EXPLORATORY ANALYSIS OF FIRE STORMS

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EXPLORATORY ANALYSIS OF FIRE STORMS

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ABSTRACT

This study is an evaluative review of existing knowledge and opinion relating to fire storm phenomenology. It develops interim critical values of fire storm parameters that may be used in target analyses to establish conditions for possible occurrence of fire storms. The basic factors in initiation and development of fire storms are identified and are organized into a format to serve as the framework for a fire storm model. The casualties resulting from fire storms are discussed, and a possible method for predicting fire entrapment areas is presented. It is concluded in the investigation that major parameters and constraints affecting the initiation and development of fire storms include fuel loading, initial fire density, size of the initial fire area, surface wind, and topography and configuration. Factors which in general appear to determine the extent and nature of fire storms, as opposed to their possible existence, include combustibility, fire intensity buildup rate, atmospheric stability, temperature, humidity, and precipitation. Recommendations are given for further investigations to improve the state of knowledge in those areas where valid information is lacking.

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I INTRODUCTION

One of the possible hazards that might result from nuclear attacks on U.S. urban areas is the occurrence of fire storms. The great destructive powers of such storms with the concurrent high fatality rates were amply demonstrated during World War II. Thus the ability to establish a set of values for use in determining the probability of occurrence of a fire storm in any urban area and in understanding the environmental characteristics of such fires becomes highly important. The fire storm created by a 20 kt weapon at Hiroshima burned out an area of over four square miles, and 68,000 of Hiroshima's 75,000 buildings were destroyed or damaged.(47) The severely burned out area from the Hamburg fire storm was about the same size as that at Hiroshima; some 40,000-50,000 people were killed by effects of the fire alone.(52) These statistics, as well as others from World War II fire storm areas, are impressive with respect to the killing potential of fire storms.

A heading in one recent report concerned with effects of nuclear detonations reads, "Megatons Mean Fire Storms," and the report predicts that a 20-megaton nuclear burst is sure to produce a 300-square mile fire storm.(35) The report further states that blastproof bomb shelters afforded no protection in World War II fire storms, and the reader is left to conclude that vast fire storm areas in which there will be no survivors are an assured consequence of future nuclear attacks. Impressions such as these are not in accord with the facts, and their acceptance would lead to unsound civil defense planning.

It is difficult to specify directly the significance of the statistics and predictions presented above, and to evaluate objectively the relative importance of fires and fire casualties that might occur as a consequence of nuclear attack. For example, the 40,000-50,000 persons killed by the fire storm at Hamburg constituted only 14 to 18 percent of the people in the fire storm area and 3 to 4 percent of Hamburg's total population at the time of the attack. It is significant also that the heavy loss of life and property resulting from the 27-28 July 1943 Hamburg fire storm raid, as well as other severe raids that Hamburg suffered about the same time, did not disrupt industry to the extent that one might expect. In fact, industrial production in Hamburg recovered to the point where it had attained slightly more than 82 percent of normal capacity during the last four months of that year.(46) It is important also to realize that the probability of fire storm occurrence is limited by the many unique physical conditions of the target and weather that must be present to produce a fire storm. It may readily be shown that the optimum combination of the many conditions necessary to initiate such a storm will be encountered infrequently.

Accordingly, the purpose of this analysis is to make a comprehensive evaluative review of existing knowledge and opinion relating to fire storm phenomenology, and to develop interim criteria for predicting the occurrence of fire storms. Validity of the critical parameters selected are estimated by an analysis of the supporting data and value ranges of contributing factors. The study makes recommendations for further investigation to improve the state of knowledge in those areas where information is uncertain or lacking. Emphasis has been placed upon urban, as compared to wildlands, areas.

We are grateful to Elmer Robinson and Francis L. Ludwig, meteorologists of Stanford Research Institute, for valuable assistance in the preparation of this report. Mr. Robinson and Mr. Ludwig have critically reviewed the report in its entirety and have made major contributions in the sections dealing with possible meteorological effects on fire storms.

The work on this project was done under the general guidance of Dr. Carl F. Miller, Director, Operations Evaluation Programs.

II SUMMARY AND CONCLUSIONS

The present study is an evaluative review of existing knowledge and opinion relating to fire storm phenomenology. It develops interim critical values of fire storm parameters that may be used in target analyses to establish conditions for probable or possible occurrence of fire storms. Recommendations are included also for further investigation to improve the state of knowledge in those areas where valid information is lacking.

The definitions of a fire storm commonly found in the literature are accepted for purposes of this investigation, but the absence of a precise generally accepted description of fire storm conditions makes it difficult to analyze the existing data on fires reported to be fire storms. For example, there is disagreement even among fire experts regarding which cities actually sustained fire storms in World War II. It is clear from this lack of agreement among the experts and from the various descriptions of fire storm conditions in the published literature that there are many concepts as to what critical values of the various fire parameters represent the necessary conditions for a mass fire to be classed as a fire storm.

The basic factors in the initiation and development of fire storms are identified and described. The report presents a pictorial concept of the important stages in fire storm development, showing possible idealized conditions that might exist at four selected times during the evolution of a fire storm. Also given, as a function of time, are curves representing the rates at which thermal energy might be released into the atmosphere by the fires. The basic factors in the chronologic evolution of a fire storm are: (1) the time-space distribution of initial fires resulting from primary and secondary fires, (2) the rate at which thermal energy is being released into the atmosphere, (3) the influence of atmospheric conditions, and (4) the general pattern of air circulation.

The characteristics of fire storms and the basic factors in their development are organized into a format to serve as the framework for a fire storm model. The development of a fire storm model is divided into three stages: (1) the "definition" stage, in which a fire storm is defined and the boundary conditions for the existence of fire storm conditions are established; (2) the "parametrization" stage, in which these boundary conditions are specified in terms of estimable parameters and methods for estimating these parameters are developed; and (3) the "implementation" stage, in which physical or analytical models are developed to simulate interactions of processes that produce and maintain fire storms.

The basic factors relating to initiation and development of fire storms are examined in detail. The incompleteness or, in many cases, the total absence of information and data adequate for a thorough analysis of these factors indicates the need for much further study. On the basis of currently available information, it is concluded that major parameters and constraints affecting the initiation and development of fire storms include fuel loading, initial fire density, size of the initial fire area, surface wind, and topography and configuration. It is considered that these factors are probably the ones that determine whether fire storms are possible in given circumstances. Factors that in general appear to determine the extent and nature of fire storms, as opposed to their possible existence, include combustibility, fire intensity buildup rate, atmospheric stability, temperature, humidity, and precipitation.

Interim criteria for predicting the possible occurrence of fire storms are selected and discussed in detail in the report. These criteria are:

Fuel loading	≥ 8 pounds of combustibles per square foot of fire area
Fire density	$> 50\%$ of structures in fire storm area on fire simultaneously (for practical purposes, initial fire density)
Surface wind	< 8 miles per hour at time of attack
Fire storm area	> 0.5 square miles
Unstable atmosphere	+
Stable atmosphere	-

Except for the atmospheric stability factor, it is considered that all of the conditions shown must be approximately met. Fuel loadings in the severe fires, including fire storms of World War II, have in general been reported in terms of building density only, and to a first approximation, fuel loading may be estimated by building density; but fuel loading is dependent also on building heights, contents, and construction materials. Hence it was decided to use fuel loading rather than building density in this investigation. The fuel loading criterion given above is based largely on analysis of severe fires of World War II.

Two of three buildings in a 4.5 square mile area were burning 20 minutes after the incendiary attack began at Hamburg, and similar figures were reported for other German fire storm cities. From this and other information presented in this investigation, it seems reasonable to accept as an interim criterion for predicting the possible occurrence of fire storms a figure of approximately 50 percent of the buildings simultaneously on fire and burning rapidly.

A strong surface wind in the very early stages of a severe mass fire will cause the fire to spread and thus to become a conflagration rather than a fire storm. On the basis of available evidence the surface winds were light just prior to the fire storms of World War II. Accordingly, it is suggested that an 8-mile-per-hour ground wind (on generally level terrain) be accepted as an interim limiting criterion for development of fire storms.

The smallest generally accepted World War II fire storm area was the 1.5 square mile area of Darmstadt. Recent investigations in Germany, however, suggest that fire storms may be possible in areas as small as 1 square kilometer. A minimum fire area of 0.5 square miles is therefore proposed as an interim criterion.

It is concluded on the basis of currently available evidence that atmopsheric stability is an important but not necessarily limiting factor in the initiation and development of fire storms. As an interim criterion for fire storm formation, therefore, it is recommended only that an unstable atmosphere be considered as favorable to fire storm development.

The parameters and critical values selected must be looked upon only as "best possible" values at this time, and should be revised as new and better information becomes available.

The fire storm parameters investigated in the study are considered with respect to their importance in the estimating of fire casualties. It is shown that final estimates for fire storm fatalities are within a factor of 2 of each other, ranging from about 10 to somewhat over 20 percent of the unprotected population at risk. The concept of areas of "entrapment" from mass fires, or areas where mass fires are sufficiently widespread and intense to prevent movement of unprotected population to areas of refuge, is introduced. The study presents a possible method for predicting fire entrapment areas based on a determination of those areas in which the clothing of people attempting to escape through the streets would be ignited in a short time, assuming that most of the structures in the area are on fire.

For an understanding of fire storm behavior adequate for predicting within a specified degree of accuracy the probable occurrence of fire storms in urban areas of the United States subjected to nuclear attack, much additional research, analysis, and experimentation will be required. Because of the high casualty rate of unprotected humans in urban areas and the extensive destruction of property accompanying fire storms, the subject deserves continued attention for the purpose of diminishing the effects of such fires on persons and property. Further investigation should be made also on other types of fires, such as conflagrations.

Many aspects of the enormous release of thermal energy associated with fire storms are inadequately understood. It is clear that a tremendous amount of energy must be released within a short time, but the mechanisms and constraints controlling the factors involved require further study. Because certain atmospheric conditions may be highly important to the initiation and development of fire storms, further research on these conditions appears to be warranted. Future studies may show that selected atmospheric conditions affect the development of fire storms in marginal situations but become less important when an overwhelming thermal energy release rate is present.

