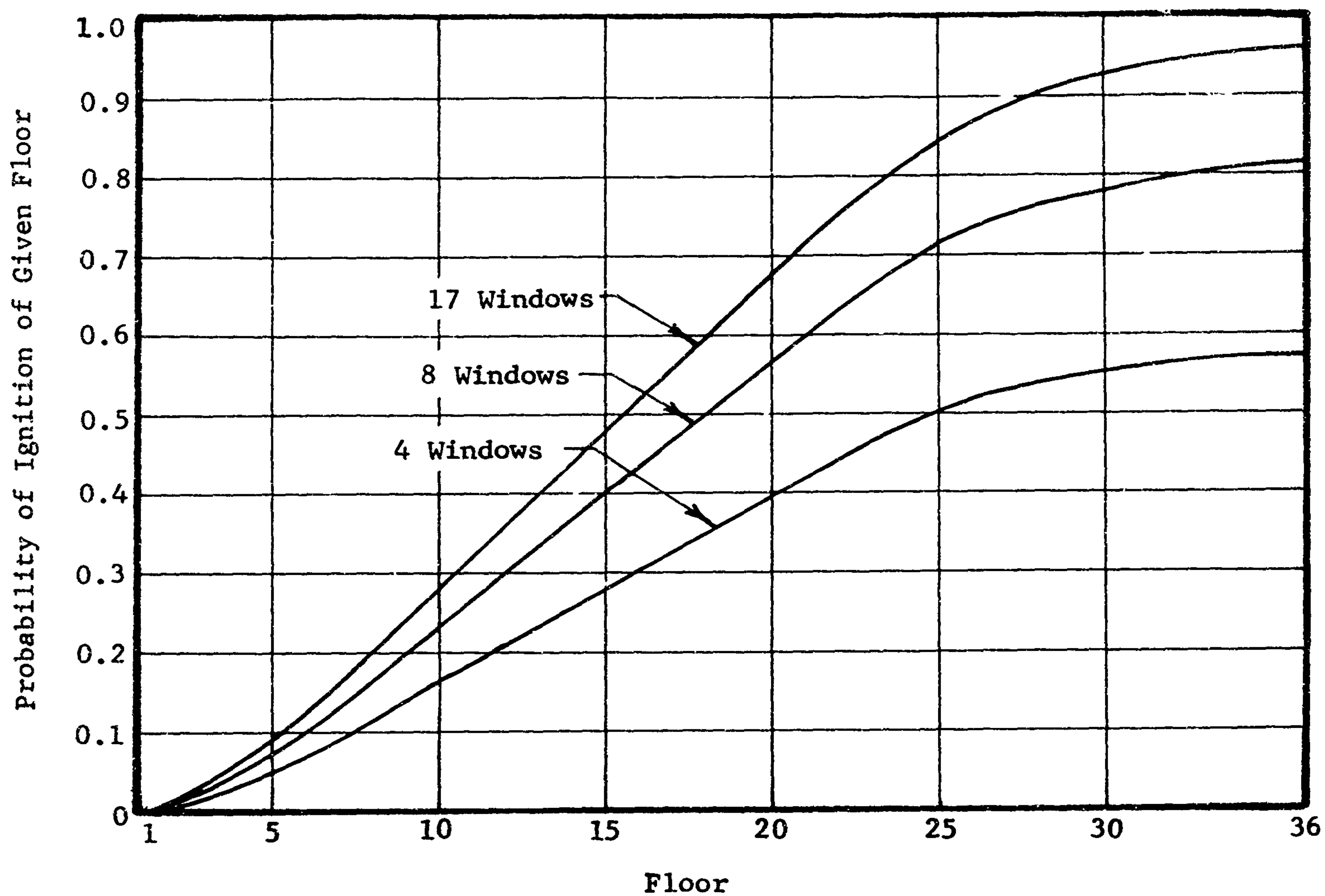

Fig. 6 ESTIMATES OF PROBABILITY OF IGNITION OF DIFFERENT FLOORS

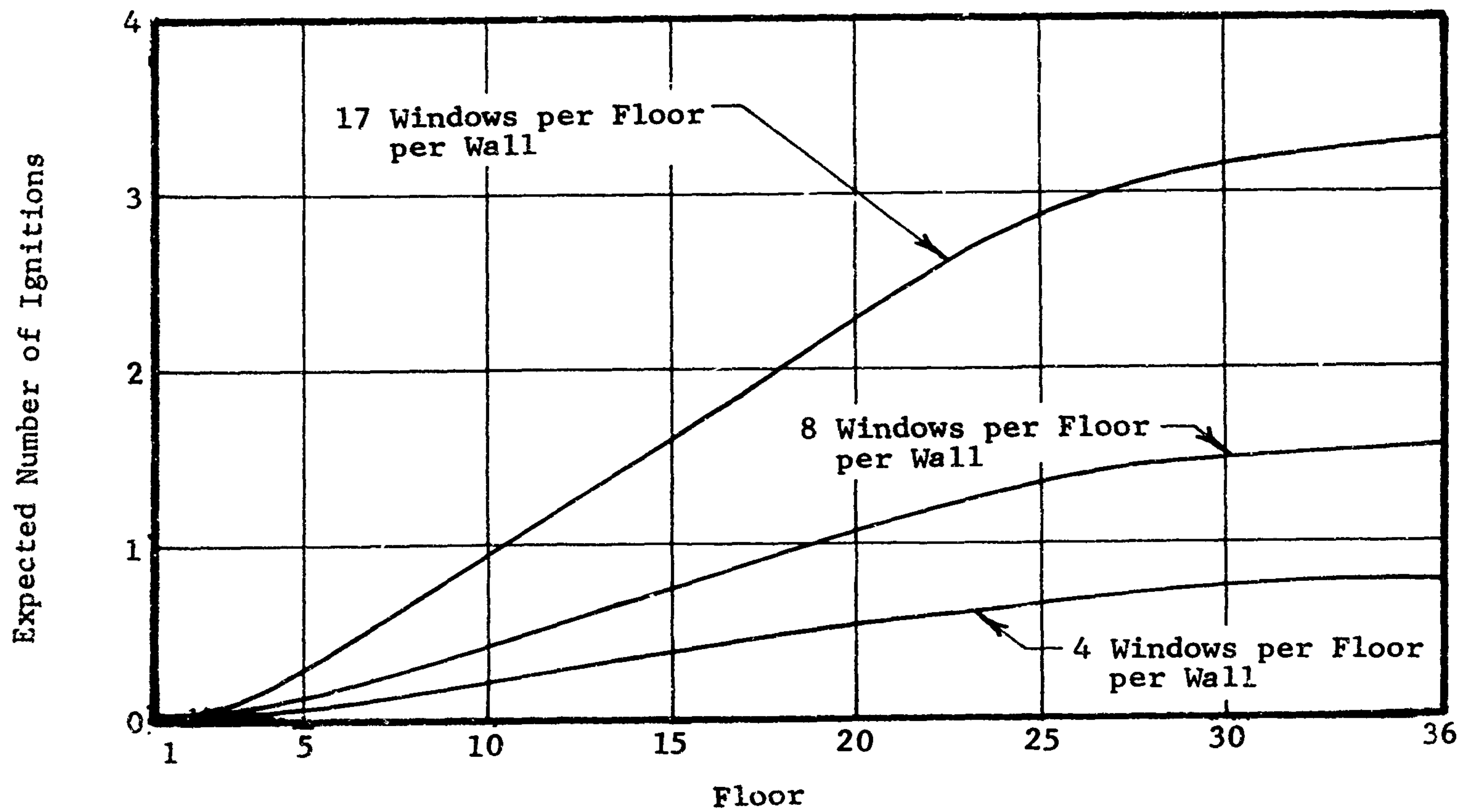

Fig. 7 ESTIMATES OF EXPECTED NUMBER OF IGNITIONS ON GIVEN FLOORS OF BUILDINGS

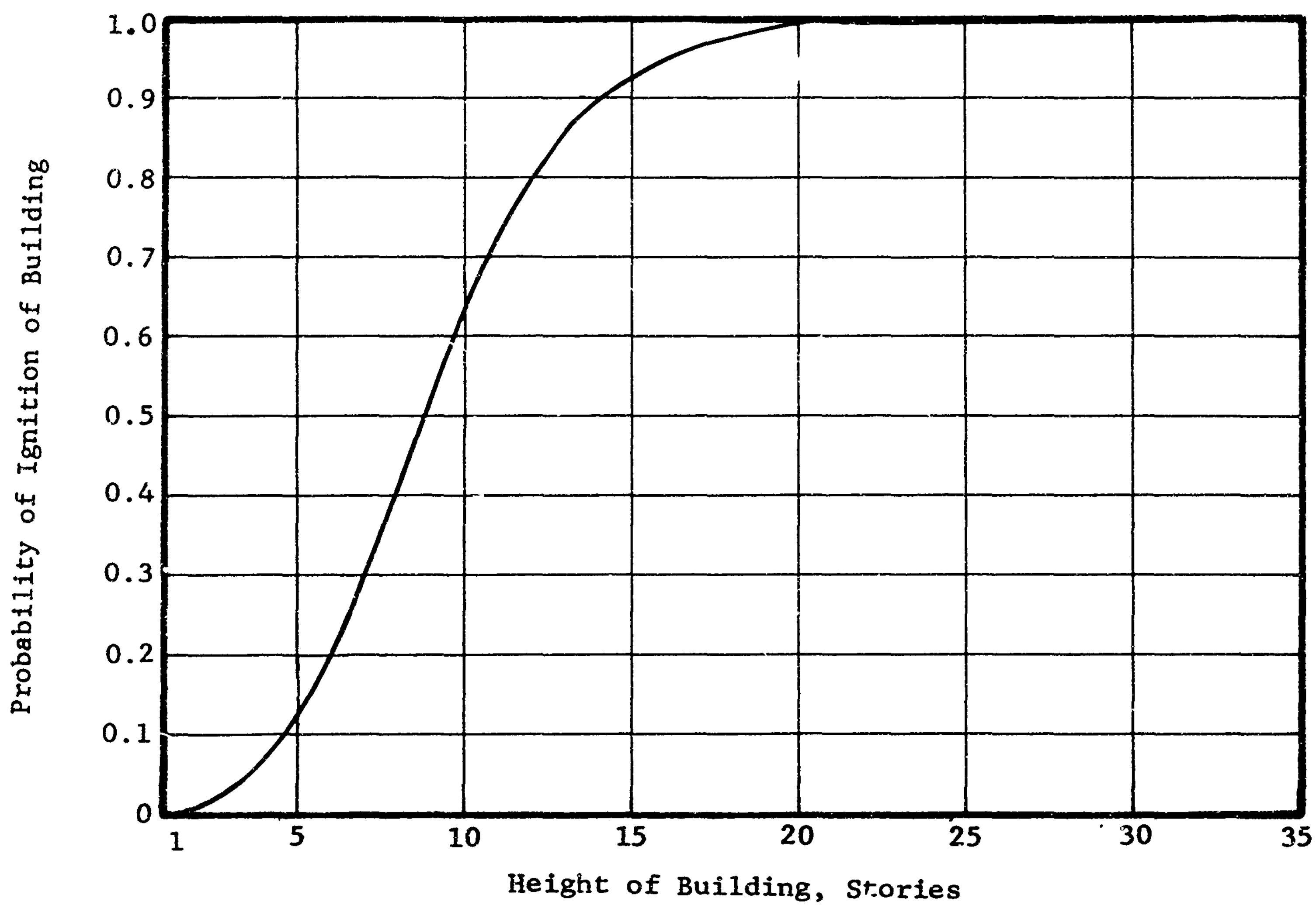

Fig. 8 ESTIMATES OF PROBABILITY OF IGNITION OF BUILDINGS OF DIFFERENT HEIGHTS

situation in the upper floors of tall buildings during the initial stages. Also there is a serious threat to the lower floors as a result of debris fires in the streets.

The very skewed nature of the ignitions is partly attributable to the closeness of the buildings and partly attributable to the nearly horizontal directions of the rays of radiation associated with the ground burst. Airbursts would produce a more uniform distribution of ignitions in the various floors. However, in all cases the pattern of increased ignitions with increased floor height will prevail, regardless of the location of the fireball.

Secondly it should be noted that the ignition probabilities are highly dependent on the number of windows. The numbers of windows associated with the three curves are typical of the numbers of windows found in small, medium and large buildings.

Figure 7 presents the expected number of ignitions per floor for buildings with fuels similar to those found in residential buildings. By adding the expected numbers of ignitions for each floor, it is found that a total of 0.9, 4.9, 11.8 and 16.5 ignitions may be expected in buildings with heights of 10, 20, 30 and 36 stories, respectively. Most modern high-rise buildings would incur less ignitions while most buildings used predominantly for merchandising would incur more ignitions.

C. Fire Spread

Evaluation of the spread of fire was made at 15 min intervals with and without appreciable debris fires in the streets. Figure 9 indicates the fraction of the various floors damaged by fire as a function of time. These results apply only to about half of the total number of buildings that will sustain and spread fire internally and only if debris fires do not ignite ground floors.

Initially, most of the fires are located on floors well above the ground level. The fact that the curves become more