III DEFINITION OF A FIRE STORM

Mass urban fires, in most technical reports, are usually classed as one of two types of fires: (1) fire storms, or (2) conflagrations. Differentiation is generally made between the two by defining the fire storm as a mass fire that does not spread (very much) from the general area that is ignited, and the conflagration as a mass fire that has a moving front and spreads mainly in one direction with the prevailing surface winds. This distinction has not always been made, however, in pseudotechnical reports and in newsprint. Any spectacular fire is frequently given the name fire storm, and this common usage of the term may in time force the introduction of a new technical term.

The distinction between conflagrations and fire storms on the basis of fire spread has arisen, somewhat naturally, because fires classified as fire storms have not occurred very frequently, and then only under special or restricted conditions. This has led to the practice of defining a fire storm in terms of the special conditions under which it seems to occur, as well as in terms of other observable associated phenomena. For example, the following have been used as fire storm definitions:

> "FIRE STORM: Stationary mass fire, generally in built-up urban areas, generating strong, inrushing winds from all sides; the winds keep the fires from spreading while adding fresh oxygen to increase their intensity."(21)

> "A fire storm is an area fire in which essentially all the fuel over the fire area is simultaneously ignited and simultaneously burns, producing a thermal convection column so strong that it completely dominates all normally important atmospheric factors. The very strong inflow of air at the periphery prevents any significant outward fire spread."(31)

> "A mass fire with stationary front. Strong inward winds are caused by rising columns of hot gases, and the spread of the fire is largely limited to the initial ignited area. Within the fire perimeter virtually complete destruction will occur."(38)

While they are accepted in general for the purposes of this investigation, definitions such as those given above are not precise definitions, and they make it difficult to analyze the existing data on fires reported to be fire storms. For example, there is disagreement regarding which cities actually sustained fire storms in World War II. The only cities generally agreed upon as fire storm cities are those of Hamburg, Dresden, and Hiroshima, and even the designation of these cities as fire storm cities may be disputed by some fire experts. Other cities which may have sustained fire storms but about which there is no general agreement include Kassel, Darmstadt, Cologne, Wuppertal, Pforzheim, Berlin, Lubeck, Bremen, Wurzburg, Mannheim, and others.(30)

In civil defense planning, the distinction between classes of mass fires might be made on the basis of the casualties to be expected in the different mass fires. From this standpoint, differences in the movements of fire fronts represent only one factor that would affect the number of casualties. However, the influence of fire spread on the number of casualties produced and its effect on the choice of countermeasures make it an important factor; so the customary separation of mass fires into fire storms and conflagrations on the basis of fire spread will be maintained in the present analysis.

If a fire storm is taken to be a mass fire that does not spread significantly into adjacent areas (even though these adjacent areas contain sufficient fuel to support a mass fire), it would appear that a primary consideration for identifying a fire storm is the implied assumption that the velocity of the induced winds prevents the fire from spreading to adjacent areas.

Of the three methods by which fire spreads across open spaces--convection, radiation, and flying brands--the direction and speed of the air flow have a direct effect on two of them: convection and flying brands. Fire spread outside the initial fire storm area by means of fire brands is greatly inhibited by the inrushing winds. Moreover, the spread of the fire by radiative means can be inhibited if the exposed surfaces are cooled by high velocity winds. Consequently, it appears that high velocity winds blowing into the fire area are a primary method of preventing significant fire spread outside the initial fire area. There remains the problem of specifying the characteristic parameters of an urban area and of a fire in that area, as well as the critical values of these parameters which, when taken together, will produce the induced winds necessary to prevent the spread of the fire.

If the minimum speed of the induced winds permits definition of the borderline conditions for the occurrence of a fire storm, some degree of freedom is possible for other "critical" parameters, and it is also possible to consider a variety of conditions under which a fire storm occurs. It is appropriate to emphasize the existence of variability among such fires, since no two fires will ever be the same in all details.

Although fire storms may be defined in terms of the limitations on fire spread, the importance of the storms lies in the high casualty rate among improperly protected people who cannot escape the affected area.

The critical levels for survival are surpassed in a relatively short time in a fire storm over areas sufficiently large that escape beyond the fire area rapidly becomes impossible. Factors that appear to be closely associated with the high casualty rates are the effects of heat absorption, the temperature of the air in contact with persons (i.e. the surface body temperature), and the carbon monoxide content of the air. Mass fires may be categorized by the rates at which the effect of these factors increases.

This investigation will consider a fire storm as a unique entity and concern itself primarily with the processes that bring it into existence. However, strictly speaking, it may in many cases be better to refer to the fire storm phase of a mass fire rather than to a fire storm per se. It is conceivable that a fire storm may be changed into a conflagration as a result of disturbances from outside the fire storm system, or from a reduction in the convection column and induced winds as the fuel supply is diminished.

IV BASIC FACTORS IN FIRE STORM DEVELOPMENT

The fire storm characteristics that have been listed in the preceding section describe conditions that exist during and after a fire storm occurrence, but they need not be characteristic of the early stages in the development of a fire storm. For example, the strong thermal convection column and high velocity surface winds are probably not present at first, but result from a sequence of events such as those described in the following (imaginary) version of fire storm evolution in an urban area.

As a result of a nuclear detonation over an urban area, primary and secondary fires will be started. The materials initially ignited will, in general, be thin combustibles in or near structures. From some of these initial ignition points the fires will spread to other combustibles and will eventually involve the entire structure in (or near) which the fire started. Once the initial structures are ablaze, a critical stage in the fire storm development is begun. As a structure burns, a column of heated gases rises, and air flow in the vicinity of the fire is increased. Radiation, heated gases, and flying brands from the flaming structures cause nearby structures to be ignited. As more and more structures are ignited, the burning rates of the individual fires are increased if the amount and arrangement of fuel is appropriate and the available oxygen is sufficient. Then, the induced air flow increases and the plumes from the fires of individual structures join and produce still larger plumes of flaming gases. Finally, a strong convection column is established, high velocity surface winds are induced, fire spread outside the fire area is restricted, most of the combustibles in the fire area are afire or burned out, and a fire storm exists.

As a pictorial presentation of the important stages in fire storm development, Figures 1 through 4 represent the idealized conditions that might exist at four selected times during the evolution of the fire storm. (No attempt has been made to present realistic numbers or locations of fires.) The basic factors affecting the conditions existing at that time are listed, and a brief statement of events that may have occurred is given.

The curves shown in Figures 2 through 4 are representative of the rates at which thermal energy might be released by the fires, into the atmosphere, as a function of time. (This is a measure of the thermal energy outside the structure, that is, the thermal energy that will affect nearby structures and the flow of air in the vicinity.) The vertical line in each graph is drawn at the time origin t = 0. The sum of all the individual functions is shown as the total rate of thermal energy release H(t).

It is impossible to depict accurately the complex air flow in the vicinity of the fires because, to a large extent, the local air flow near the earth's surface will be determined by physical features of the terrain and the configuration of the structures and streets as well as by the fires. However, an attempt has been made to illustrate the flow of air above these disturbances by showing horizontal wind streamlines.

The brief description and accompanying illustrations of fire storm development emphasize what appear to be basic factors in the chronologic evolution of a fire storm: (1) the time-space distribution of initial fires resulting from the primary and secondary fires, (2) the rate at which thermal energy is being released into the atmosphere, (3) the influence of atmospheric conditions, and (4) the general pattern of air circulation. Item (4) includes the flow of air that results from the thermal energy release and atmospheric conditions; and the interactions and feedback processes that relate the air flow to other basic factors. Because of these feedback processes, the air flow is not only the result of other basic factors, but is, in itself, a basic factor in fire storm evolution.

The factors governing the time-space distribution of initial fires are discussed in Section VI under the heading of Ignition Processes. In the remainder of this section we shall discuss the other basic factors in fire storm development.

Rate of Thermal Energy Release

The rate at which thermal energy is being released at some time, t, depends on the number of heat sources (usually burning structures and their contents) and the thermal energy being released by each source at that moment. Since we are primarily interested in the occurrence of fire storms in urban areas, it is assumed that the influence of fuels other than structures and their contents can be incorporated by making appropriate modifications of parameters related to structures. Then, if the number and location of initial fires are known, the number and

FIGURE 1

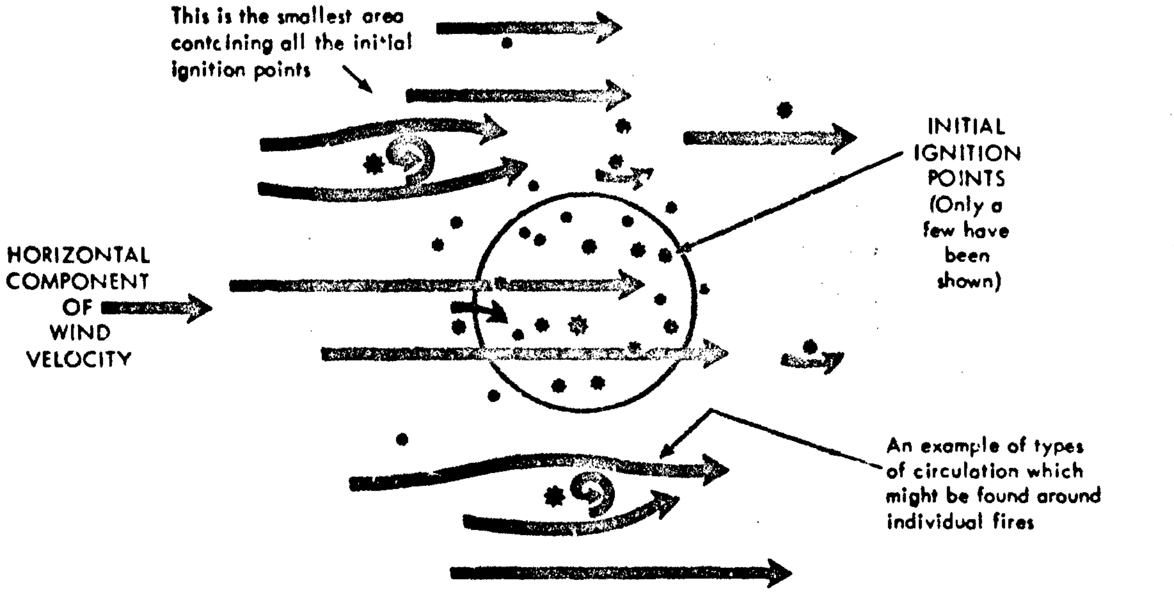
IGNITION PERIOD

Time

t = 0, shortly after detonation
of weapon

Contributing Factors

Weapon yield and burst point
Atmospheric conditions
Topography
Building configuration
Exposure and critical ignition energy of materials



This is the smallest area containing all the initial ignition points

INITIAL IGNITION POINTS (Only a few have been shown)

An example of types of circulation which might be found around individual fires

Events

THERMAL RADIATION IGNITES, OR CHARS, FUELS WITHIN RANGE;
SECONDARY IGNITIONS ARE CAUSED BY BLAST AND RELATED EFFECTS

COMMENTS:

1. Wind fields reflect effects of fire distribution and obstacles and may have very little organized pattern outside that imposed by the prevailing flow.
2. The fuel in the inner circle will be exposed to high thermal intensity and direct effects of the blast. The combined influence of these factors is not known at this time, and for large yield weapons the fire development (ignition and spread) within this area can only be surmised.