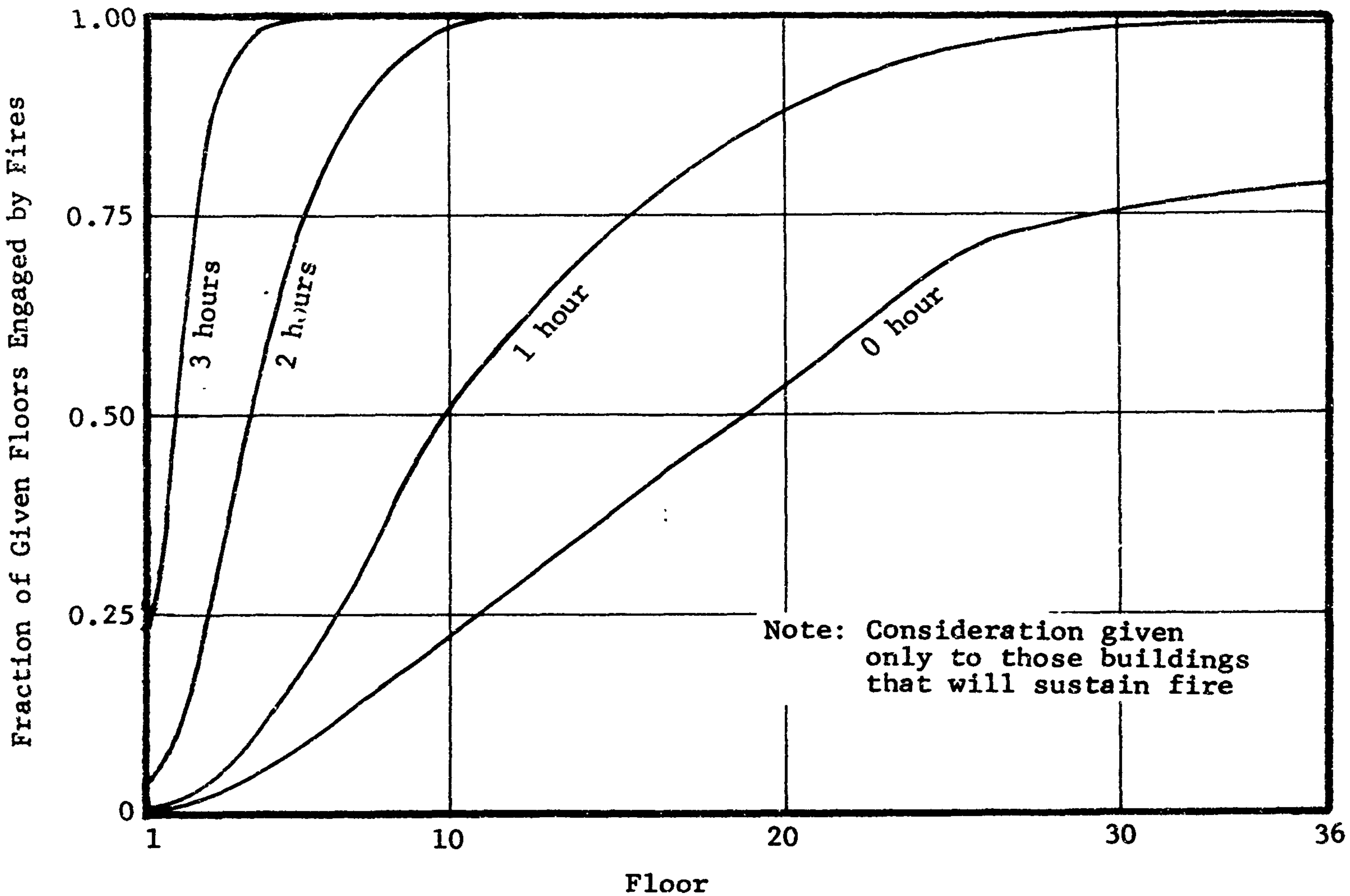

Fig. 9 ESTIMATES OF FRACTION OF FLOORS ENGAGED BY FIRE ASSUMING NEGLIGIBLE DEBRIS FIRES

upright with time is caused by the downward spread of fire within buildings either as a result of fires within the building or as a result of fires in surrounding buildings. After a few hours most of the active fire would be located on the lower floors. A more uniform pattern of fires would result either from an air-burst or if appreciable quantities of ignited fuels are blown out of buildings by the blast wave and burn in the streets.

Figure 10 illustrates the average radiant intensities in the street as a result of building fires presuming there is negligible radiation from debris fires in the streets. Irradiance levels from debris fires would be several times larger than those of Fig. 10.

For the first few hours, the peak intensities occur near the center of the streets rather than on either side. On an average, for the first few hours, the lowest intensities would be received by surfaces next to and facing the burning buildings. This is a consequence of the fact that early after the detonation most of the fires are located on floors well above the ground. Individuals at the base of buildings are shielded from fires on the upper floors while individuals in the street are not. With the passage of time, this situation changes as the fires spread to the lower floors. At times in excess of about 3 hrs, one would find the highest radiant intensities at the base of buildings. Peak intensities would occur at about 4 hrs and decrease rapidly thereafter.

Figure 11 presents the radiant intensities necessary to cause second and third degree burns as a function of exposure time (Ref. 8). Except for isolated cases, the principal threat of exposure to radiation from building fires is not burns but pain caused by exposure to at least 0.08 cal/(cm^{2}sec) for 0.5 min or more, and heat stroke which requires exposures ranging from 0.002 to 0.030 cal/(cm^{2}sec) for several minutes to an hour or more depending on the ambient temperature and on the weight and permeability of clothing. Both hazards are important -- pain