SOURCE: Stanford Research Institute.

FIGURE 2

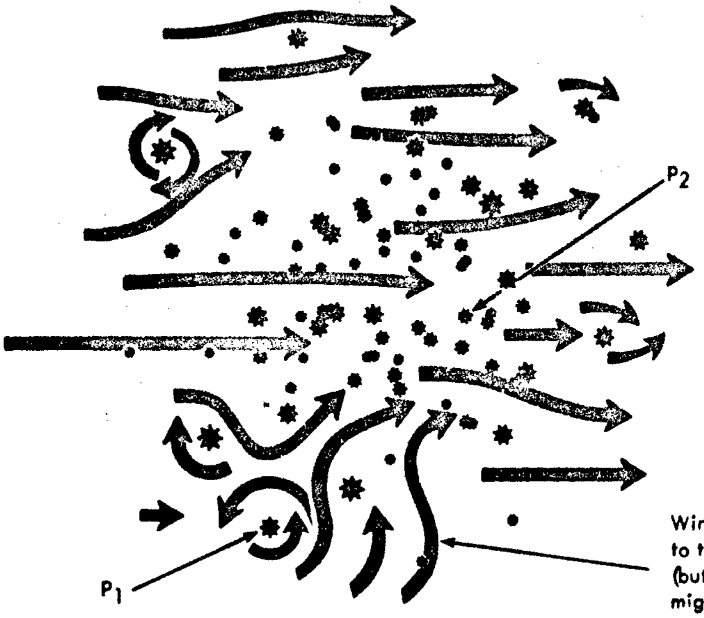
FIRE DEVELOPMENT PERIOD

Time

The period in which fires are spreading from initially ignited materials in and near structures, say $t = t_1$

Contributing Factors

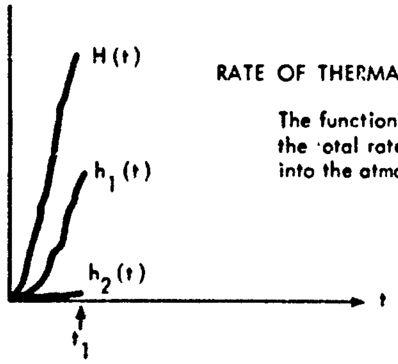
Number and location of ignition points in and near structures
Combustibility of structure and contents
Location of combustibles
Arrangement of compartments within structures



Wind circulations similar to that shown in Figure 1 (but somewhat larger) might be found in area during this stage

Events

FIRES SPREAD FROM INITIAL IGNITION POINTS TO NEARBY COMBUSTIBLES, EVENTUALLY RESULTING IN FLAMING STRUCTURES



RATE OF THERMAL ENERGY RELEASED INTO THE ATMOSPHERE

The function $h_i(t)$ represents fire at point p_i, and $H(t)$ the total rate of thermal energy released over fire area into the atmosphere.

SOURCE: Stanford Research Institute.

FIGURE 3

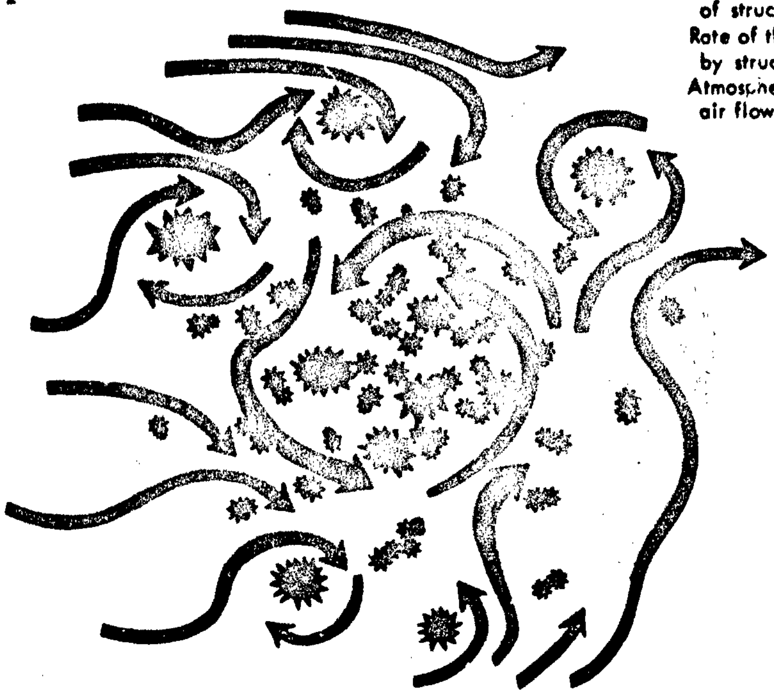
FIRE SPREAD PERIOD

Time

The period in which fires are spreading from initially ignited structures to nearby structures, say $t = t_2$

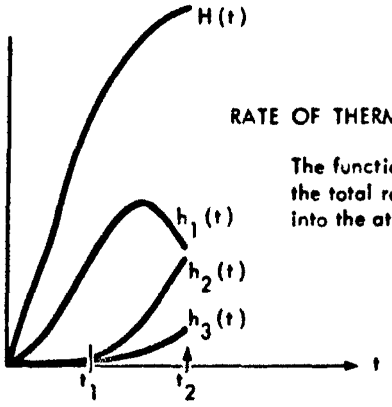
Contributing Factors

Number and location of initial fires
Relative locations of structures
Ignitability and combustibility of structures
Rate of thermal energy released by structures
Atmospheric conditions and air flow



Events

INITIALLY IGNITED STRUCTURES IGNITE OTHER STRUCTURES; AIR FLOW TENDS TO BE INCREASINGLY DOMINATED BY THE FIRES IN THE AREA; CONVECTION COLUMNS FORM OVER INDIVIDUAL FIRES AND TEND TO COALESCE OVER ADJACENT FIRES



RATE OF THERMAL ENERGY RELEASED INTO THE ATMOSPHERE

The function $h_i(t)$ represents fire at point p_i, and $H(t)$ the total rate of thermal energy released over fire area into the atmosphere.

SOURCE: Stanford Research Institute.

FIGURE 4

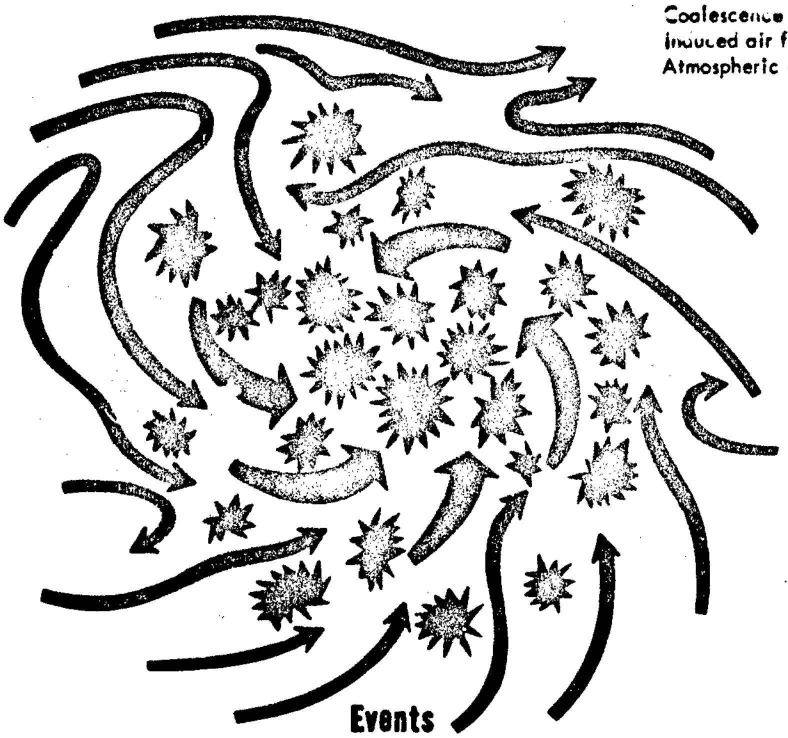
FIRE STORM PERIOD

Time

Near the onset of fire storm conditions, say $t = t_3$

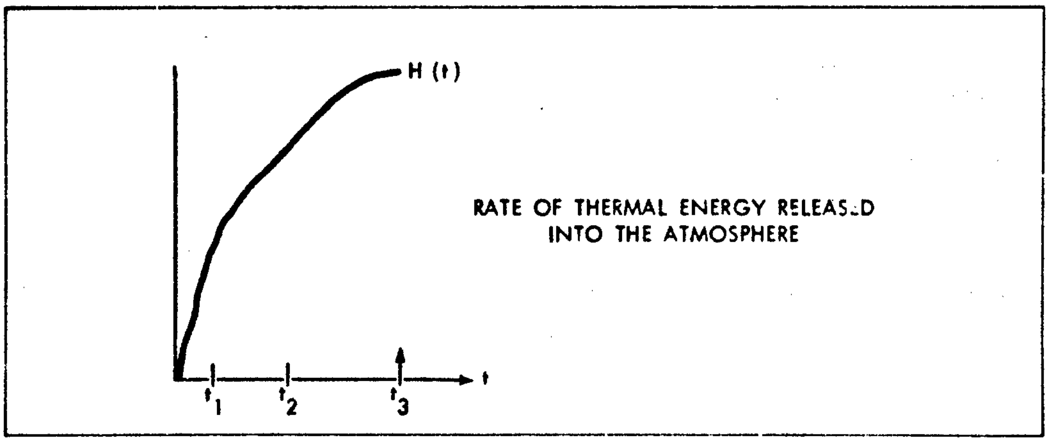
Contributing Factors

- Rate of fire spread from structure to structure
- Rate at which fires burn out
- Rate of thermal energy release
- Coalescence of convection columns
- Induced air flow
- Atmospheric conditions



Events

AS THE FIRE SPREADS, INDIVIDUAL CONVECTION COLUMNS COALESCE INTO A STRONG CONVECTION COLUMN, HIGH VELOCITY SURFACE WINDS ARE INDUCED, AND FIRE SPREAD OUTSIDE THE AREA IS RESTRICTED



SOURCE: Stanford Research Institute.

location of initial fires are known, the number and magnitude of heat sources at time t will depend on the rate at which fire spreads within and between structures.

The rate at which fire spreads within a structure will depend on the number of initial fires contained in the structure, the structural materials, the number and arrangement of compartments, the compartment dividers and openings into compartments, the type and location of combustibles within compartments, and the relative arrangement of the combustibles (after the effects of blast). There may be some influence also from the recent humidity and temperature and, if the compartments are exposed to the outdoors, the atmospheric winds and induced winds may affect fire spread. The rate at which the fire spreads inside a structure may also be affected by the presence of nearby burning structures, but this influence may be included in the rate at which fire spreads between structures.

The fire spread between noncontiguous structures will depend on the type of structures and their contents, on the burning rates and thermal energy released by the structures and their contents, on the location and orientation of structures relative to one another, and on the topography and the meteorological conditions. The relative importance of these various factors and their influence on the rate of fire spread is covered in Section VI.

As previously mentioned, the rate at which thermal energy is released in the fire area will depend, in general, on the number and location of initial fires in the structure, the heat capacity and heat of combustion of the structure and its contents, the fuel arrangement, the availability of oxygen, the length of time the structure has been burning, and the influence of other burning structures. The choice of parameters to represent these various factors and methods of estimating the parameters is given in Section VI.

Atmospheric Conditions

The probable effects of atmospheric conditions on the number of initial fires and on the rate of fire spread have already been indicated. A potentially greater effect may be exerted through their influence on the flow of air in and around the fire area.

The motion of the gases heated by the fires will be determined by the forces acting on them, and the magnitude of some of these forces will depend on the ambient atmospheric conditions. For example, the buoyancy force is proportional to the density difference between the heated air mass and the surrounding air, and this difference will be affected by the lapse rate, the atmospheric temperature, and the humidity.

A more obvious influence on fire storm development is provided by the winds. It is apparent that strong prevailing winds will transport heated gases and flying brands and cause the fire to spread primarily in one direction. If a fire storm is to develop, the heated gases must rise fast enough to overcome the influence of the prevailing winds.

The resultant vertical velocity of the rising gases will also be related to the rate at which air moves into the column, but unfortunately the extent of this relationship is one of the many unknowns in fire storm phenomenology. Some estimates have been made on the basis of entrainment velocities measured in the laboratory, and in the models of steady-state convection columns the ratio of the vertical mass transport to the mass inflow is usually assumed to be constant. The effects of vorticity have not generally been considered.

Many features in the evolution of a fire storm seem to parallel the development of natural phenomena, such as cumulus clouds, cumulonimbus towers, and tornadoes. In spite of rather obvious differences between the natural and fire-produced phenomena, it might be possible to exploit the similarities to a greater extent than has previously been done. For example, mathematical models of convective processes might be modified to include intense heat sources similar to those found in mass fires.

Air Flow and Feedback Processes

The rate of thermal energy release and the atmospheric conditions will affect the air flow in the vicinity of the fire area, but the air flow may have an important influence also on the rate of thermal energy release and on the extent to which the effect of atmospheric conditions is diminished. In general, as the air flow increases, the burning rate increases and the resulting increase of air flow in the convection column induces additional air flow in the vicinity of the fire.

The flow of the air may influence also the formation of convection columns over individual fires and the coalescence of separate convection columns into a predominate convection column over the fire area. As the heated gas rises in a convection column, cooler ambient air mixes with it and tends to slow the rate of rise. The resulting reduction in vertical velocity may allow the large scale winds to dominate and hence produce fire spread. However, if the mixing process is hindered, the rate of rise may remain high. Vorticity in the flow of the heated gases or the air around them would tend to restrict mixing by producing an envelope effect. H. Emmons (20) has reported on laboratory experiments in which a flame, normally one foot high, became a fire whirl ten feet high when a small angular momentum was added to the surrounding air.

Small scale fire whirls might be formed by flames coming out windows or other openings, since the air flow parallel to the outside of the building would provide angular momentum to the escaping gases. Certainly in large scale air movements, vorticity would be expected as a result of conservation of angular momentum. In fact, it would be expected that a strong influx of air toward a convective column might veer and tend to form a counter-clockwise circulation around a strong convective cell. Moreover a counter-clockwise wind pattern appears to have existed at the Hamburg fire storm, (17) and it is possible that such air flow might develop under severe fire storm conditions similar to the Hamburg case. However, in the early stages of fire storm development, there are probably many convection columns and vorticity in the air flow that may not be evident until several convection columns coalesce.

Coalescence of the convection columns is another instance in which feedback processes may operate.(41) Experiments indicate that the air pressure is reduced at points between convection columns, causing the columns to bend toward one another. When the columns coalesce, convective and radiative means of igniting intervening fuels are enhanced with the result that the interval spread of the fires within the area progresses more rapidly than before coalescence. This produces a stronger convection column than existed previously, and the resulting air flow would increase burning rates and further accelerate the fire storm development.

V FORMAT FOR DEVELOPMENT OF A FIRE STORM MODEL

In this section the characteristics of fire storms and the basic factors in their development are organized into a format to serve as the framework for a fire storm model. Although the word "model" frequently connotes an analog device for imitating the behavior of the object or phenomenon being modeled, the term is used here in a broader sense.

The development of a fire storm model may be divided into three stages: (1) the "definition" stage, in which a fire storm is defined and the boundary conditions for the existence of fire storm conditions are established; (2) the "parametrization" stage, in which these boundary conditions are specified in terms of estimable parameters and methods for estimating these parameters are developed; and (3) the "implementation" stage, in which physical or analytical models are developed to simulate interactions of processes that produce and maintain fire storms. Each of these stages, with accompanying illustrations, will be discussed.

Fire Storm Definition and Boundary Conditions

Although a generally accepted quantitative definition of a fire storm (see Section III) probably cannot be given at the present time, the following example shows how such a storm might be defined.

The pattern of air flow in the vicinity of the fire area influences fire spread and development; and although air movements depend strongly on local topography, building arrangement, heat sources, and atmospheric conditions, the wind field above some height over the fire area might provide a criterion for fire storm existence. For instance, a definition of the following type might be used: A fire storm exists when a velocity function, V, attains a value in a certain set of values. For example, V may be expressed in terms of a time-space average or a velocity vector field.

Next, the factors on which V depends and a functional relationship expressing this dependence must be determined. Since the air flow at some time, t, depends to a large extent on the thermal energy, H, released by the fires and derivatives of H, the atmospheric variables, A, and the interactions between these factors, the functional relationship might be denoted by $V = f(A,H,t)$. Presumably this relationship might be expressed by a system of partial differential equations determined from the gas laws, the conservation laws, and the laws of motion that relate the forces (such as gravitational, pressure gradient, and viscous), the existing wind field, energy sources and sinks, and the rates of change of all of these. (This has been done for the steady-state, time-independent model of the convection column, e.g., see Reference 32.) Once the relationship $V = f(A,H,t)$ and the values of V corresponding to fire storm conditions are established, the equations can be used for determining the existence of a fire storm and evaluating the influence of parameters.

Parameters Required for Boundary Conditions

The particular choice of parameters will depend on the functional relationship used to define fire storm conditions. Some functional relationships will probably represent time and space averages, whereas in complex relationships the atmospheric conditions and the thermal energy input would have to be specified in detail over the volume and time interval of concern. Some of the parameters that have been studied and might be used in functional relationships are given below.

Meteorological Parameters

The atmospheric variables are usually available only in customary meteorological terms such as temperature gradient and wind profile. Moreover, observations are made at discrete points in space and averaged over finite intervals of time.

Fire Parameters

Fire parameters may be classified as those pertaining to rate of fire spread within and between structures and the rate of thermal energy released by burning structures.

Fire Build-up Time

The fire build-up time during the burning of a structure can be characteristized by broad classifications of building construction, light residential, heavy residential, commercial, city center, and massive manufacturing.(18) Another basis for estimating the rate of fire spread within a structure (specifically, the time from ignition to flashover within a compartment) is the combustibility of the walls and ceiling in a compartment of given size. Estimates of this parameter are given in Reference 37 and are used in the IITRI model discussed later.

Rate of Fire Spread

The rate of fire spread between structures depends largely on the intensity of the thermal radiation reaching an unignited structure from burning structures. The intensity of the radiation is a function of the fire temperature, the effective area of the radiating surface, and the relative locations of the burning and unignited structures. If the fire temperature is a constant, the radiative effects may be most simply expressed in terms of a configuration factor. This factor is used to account for the geometrical relationship between the radiating and exposed surfaces.

Other parameters sometimes used to estimate the rate and probability of fire spread between structures include: the distance between structures alone and in combination with the structure volume, structure height, and structure density (or percentage of the ground area covered by structures).(1,25,55)

Thermal Energy Output

The most common parameters related to thermal energy released by burning structures are the radiant energy released and the fire temperature. Eggleston et al.(18) estimate the percentage of radiant energy released during periods of violent and residual burning for various types of building construction. They estimate also time-temperature curves for structure types. Related time-temperature curves are given in the NFPA Handbook. The influence of various factors on the thermal energy released by burning structures has been determined. For example, there have been field and laboratory experiments showing the effect of nearby fires on the burning rates. Factors for estimating the change in burning rates caused by variations in ventilation (oxygen supply) and the effects of wind have been estimated by Salzberg et al.(37) Experiments have been conducted also to determine the influence of forced drafts and blowing air into the fuel bed (see Section VI).