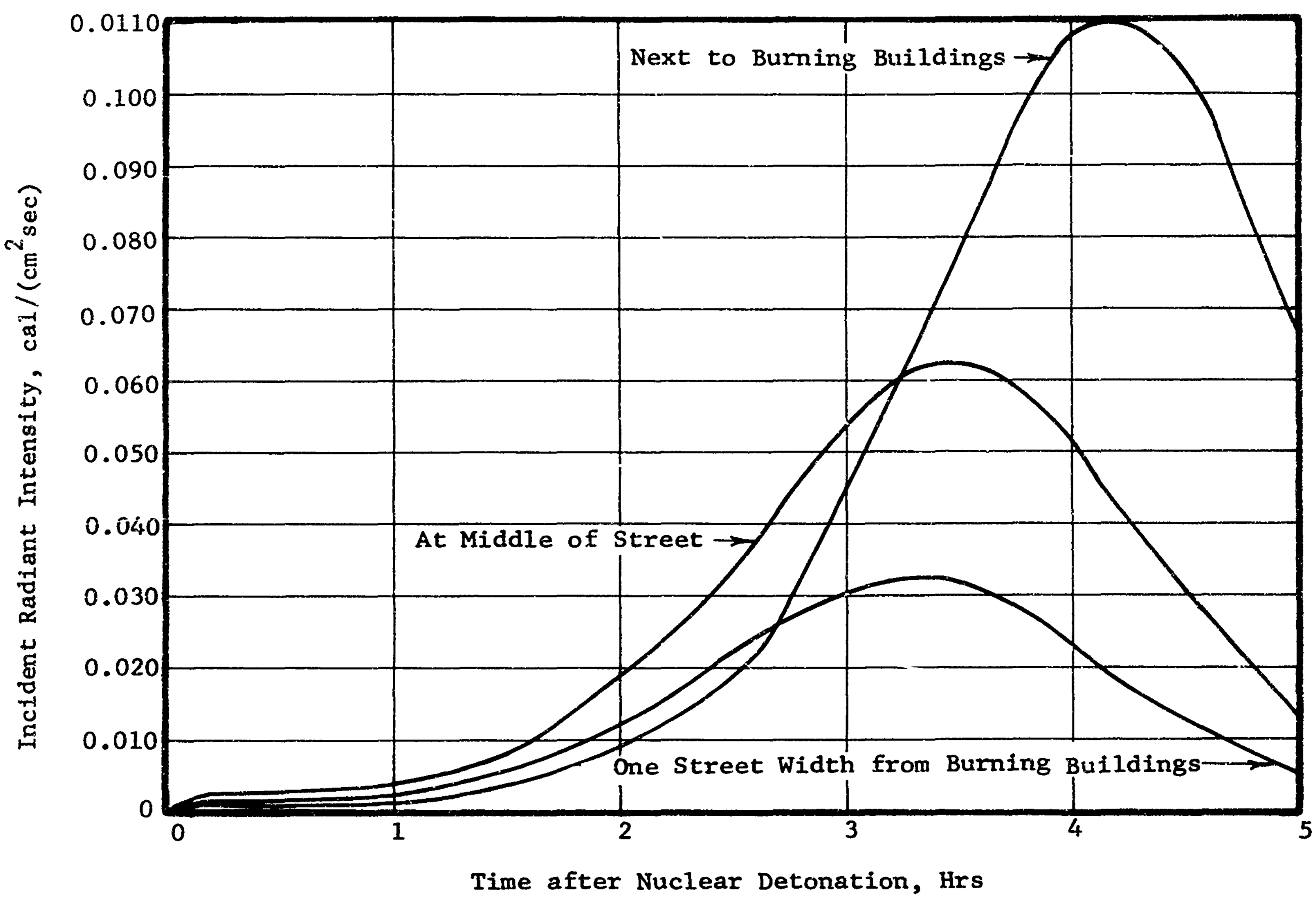

Fig. 10 ESTIMATES OF RADIANT INTENSITIES IN STREET ASSUMING NEGLIGIBLE DEBRIS FIRES IN STREET

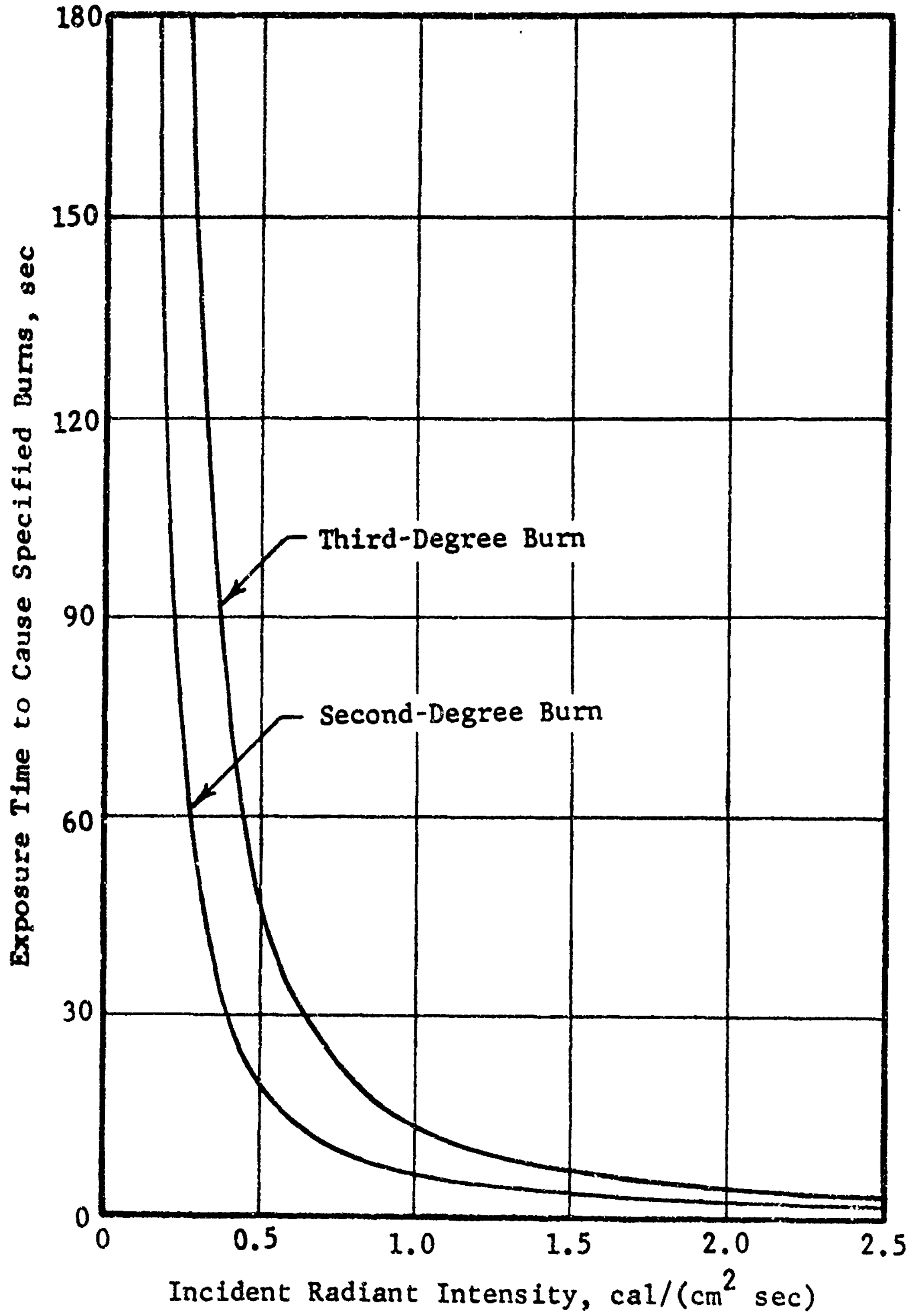

Fig. 11 RADIANT EXPOSURES TO CAUSE VARIOUS FLESH BURNS

because it will present a psychological deterent to the movement of people on the streets and heat stroke because it will probably prove fatal in a nuclear emergency.