Implementation of a Fire Storm Model

The final form of the fire storm model depends on the fire storm definition, the criteria for fire storm existence, and the feasibility of simulating "real-life" conditions with analog devices. Whichever form of model is used, however, certain stages in fire storm development can be distinguished. We shall discuss "submodels" related to each of these stages and shall indicate the role they play in the complete fire storm model, but it is recognized that in a single analog device they might correspond to components of the device rather than separate submodels.

The basic components of a fire storm model are shown in Figure 5. The labeled boxes may be thought of as input and output parameters while the directed line segments (arrows) denote functional relationships. To illustrate how such a model might be implemented, we use the following simplified example of a computer model for a fire storm. It is a continuation of the example used earlier in this section in connection with the establishment of fire storm existence criteria.

Suppose that the rates of change of the velocity function, V, the current atmospheric conditions, and the energy input have been determined, and suppose that initial values of the parameters (such as wind, temperature, pressure, and heat input) are specified for a grid of points in space. Using difference quotients to approximate spatial derivatives and assuming the rate of change of each variable is constant over a short time period, we can calculate parameter values over successive time intervals. Values of V can be estimated in this fashion and decisions about the existence of a fire storm can be made. By repeating the experiment with different parameter values, we can then study the effects of changes and the relative importance of parameters determined.

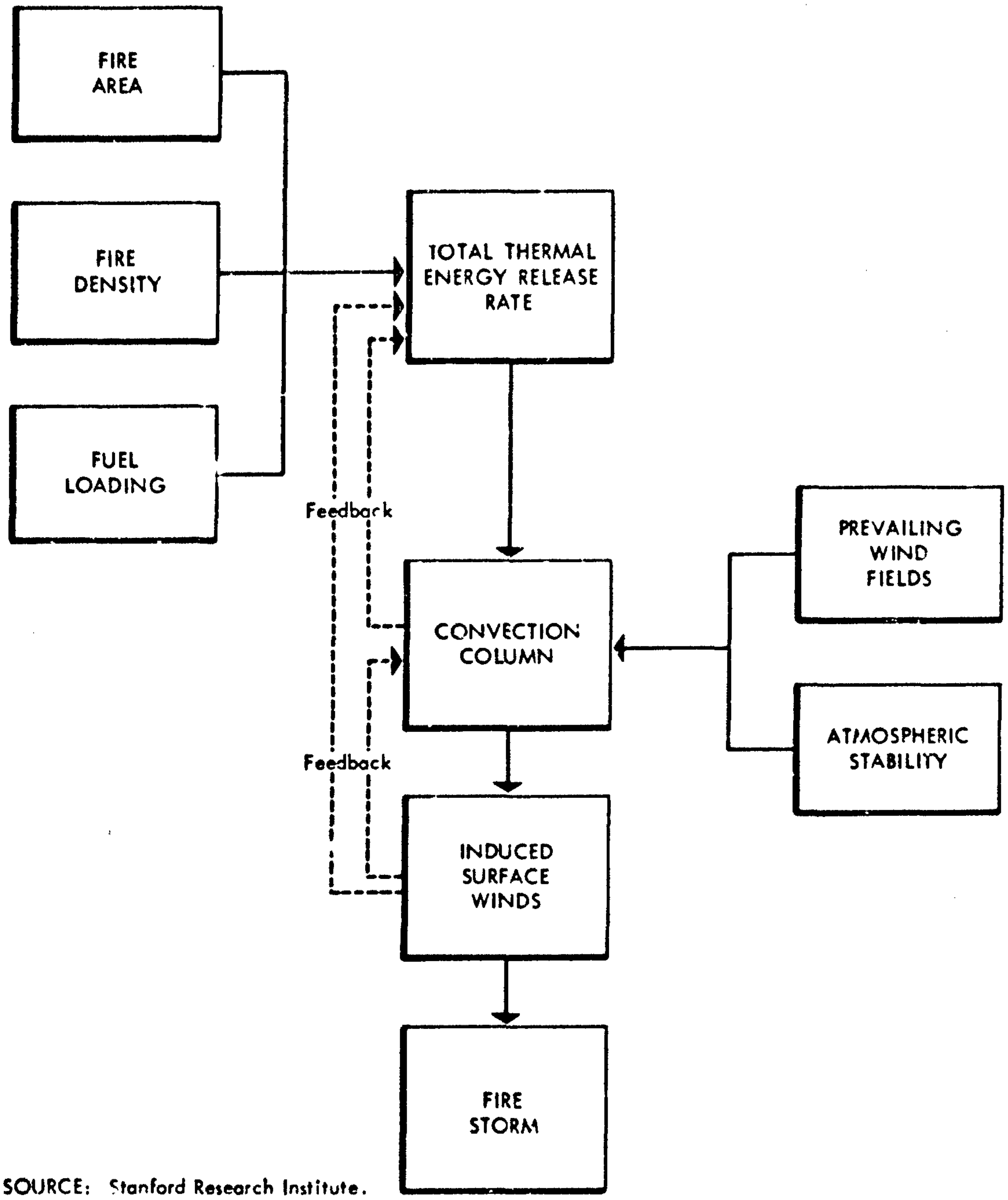
Necessary inputs for the fire storm model include initial fire density and the rate at which the fire spreads. These inputs may be obtained from ignition and fire development submodels.

Ignition Submodels

The ignition of fuels as a result of a nuclear detonation may be categorized in terms of the cause of the ignition. If thermal radiation from the weapon ignites a combustible, the object ignited is called a primary ignition point. If an occurrence caused by some other weapon effect, such as direct blast, results in an ignition, the object ignited is called a secondary ignition point. An ignition model should yield

FIGURE 5

BASIC COMPONENTS OF A FIRE STORM MODEL



SOURCE: Stanford Research Institute.

an estimate of the number of initial (primary and secondary) ignitions for a given city, weapon, burst point, and atmospheric conditions. Strictly speaking, an ignition model should yield also an estimate of the time after detonation that an ignition occurs. However, except for some examples of secondary ignitions, it is probably safe to assume that all initial ignitions occur simultaneously and to let this moment be the time origin, say t = 0.

A computer model developed at IITRI(38) might be used as an ignition submodel to estimate the probability that combustibles are exposed to and ignited by thermal radiation.

Fire Development Submodels

With the use of the ignition model outputs, atmospheric conditions, topographical information, structure construction and configuration, and information about the combustible contents of structures, the fire development model will determine (1) the rate at which fire spreads within and between structures and (2) the rate at which thermal energy is released. As indicated, the fire development model might be subdivided into two parts. Just after the initial ignitions occur, the fires will spread within structures or from outside ignition points to structures. During this time period the amount of thermal energy released into the atmosphere is small. Also, because the thermal energy transmitted to other structures during the early stages of fire development tends to be small, the fire spread between structures is limited. Once the structure containing interior ignition points or near exterior ignition points are aflame, the thermal energy released into the atmosphere is significant and the fire spread between structures is an important factor. It is somewhat difficult to distinguish between the two phases of the fire development period, but a convenient dividing point might be the first time at which flashover occurs in a compartment within the structure.

There are, at the present time, computer models that would be suitable for use as submodels for the stages in fire storm development. Models developed at IITRI(38) include (1) a fire history model that is used to estimate the fire spread within structures on the basis of fire resistance ratings of the structural components and to estimate, as a function of time, the duration of the fire within various parts of the structure as well as the flame area visible outside; and (2) a fire spread model that is used to estimate the heating and possible ignitions of exposed structures. These computer models can be used to study, in detail, small groups of buildings, such as city blocks. Furthermore, by using Monte Carlo methods, it is possible to obtain parameters that will characterize fire ignition, build-up, and spread in certain areas.

Another computer model that can be used to study fire spread has been developed at URS. (53) Although it is probably more suitable for studying conflagrations, it might be adapted to studying fire storm problems. Other types of models that have been developed to study fire spread include scale models and physical simulation models. (2)

Models for the Fire Storm Period and Post-Fire Storm Period

An evaluation of the environmental conditions and estimates of damage, casualties, and the duration of the fire storm are important in preattack planning. The model of the convection column developed by Nielsen, *et al*. (32), is an example of a model for the fire storm period. Their analysis of oxygen concentrations is useful in the planning of shelter and vent locations.

Following the fire storm period, the fire may become a conflagration and spread across a larger area or it may die as it burns out the remaining fuel in the fire area. The continuation of the fire will depend to a large extent on the existence and location of unignited fuels and on atmospheric conditions. The post-fire storm period could have an important influence on damage and casualty estimates from any given attack.

VI DISCUSSION OF FIRE STORM ELEMENTS

Preceding sections have brought out the basic factors relating to initiation and development of fire storms and have presented the format for development of a fire storm model. A concept of fire storm evolution and a format for a model giving the framework for incorporating the results of past and present research programs have also been presented. This section will examine the primary individual factors in more detail and will cover also some secondary factors not previously considered.

It is emphasized that the present research is based upon the hypothesis that initiation and development of fire storms are dependent upon two basic underlying requirements--high thermal energy release rate and certain meteorological conditions. The phenomenology of fire storms requires that vast amounts of fuel must be ignited and burned within a short time, thus providing a tremendous energy release rate by the fire. It is believed also that fire storms will occur only when meteorological conditions assist in or permit the creation of a strong convection column and high velocity inrushing surface winds as the fire storm develops. It should be recalled, however, that other types of highly destructive mass fires may occur regardless of meteorology.

Topics to be covered in this section are arranged in groups as follows: those influencing nature of the target, those affecting fire ignition and spread, and meteorological considerations.

Fuel Loading

Fuel loading, or weight of combustibles per unit area, is one of the principal inputs to the energy released by the fire, and as such becomes one of the most important parameters in predicting possible fire storms. The fuel load plus the heat of combustion determines the energy that can be released, per unit of area. To a first approximation, fuel loading may be estimated by building density, but fuel loading is dependent also on building heights, contents, and construction materials.

Reliable information on the range of fuel loading required to support a fire storm is not available, but it may be reasoned that the required loadings must be high and could be expected in urban areas only where building densities are uncommonly high. Building density at

Hiroshima was reported at 27 to 42 percent in 94 percent of the central four square-mile area.(48) At Hamburg, building density of the fire storm area was estimated at approximately 30 to 40 percent in the fire storm area,(45,50) with some typical blocks having a built-up area up to 67 percent.(17) Other German fire storm cities had building densities comparable to those at Hamburg.

In the example of 67 percent building density for a typical Hamburg city block, German fire engineers estimated that the block contained 1,402 tons of wood.(17) This yields a fuel density of approximately 100 pounds of wood per square foot of buildings, or about 67 pounds of wood per square foot over the block. Since the overall building density in the fire storm area was closer to 30 to 40 percent rather than 67 percent, the fuel loading in the fire storm area was probably on the order of 30 to 40 pounds per square foot. A figure of 32 pounds per square foot has been reported by H. Brunswig for the Hammerbrook area of the Hamburg fire storm.(57)

An estimate of the range of fuel loadings per story in pounds of combustibles per square foot for several types of occupancy is shown in Table 1. These values are broad estimates derived from information contained in References 44, 4, 23, 43, and 56.

Table 1

ESTIMATED RANGE OF FUEL LOADINGS FOR
SEVERAL TYPES OF OCCUPANCY

Occupancy	Fuel Load of Combustibles per Story, Building and Contents (lb/sq ft)
Residential	10-20
Office and commercial	10-40
Industrial	10-30
Storage	20-80

It appears that a reasonable mix of occupancy types in a densely built-up area would provide about 15 pounds of combustibles per square foot for each story of structure. This figure conforms fairly well to the 55 to 75 foot building heights in Hamburg that produced fuel loadings on the order of 100 pounds per square foot of building ground surface area.

The four square miles of densely built-up area in the heart of Hiroshima consisted largely of commercial, military, and residential zones.(47) The bulk of the industries was located on the perimeter of the city. The dwellings were of wood construction, about half of them one story and the remainder either one and one-half or two stories. By correlating this information with the fuel loadings given in Table 1, we estimate that the overall fuel loading in the Hiroshima fire storm area was 8 pounds of combustibles per square foot or more in the fire area.

Bond has stated that three-story dwellings not over 3,000 square feet in area in 15,000 square foot lots would probably burn individually rather than in groups if spacing is approximately uniform.(6) If a fuel loading of 15 pounds per square foot per story for building and contents is assumed, it could be estimated that the point at which fire storms might become possible is about 9 pounds per square foot of fire area.

It was reported that the weight of fuel per acre in several California cities is 70 to 100 tons per acre.(9) This amounts to about 3.5 to 5 pounds per square foot of fire area, a fairly low figure that does not seem unreasonable when one considers that most California cities do not have a high percentage of tall buildings and that the spacing between them is generally wide.

The Camp Parks burn(8) in connection with a 100-man prototype underground shelter at Camp Parks, Pleasanton, California, was planned to include the investigation of possible fire storm behavior. The original plans for this burn had included provision for burning about 500 tons of combustibles, distributed over a 4-acre area to simulate a building density of about 30 percent in an area of single story dwellings. For a variety of reasons, the final fuel loading was only about half that planned, or perhaps 3 pounds per square foot of fire area. All of the fuel was ignited almost simultaneously. Within 20 minutes after ignition, some of the piles of fuel had been reduced to a bed of coals and had stopped flaming. While the burn did to some extent exhibit characteristics of fire storm behavior, i.e., strong indrafts from all sides toward the center of the fire and brief merging of flames from individually burning fires, it seems clear that the fuel loading used was insufficient to support fire storm conditions.

Fuel arrangement is itself a variable. It has been estimated, for example, that fire storms are not likely in areas where buildings have been collapsed.(39) Whether this is true generally, or even for British-type cities, is not known. Certainly, it does not appear to be true for cities like Hiroshima.

The relationship of fuel loading to fire severity (measured by temperature and duration) as presented in Reference 43 is shown in Table 2. The data in this table show the probable intensity and duration of fires as a function of fuel loading. The values given are for fire resistive structures with combustibles having a calorific value in the range of wood and paper. It may be observed that the Hamburg fire storm duration of approximately 5 to 6 hours would place fuel loading in the fire area at 40 to 50 pounds of combustibles in the fire area. Considering the many uncertainties involved, this is in reasonable agreement with the 30 to 40 pounds of combustibles per square foot of fire area which has already been estimated.

Table 2

RELATION OF FIRE LOAD TO FIRE SEVERITY

Average Weight of Combustibles, psf of Floor Area (pounds)	Fire Severity, Hours of ASTM Time-Temperature Curve
5	1/2
10	1
20	2
30	3
40	4-1/2
50	6
60	7-1/2

Combustibility

Combustibility of inflammable materials in a potential fire storm area has a direct bearing on the energy release rate of the fire and on the spread and buildup of the fire. Combustibility is important also because of the influence it has on the range and numbers of fires resulting from primary thermal radiation from a nuclear detonation.

Factors affecting combustibility of materials include fuel chemical composition, flash point, shape and dimensions, ability to produce inflammable gases, moisture content, and others. The weather factors of humidity, temperature, and time since last precipitation have an effect on fuel combustibility through their influence on moisture content of materials.

Some indication of combustibility of structures, as well as fuel loadings, may be obtained from Table 3, presented by Chandler, et al. in "Prediction of Fire Spread Following Nuclear Explosions."(15) It is seen from Table 3 that the generally more combustible materials found in light residential areas produce short violent burning times with a high percentage of total energy release. The combustibility of light residential construction types is directly related to the materials of construction and contents as well as to their dimensions and configurations. The total burning time for a structure in city center, approximately three hours, is in reasonable agreement with fuel loading in these areas of about 30 pounds per square foot of floor area (Table 2) when allowance is made for fire spread in and between structures.

The combustibility of structures in an expensive residential area of the United States was illustrated dramatically by the Los Angeles conflagration of 1961.(54) This disastrous fire consumed over 500 homes in a short time. The homes were constructed largely of light wood frame with stucco, or brick veneer and wood walls. Most of the roofs were made of wood-shingle or wood-shake, the remainder being of rock, gravel, or occassionally tile. Analysis of results from this fire showed wood-shingle or wood-shake homes to be far more vulnerable to fire spread than homes with fire-retardant roofs. On a percentage basis, with brush spacing of 30 feet from the home, for example, four times as many wood-roofed homes were destroyed as fire-retardant-roofed homes.

Table 3

VIOLENT AND RESIDUAL BURNING TIMES OF URBAN FUELS

	Violent Burning		Residual Burning	
Construction Type	Time (minutes)	Total Energy Release (percent)	Time (minutes)	Total Energy Release (percent)
Light residential	10	80%	12	20%
Heavy residential	13	70	20	30
Commercial	25	60	60	40
City center and massive manufacturing	55	30	120	70

Note: These times apply to dry weather conditions with light winds.

Attempts have been made(23,7) to establish combustibility indices, primarily for fire insurance purposes. The indices established in this way do not appear to be directly applicable to the problem of predicting possible fire storms.

Topography and Configuration

It is probable that the most significant effect of topography on fire storms resulting from nuclear detonations is its control over the amount of thermal radiation reaching a given area. Topography can be an important factor also in determining the rate of fire spread.

The presence of hills could effectively shield large parts of a potential fire storm area from direct thermal radiation, thereby limiting ignitions and fires in the shielded areas. If these parts of the area are significant with respect to the total area, it is probable that a fire storm would be prevented, since fire storms appear to require a high density of simultaneous ignitions over virtually the entire fire storm area. Hills, too, will have an effect on wind patterns in the area, and for this reason could influence the spread of fires.

The effect of terrain on fires started by the nuclear detonation at Nagasaki(51) illustrates the possible effects of hills and uneven terrain on creation of a fire storm. Because hills shielded large sections of Nagasaki, leaving large unignited pockets in the area, no fire storm developed. In addition, the hill areas were not densely built up, and thus did not provide the high fuel loadings required by fire storms.

The possible effects of target configuration on formation of fire storms are not clear, but it is observed that World War II possible fire storm areas followed non-elongated patterns. The rather long, irregular shape of Nagasaki gives rise to the thought that configuration might have been a factor in preventing the development of a fire storm there. Certainly, if taken to the extreme, a long, narrow fire area becomes a line fire and is unlikely to develop the single strong convection column necessary in the development of a fire storm.

Size of Fire Storm Area

One of the smallest probable fire storms of World War II was that at Darmstadt, in which the fire storm area was reported to be about 1.5 square miles.(50) A momentary fire storm of about 0.5 square miles was reported at Ube, Japan,(49) but it is doubtful whether this would fall within the present definition of a fire storm. Fire storm areas of approximately 4.5 square miles were reported at Hamburg and Hiroshima, and one of 8 square miles at Dresden.(24) Information on the Dresden fire storm has been especially difficult to obtain and is probably somewhat less reliable because Allied survey teams were not permitted to enter Dresden after the war.

A basic hypothesis of this research is that vast amounts of thermal energy are released by fire storms and that most or all of the energy required to produce a fire storm must come from the fire itself, and not from atmospheric sources. Thus, if reasonable upper limits are placed on fuel loadings, fire density, and rate of combustion, it is apparent that the fuel area must exceed some critical minimum. Until this minimum area is better defined, interim estimates from the standpoint of thermal energy release must be based largely on case-history studies of World War II fire storms.

It has been reported that the violent indrafts characteristic of fire storms can penetrate no more than about half a mile into the fire area.(19,29) It is postulated that inside these limits, air to feed the fire comes as a result of mixing with the atmosphere above, rather than laterally. Assuming this is true, the maximum size of a fire storm also is limited. Experimental evidence(22) as well as actual observations suggest that fire storm development may require that the fuel bed be fanned by inrushing winds. If there were a large central core not reached by these winds, development of a fire storm in the core region would be made difficult for several reasons. First of all, a single fire storm convection column would tend to break up into several columns as the core radius becomes large relative to one-half mile. Secondly, the uneven distribution of fuels and irregular topography of most urban areas is such that the combination of conditions required to support a single gigantic fire storm over an extremely large area are unlikely. This concept is supported by the study of Chandler,(15) who concluded that several mass fires scattered throughout a large burning area will probably be more typical of the first 12 to 24 hours following nuclear attack than is the often postulated picture of hundreds of square miles going up in flames at once.

Factors having a significant influence on fuel loading, combustibility, topography and configuration, and size of the fire area are summarized in Table 4.