Figure 12 illustrates the rate of heat generation from fires in the built-up area for cases in which the debris fires do and do not ignite ground floors of buildings. The first peaks are a consequence of fires on floors initially ignited by the fireball while the second peaks reflect the spread of fire mostly in the upper portions of buildings. The decrease in the rate of heat generation after a few hours is a consequence of the fact that most of the upper floors have been engaged by fire and much of the subsequent spread is downward one floor at a time. The difference in the rates of heat generation for the two cases serves to illustrate the potential hazards of debris fires in increasing the rate of heat generation as well as in eliminating streets as transportation arteries. Under conditions of very severe blast, sufficient depths of combustible and noncombustible debris may be deposited in the streets to actually reduce the availability of fuels and hence the rate of heat generation.

The radial wind velocities induced at the perimeter of the Loop for the two conditions of debris fires are presented in Fig. 13. The fact that the induced velocities are less than the computed minimum velocity of approximately 54 mph associated with fire storms in World War II (Ref. 9) suggests that the fire intensities in the Loop area would not be sufficient by itself, to produce a fire storm.

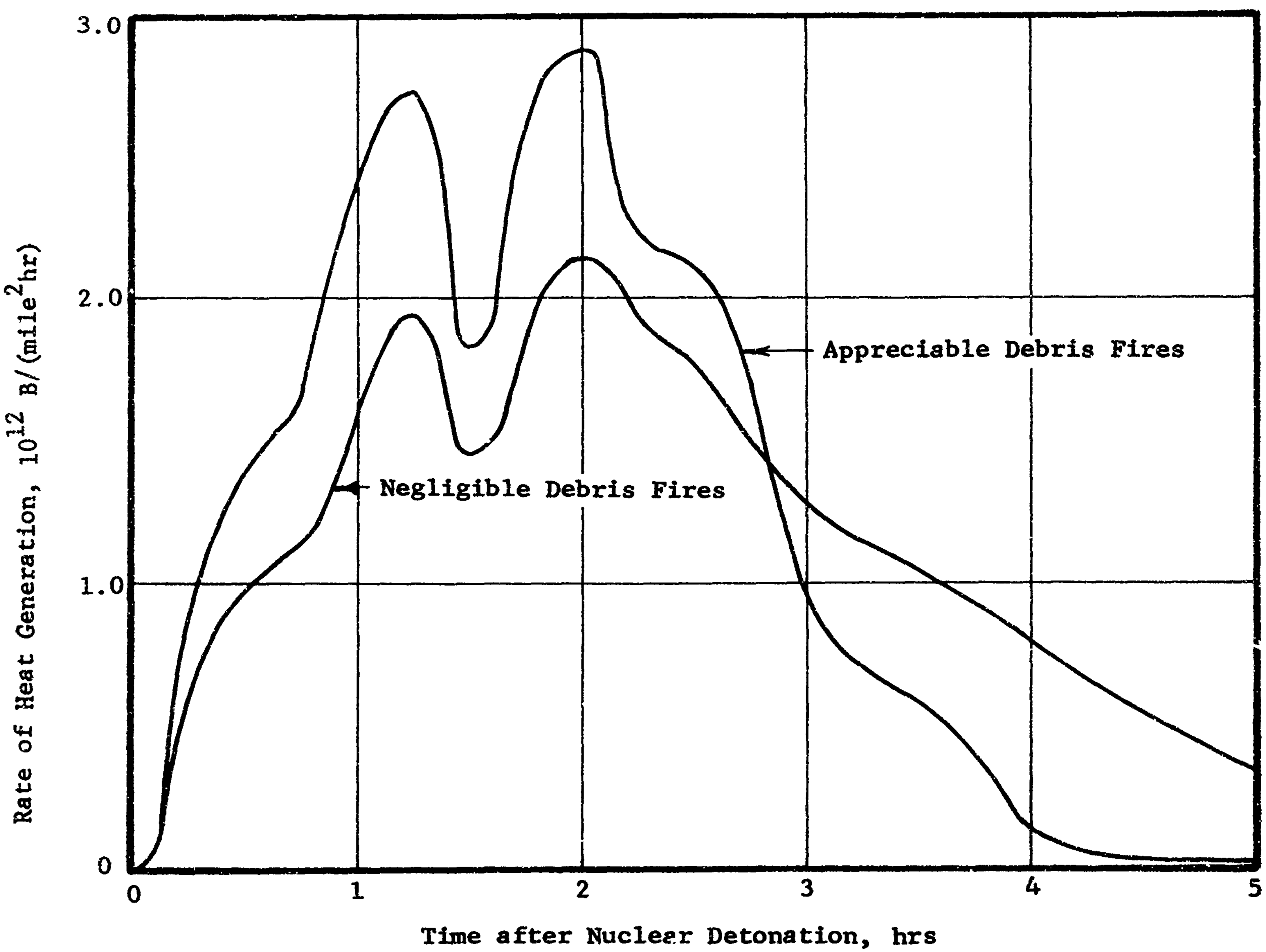

Fig. 12 ESTIMATES OF RATE OF HEAT GENERATION FROM BUILT-UP AREA

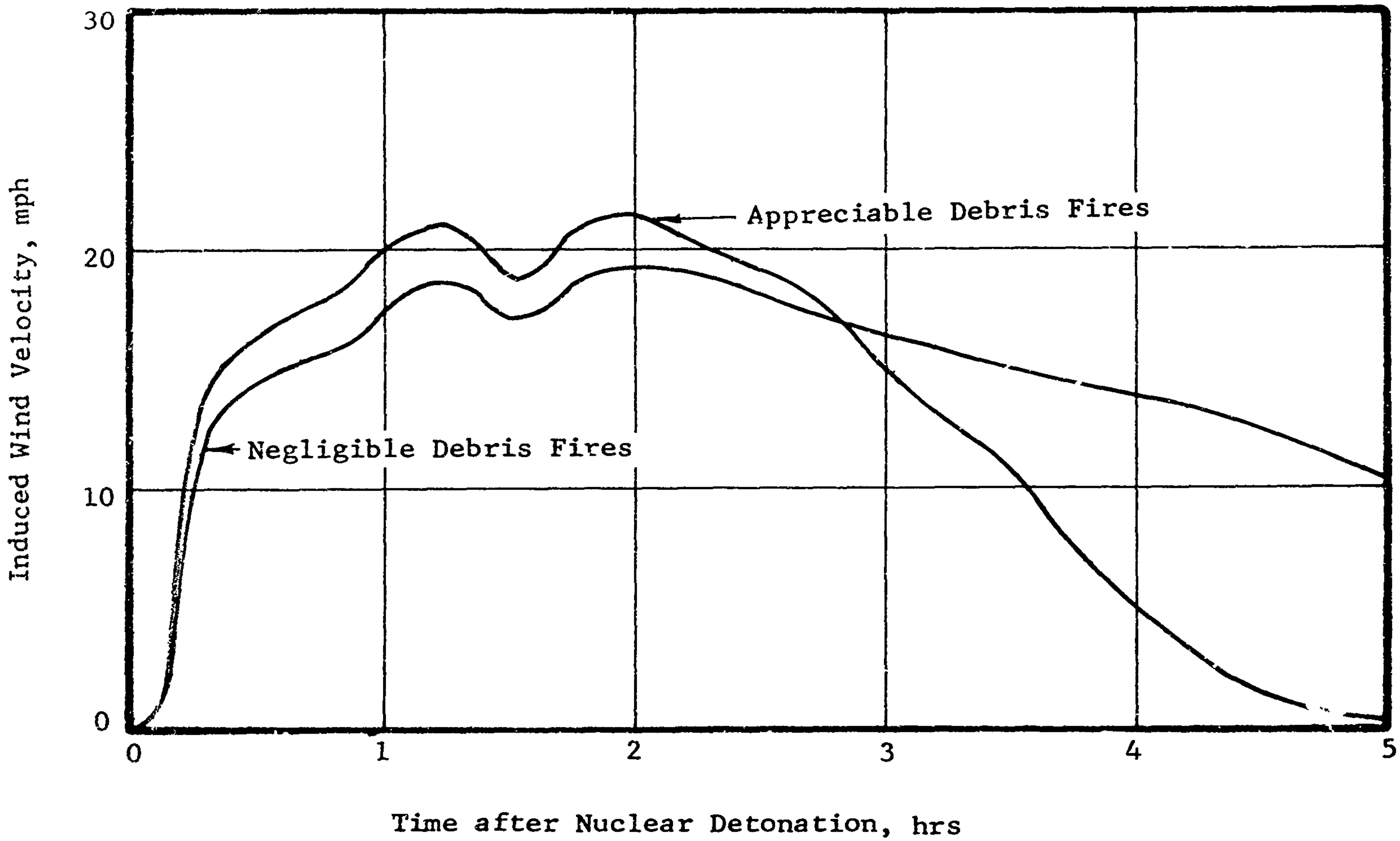

Fig. 13 ESTIMATES OF RADIALLY INDUCED WIND VEI^CITIES AT PERIPHERY OF HIGH DENSITY AREA

V. CONCLUSIONS

Aside from smoke, each of the high-rise office buildings examined in Chicago's Loop were, apart from blast effects, very hard from the standpoint of fire. In fact of all the types of buildings surveyed, modern high-rise buildings were the less susceptible to fire. The most susceptible buildings tended to be the old ones -- especially those used for merchandising. The most surprising results of the survey are the large variety of buildings in the Loop and the large variations in the content of buildings on either a room by room or floor by floor basis.