The next group of factors to be considered are those which strongly affect the initiation and spread of fires. These factors are the nuclear detonation, the ignition processes, the initial fire density, and fire spread and buildup.

Table 4

SUMMARY OF IMPORTANT FACTORS AFFECTING THE TARGET AREA

Fuel Loading

Building density
Building heights
Building materials
Building contents

Size of Fire Area

Area of initial fires
Fire spread and buildup
Countermeasures (fire fighting)
Combustibility of target
Topography and configuration
Penetration of indrafts

Combustibility

Target materials
Recent precipitation history
Recent humidity history
Temperature
Geometry and configuration

Topography and Configuration

Hills
Bodies of water
Other natural firebreaks
Geometry

Detonation

One of the factors to be considered in developing interim criteria for predicting the occurrence of fire storms resulting from nuclear detonations is, of course, the nuclear detonation itself. Major inputs include yield and height of burst, and expected outputs are release of thermal energy and the blast wave. Quantitative measures of both the thermal energy release and blast overpressure levels are readily predictable, subject to certain significant limitations.

Substantially all energy released in a nuclear detonation is ultimately converted to heat, but only the part of the energy emitted by the fireball within the first minute following the explosion is regarded as prompt thermal radiation. That portion of the thermal radiation capable of igniting combustible materials at great distances is found mostly in the visible and near infrared part of the spectrum, and reaches a target on the ground within seconds after the detonation. Thermal energy emitted by the fireball in air bursts at low or moderate altitudes is reported to range from 30 to 40 percent of the energy yield of the explosion.

Approximately 50 percent of the energy from nuclear detonations at low and moderate altitudes is converted into blast and shock. The blast effects can start secondary fires through the means of upset stoves and furnaces, electrical short-circuits, overturned gasoline containers, and other damage.

Ignition Processes

The ignition of fuels by primary thermal radiation is a major means by which fires would be started, affecting both the initial fire density and the size of the fire area. The exposure of fuels to sufficient thermal radiation to result in significant numbers of ignitions depends on many factors, such as the transmission of thermal radiation through the atmosphere, the exposure of kindling fuels to radiation, the critical ignition energy of the exposed fuels, and spread of flames to other fuels.

Secondary ignitions are caused by nuclear detonation effects other than the thermal pulse; that is, by blast effects and by subsequent effects (such as accidents resulting from unattended processes and recovery-period improvisations). These secondary ignitions can create serious fires even where thermal radiation is not present, as illustrated by fires following earthquakes. Secondary fires are generally considered to be less numerous than primary fires, but no method exists for estimating the likely number of secondary fires from air overpressures or earth shock that might occur in U.S. cities.

Initial Fire Density

Accounts of World War II fire storms indicate strongly that fire density--in terms of the proportion of structures on fire--was a key factor in the initiation and development of those initial fire storms. Two out of three buildings were on fire in the Hamburg fire storm within 20 minutes after the attack had begun.(5) At Hiroshima, it was reported that hundreds of fires occurred almost simultaneously throughout the heavily built-up center immediately after the attack.(51) These observations tend to confirm the basic fire storm hypothesis that a critical requirement is the presence of vast amounts of fuel on fire and burning simultaneously.

Observations made during World War II indicate that the division between the density of a fire required to produce a fire storm and one that will not may be a narrow one.(26) Hence our ability to predict accurately the density of fires following nuclear explosions may be critical to the prediction of fire storms.

The essential requirement for a fire storm is the attainment of a minimum fire density at some time during the course of the fire, but not necessarily at the very beginning. The critical minimum fire density for a fire storm might be achieved either with very high initial fire density or with a somewhat lower fire density with a greater rate of fire spread. As a practical matter, however, the minimum fire density was achieved at an early stage of the fire in World War II fire storms.

Fire density and fuel loading combine with the rate of combustion to provide the total energy released by a fire, and all of these factors must exceed certain minimum values to provide the thermal energy release rate required for fire storm development. Once these minimums have been met, it seems probable that it would be possible to produce the required thermal energy release rate through many different combinations of these factors.

Stanbury(39) has reported that the most critical factor distinguishing the fire storm raids in Germany from others was that a much higher concentration of bombs (including incendiary bombs) in the fire storm target areas was achieved. Stanbury concludes from his analysis of the German fire data that a fire density of about 50 percent or more is required to initiate a fire storm.

Buildup

One of the most striking characteristics of the World War II fire storms was the very rapid increase in the fire intensity, which in turn made escape from within the burning area difficult or impossible. It was reported at Hamburg that thousands of individual fires produced huge area fires that developed into a fire storm within barely half an hour.(26,14) Maximum fire storm intensity was reached in some 2 to 3 hours after the attack had begun, and virtually complete burnout of the fire storm area was accomplished in about 6 hours. Similar conditions were reported from other fire storms in Germany.

The fire storm at Hiroshima was reported to have developed about one-half hour after the nuclear detonation, and induced surface winds reached a maximum of 30 to 40 miles per hour about 2 to 3 hours after the explosion.(47) Most of the fire had burned itself out or had been extinguished about 10 to 12 hours after it began.

The conclusions to be drawn from the rapid buildup of fire intensity during the fire storms of World War II are not altogether clear. There is strong indication, however, that there must be a rapid use of the available fuel, or else sufficient energy for a fire storm will not be generated.

A summary of some of the more important factors affecting initiation and spread of fires is given in Table 5.

Table 5

FACTORS AFFECTING INITIATION AND SPREAD OF FIRES

Detonation

- Yield
- Height of burst
- Thermal energy released
- Blast energy released

Buildup

- Initial fire density
- Topography and configuration
- Combustibility
- Countermeasures
- Type of fuels
- Wind

Ignition Processes

- Atmospheric transmission of thermal radiation
- Exposure of kindling fuels
- Critical ignition energies
- Development of significant fires
- Secondary fire hazards
- Topography

Initial Fire Density

- Ignition processes
- Combustibility
- Topography (incl. city building profile)

Wind

The movement of air is a major factor in the behavior of fires. The wind speed, both at ground surface and above ground, appears to play an important part in the convection process over mass fires. Fire spread is influenced by surface winds, and it may be assumed that fire storms will not develop in the presence of initial high velocity surface winds. Rather, the fire will spread as a conflagration. Strong variations in wind speed or direction with altitude may also prevent the formation of the strong convection column associated with fire storms.

Strong surface winds cause flames to slant forward, and fire to spread in the direction of the wind through radiation, convection, and firebrands carried by the wind. Since fire storms are characterized by little outward spread, it is clear that in the general case fire storms will not develop in the presence of ground winds strong enough to spread the fire to an appreciable extent. The point at which the wind becomes strong enough to prevent development of a fire storm is not known. Future research will probably show that trade-offs among the critical wind speed, thermal energy release rate, and atmospheric stability are possible.

Reports from the fire storms of World War II indicate that they occurred when surface winds at the time of attack were about 5 miles per hour or less. Based on information presented by Nielsen,(33) the critical surface wind speed that will just prevent development of a strong convection column under what might otherwise be fire storm conditions is on the order of 8 miles per hour. This estimate depends largely on considerations regarding the entrainment of air into the convection column.

A fire storm did not result from the fire raid on Tokyo of 9-10 March 1945, though all major conditions other than surface wind speed appeared to favor the development of such a storm. The wind speed at the time of the Tokyo attack was reported to be 17 to 28 miles per hour.(49)

Unfortunately, very little is known also about the possible effects of strong variations in wind speed or direction at higher altitudes on the development of convection columns. From information presented in References 17, 12, and 42, it is clear that upper level winds are important factors to mass fires and their convection columns. Additional research and experimentation are needed to define their roles satisfactorily.

Atmospheric Stability

In descriptive accounts of fire storms that occurred during World War II, the rapid rise of gases in the convection column has usually been attributed solely to the intense heat from the fires. Ebert's study of the weather at Hamburg just prior to the fire storm(17) indicates that this impression may not be correct and that the air aloft, as well as other weather factors, had an important influence on fire storm development in that case.

It is known that instability in the air, i.e., its tendency to vertical motion, is a condition associated with turbulence. If a volume of air tends to remain in its position, or returns to that position when displaced, it is stable. It is unstable if vertical displacement results in further movement of the air from its original position. There is a strong implication, therefore, that the tendency to develop the convection column as part of a fire storm would increase with increasing atmospheric instability.

Atmospheric stability is closely related to the vertical temperature gradient, or lapse rate. Lapse rate is defined as the rate of decrease of temperature with altitude. If temperature increases with height, the lapse rate is negative. The atmosphere is strongly unstable when the lapse rate is 5.3 degrees Fahrenheit or more per thousand feet. This condition will not generally exist for a long period of time over a large area, being quickly corrected by turbulence.

The lapse rate at Hamburg shortly before the fire storm was reported(17) to be about 4.8 degrees Fahrenheit per 1,000 feet up to the 12,500-foot altitude level. While this is slightly less than the adiabatic rate, this gradient represents a condition of near instability, and it could have been an important factor in the development of the Hamburg fire storm. Vertical lapse rate was taken as a principal variable by Nielsen, indicating acceptance of this hypothesis.(33)

The question of whether an unstable atmosphere is a necessary condition for the development of a fire storm has by no means been answered, however. In a study of forest fire behavior,(12) it is observed that, while an unstable atmosphere with its accompanying thermal turbulence was often associated with mass fires, severe fires occurred also when the air was stable. Whether this has significance for fire storms in urban areas is not clear.

Possible effects on a mass fire from a weak inversion or negative lapse rate (a stable condition) were presented by Arnold and Buck.(3) It is suggested that while a convection column might be held in check by an inversion, the inversion might be pierced by the convection column if it is sufficiently weak or shallow. The piercing of the inversion might act on the fire as if a damper were opened or forced draft employed, if the air above is unstable. Such conditions are not unlike those of a fire storm.

It is possible that a study of thunderstorms and head clouds may be helpful in an analysis of the effect of atmospheric stability on fire storm phenomenology. Thunderstorms are associated with strong vertical air currents and unstable air, and they produce strong convective columns that have chimney-like effects. Turbulence and winds accompanying thunderstorms show many striking similarities with those reported at fire storms.