Several important quantitative results were observed in evaluating the consequences of fire in high density high-rise areas. Those having general application are:

- The importance of multiple shielding of buildings by individual buildings. Multiple shielding is particularly prevalent for low altitude detonations and is a consequence of the pronounced and varied heights of the buildings as well as the relatively short distances between buildings.
- The high concentration of ignitions in the upper floors. In the upper floors, the number of ignitions ranged from one to three ignitions per floor depending on the fuels and number and sizes of windows. In the lower floors, the number of ignitions was less than one per floor. Very few ignitions were effected on the ground floor.
- The relatively high radiant intensities near the center of the street for the first few hours. Because initially there are only a few fires in the lower floors, the radiant intensities from fires within buildings are lower close to the buildings during the first hour or two. Subsequently, the radiation emitted by building fires is less intense at the center of the streets.
- The effects of blast. Blast may appreciably alter the availability and location of fuels, and the consequence of fire on personnel in shelters or in the streets. In situations of moderate to severe blast damage, vehicular travel in high density areas will be blocked by large quantities of debris and any appreciable debris fires could make the streets impassable to rescue teams and fire fighters for many hours. Ordinary fire protection suits would be effective only in situations requiring limited exposures.

More specific results estimated as a consequence of the given attack are:

- Power density (rate of heat generation per unit built-up area) reaches its peak intensities for the surface burst considered between 1 and 2 hours after the nuclear detonation. The peak will occur somewhat later for bursts that cause less ignitions and slightly sooner for bursts that cause more ignitions.

- Radial wind velocities induced at the perimeter of the high density area will be approximately 20 mph. According to the studies of Lommasson (Ref. 9), this velocity is not sufficient to produce what is commonly referred to as a fire storm. However, such winds will very appreciably change the rate and extent of fire spread both within and at the boundaries of the area.

- Less than one out of ten of the ground floors of the buildings will burn during the first hour following the nuclear detonation provided there are little or no debris fires in the streets. This is a result of shielding by tall buildings and of the slow rates of fire spread downward from the upper floors. Intense debris fires in the streets, however, could drastically alter this situation.

- Personnel in the streets will not be seriously threatened by thermal radiation from building fires for the first few hours following the nuclear detonation provided there is insignificant debris fire in the streets. Burning debris in the streets could make the streets untenable. With time, heat stroke will become increasingly serious for personnel that are in the streets for periods in excess of 0.5 hour. Heat stroke would most likely be fatal in a nuclear emergency (Ref. 1).

VI. FUTURE STUDIES

Two important results have been achieved in developing a computer code to evaluate the consequences of fire in a high density high-rise area. The first is an overall appreciation of the effects of fire in such areas, and the second is an indication of major deficiencies in the predictions either in the input data or in phenomenology. While most areas of inadequacy are well known to OCD, a review is worthwhile.

- Blast-fire Interaction

Here, data are needed to describe the effect of blast on the initial fires; the consequences of blast damage on rates of fire spread; the effects of blast on the location and availability of fuels; and the possibilities of intense debris fires in the streets. Furthermore, there are no significant velocity data associated with movement of individuals or vehicles through realistic kinds and quantities of debris. This makes it difficult to make realistic evaluations of the possibilities of rescue, evacuation and firefighting.

- Effect of Induced Winds

Induced winds, while known to be important in spreading fire between buildings, have not been related to fire spread. While this is understandable because of the complex nature of the problem, the fact that it has been omitted raises a serious question as to the accuracy of predicted fire environments. Errors caused by the omission of the effects of induced wind will minimize the fire threat within the initial fire area and overestimate the fire threat within outlying areas. Furthermore, unless one has a detailed knowledge of the induced winds, one cannot accurately predict the temperatures of the air in the streets or the thermal threat to shelter occupants and to individuals in the streets.

- Fire Spread within Buildings

Here data are needed to describe fire spread not only across floors but more importantly between floors. The importance of spread between windows or other wall openings created by blast deserves particular attention.

Each set of data must be developed for various representative buildings within the major use class areas of a city. The most obvious need is data for business and shopping areas. Two steps must be taken to acquire the desired information. These are a specification of major categories of buildings with which to describe the variety of buildings in the area, and determinations of the rates of internal fire spread within buildings of each category. Both tasks are interrelated. The first requires an overall survey of typical shopping and business districts to describe the buildings in terms of the designated categories, and detailed surveys of the interiors of typical buildings within each category. The second requires a combination of analytical and experimental work utilizing data and information from the surveys.

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FIRE SPREAD IN HIGH DENSITY HIGH-RISE BUILDINGS (Unclassified)

Final Report 44 pages

Contract No. DAHC-20-70-C-0286 IIT Research Institute
OCD Work Unit 2538F February 1971

ABSTRACT

This program has the objective of developing a computer routine to determine the initiation and spread of fire in high density high-rise areas following a nuclear detonation, and its effects on the street environment. The result of this endeavor is a computer code that evaluates the probable number and floor locations of fires, the rate of heat generation from built-up areas, the radiant intensities in the streets, and the induced winds as functions of time.

Provisions were made to keep the code sufficiently flexible to allow for improved data and information as they become available. Also, provisions were made to simplify the problem of incorporating the routine in a more general code for an entire urban area. Preliminary calculations were conducted to gain an appreciation of how the fires develop in time, the threats to personnel in the streets and the possibility of a fire storm.

Additional key words: high-rise buildings; mass fire; urban fires.

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2. Fire Storm						
3. High-Rise Buildings						
4. Mass Fire						
5. Urban Fires						

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