As with wind profile, it seems probable that there is an area where trade-offs with thermal energy release rate are possible. If the thermal energy release rate is somewhat marginal for fire storm development, an unstable atmosphere might be the factor that could swing the balance to a fire storm, or a stable atmosphere could prevent one.

Temperature

The fact that surface air temperatures had been abnormally high at Hamburg for some time prior to the fire storm is sometimes considered a major contributing factor to the Hamburg fire storm. There is no really conclusive evidence, however, that temperature was a critical factor at Hamburg or at other fire storm cities. The Dresden fire storm occurred in February, for example, and the weather was exceptionally cold at the time.(24)

There is no question that ground temperatures can influence the ignition and propagation of fires. It should be pointed out also that air temperature is often a poor indication of fuel temperatures because of absorption of solar energy or shadow effects. The most important temperature factor is probably the drying-out of combustible materials. It can be shown that the effect of temperature changes on moisture content will generally be less than from changes in relative humidity.(13) The following section of the report shows that moisture content changes resulting from variations in humidity can seldom if ever be a limiting parameter in development of fire storms, and it therefore seems reasonable to draw the same conclusion for moisture content changes as from changes in temperature.

There had been a prolonged heat wave at Hamburg, and the resulting hot layer of surface air may have contributed to formation of the fire storm convection column through its influence on the lapse rate and atmospheric stability. It is possible also that the high temperatures at Hamburg made that city particularly susceptible to a fire storm, perhaps through some phenomenon that has not been explained. However, in the face of direct evidence that fire storms can occur when ground temperatures are very low, as was the case, for instance, at Dresden, it is concluded that near-ground air temperatures prior to attack are less important than many of the other fire storm parameters.

Humidity

The effects of humidity to be considered in this analysis as they pertain to fire storm phenomenology are related primarily to the moisture content of materials in the fire storm area. The moisture content of materials will influence the ranges at which kindling fuels are ignited by direct thermal radiation from a nuclear detonation and the rate of fire spread. Humidity will affect also atmospheric transmission of thermal radiation, but this effect will not be considered in this report.

Equilibrium moisture content for some typical kindling fuels ranges from about 2 to 5 percent at 10 percent relative humidity to about 10 to 24 percent at 90 percent relative humidity.(36,10) When these variations are translated into differences in ignition ranges, however, these differences are generally too small to be an important factor in the initiation of a fire storm.

Moisture content of fuels does not affect the spread of fires in urban areas as much as has sometimes been assumed. The spread of fires is dependent mainly upon the processes of convection, direct radiation, convection from hot gases, or transport of firebrands. Moisture is quickly driven out of fine fuels and has little effect in retarding fire growth in kindling materials. Heavier materials can become difficult to ignite when the moisture content becomes very high, but studies in urban areas have shown that these levels are rarely reached.(28,34)

Humidity was reported as being fairly high at the time of the Hiroshima fire storm,(47) supporting a general conclusion that variations in humidity are not likely to be critical factors in development of fire storms.

Precipitation

The fact that several of the World War II fire storm cities had experienced no precipitation for some time prior to the attacks has been cited as a contributing factor to the fire storms. The absence of precipitation undoubtedly had some influence on development of the fire storms, but the extent of this influence was probably small.

Precipitation or the absence of it will affect the initiation and spread of fires in urban areas through approximately the same mechanisms that have been explained for temperature and humidity effects. The result can be expected to be about the same; that is, precipitation can be treated as an influencing factor to the development of fire storms, but rarely if ever as a limiting factor.

This conclusion in the present context is supported by the fact that most ignitions to be expected from nuclear detonations will be interior ignitions,(38) where the kindling fuels will be largely protected from precipitation. The initial spread will also take place primarily in the interiors of structures, where the effects of precipitation will not be felt greatly. Precipitation could be important in limiting the spread of fire from structure to structure, particularly that spread by firebrands. On the other hand, the intensity of the fires by the time this stage is reached will probably be great enough to overcome the effects of all but very heavy precipitation.

Results from incendiary raids on Japan during World War II showed that the effect of precipitation were not as great as might have been expected. Humidity had been high prior to the fire attack on Amori, Japan, and rains were experienced during part of the attack, but these conditions were reported as having little effect on the intensity of the fires.(49) A successful incendiary attack was delivered on Akashi, Japan, with a light rain falling immediately before and during the attack, and rain had fallen intermittently during the week prior to the attack. Overall, the attacks on Japan were found to be only slightly less effective when delivered following damp or snowy weather, and damage from attacks carried out in rainstorms averaged only 20 percent less than that in most cases studied.(5)

Summary

Conclusions reached in this section regarding the principal factors influencing development of fire storms are summarized in Table 6. The various factors have been separated into parameters and constraints, as some factors appear to be variables that are important over a considerable range of values, whereas others appear to be important only when certain boundary conditions or limits are reached. It is considered that, in general, key parameters and constraints, as indicated in Table 6, determine whether fire storms are possible in given circumstances, while the other factors determine extent and nature of fire storm development.

Table 6

SUMMARY OF CONCLUSIONS REACHED REGARDING SELECTED FIRE STORM ELEMENTS

Factors	Constraint	Parameters Key Parameter	 Highly Important	 Somewhat Important
Fuel loading		*		
Combustibility			*	
Topography and configuration	*			
Size of initial fire area	*			
Initial fire density		*		
Fire intensity buildup rate			*	
Surface wind	*			
Atmospheric stability			*	
Temperature				*
Humidity				*
Precipitation				*

VII INTERIM CRITERIA FOR PREDICTING THE POSSIBLE OCCURRENCE OF FIRE STORMS

Despite the lack of data and the pressing need for further research and analysis, the ever-present possibility of nuclear attack points up the need for interim criteria for predicting the possible or probable occurrence of fire storms. Such criteria, which have been derived from the discussion in the preceding section, will now be examined. Because it is not possible to measure some of the factors quantitatively, not all the factors that influence initiation and development of fire storms have been included in these interim criteria. It must be recognized also that the critical values selected must be looked upon only as "best possible" values at this time, and should be revised as new and better information becomes available.

The interim criteria for predicting the possible occurrence of fire storms given in this section are related to boundary conditions in terms of limiting or critical values of controlling parameters. The criteria are related also to the definition of a fire storm as given earlier in this report.

Application of interim criteria may be helpful in defining potential fire areas that would present the greatest hazards to persons in mass fire situations. That is, based on fuel loadings, target area, topography, average surface winds, or other factors, it will be possible to predict that fire storms are more likely to occur in some potential target areas than in others.

The factors selected as interim criteria for assessing vulnerability to fire storms are fuel loading, initial fire density, size of area, surface winds, and atmospheric stability. Combustibility, fire spread and intensity buildup, and countermeasures would have been included in this listing if quantitative information upon which to base interim criteria for these factors had been available.

Fuel loadings in the severe fires of World War II have generally been reported in terms of building density only. Building densities in the fire storm cities of World War II ranged from about 27 to 42 percent in Hiroshima to 67 percent or more in some German cities. The fuel loading in Hiroshima has been estimated conservatively in Section V at eight pounds of combustibles per square foot of fire area; and this figure is regarded as acceptable as an interim criterion for predicting the possible occurrence of fire storms.

Two of three buildings in a 4.5 square mile area were burning 20 minutes after the attack began at Hamburg. Similar figures were reported at Kassel and Darmstadt.(50) The initial fire density at Hiroshima has not been reported, but there are indications that it may have been somewhat lower than those of the German fire storm cities. Consequently, it seems reasonable to accept as an interim criterion a figure of approximately 50 percent buildings simultaneously on fire and burning rapidly. In theory, this condition could occur at any time during the course of a mass fire. In actual practice, however, it would probably occur only shortly after the attack. Fifty percent structures on fire is the same figure as that selected by Stanbury(39) in the prediction of possible fire storms.

Surface wind at Hiroshima just prior to the attack was reported as being under five miles per hour,(51) and there was little or no ground wind at Hamburg at the time of the attack.(17) Surface winds at the time of the 9-10 March 1945 fire raid on Tokyo were reported to be in excess of 17 miles per hour.(49) Estimates based on Nielsen's work(33) place the figure at which entrainment of ground winds into the convection column would be prevented at 8-10 miles per hour. Accordingly, it is suggested that an 8-mile-per-hour ground wind (on generally level terrain) be accepted as an interim limiting criterion for development of fire storms.

The smallest generally accepted World War II fire storm area was the 1.5 square mile area of Darmstadt. The 0.5 square mile fire storm reported at Ube, Japan, was probably not a fire storm in the generally accepted sense, but recent investigations in Germany by Miller(30) suggest that fire storms may be possible in areas as small as 1 square kilometer. It is therefore proposed that for prediction purposes a minimum fire area of 0.5 square miles be taken as an interim criterion.

It was concluded in Section VI on the basis of currently available evidence that atmospheric stability is an important but not necessarily limiting factor, despite the fact that some investigations have suggested that atmospheric instability may be a critical factor to the initiation and development of fire storms.(22) As an interim criterion for fire storm formation, therefore, it is recommended only that an unstable atmosphere be considered as favorable to fire storm development.

The above recommended interim criteria for predicting fire storms are summarized in Table 7. Aside from the atmospheric stability factor, it is considered that all of the criteria shown must be approximately met.

Table 7

INTERIM CRITERIA FOR PREDICTING FIRE STORMS

Fuel loading	≥ 8 pounds of combustibles per square foot of fire area
Fire density	> 50% of structures in fire storm area on fire simultaneously (for practical purposes, initial fire density)
Surface wind	< 8 miles per hour at time of attack
Fire storm area	> 0.5 square miles
Unstable atmosphere	+
Stable atmosphere	-

VIII FIRE STORMS AND FATALITIES

The preceding sections have indicated that there is a great variety of factors entering into the prediction and description of fire storms. Each of these factors could provide the topic for a very large amount of research. It is therefore of interest to provide some degree of focus to the study of fire storm parameters in order to obtain the applicable results within reasonable time and budgetary constraints. An approach can be made by addressing two rather fundamental questions: Why is OCD Research concerned with fire storms? And, why have fire storms been singled out from other types of mass fires?

The primary interest of OCD is, of course, to determine wartime hazards to the civilian population and national resources, and to provide countermeasures for the reduction of these hazards. Fire storms are alleged to be one of the principal likely causes of high mortality rates following nuclear attacks on metropolitan areas and a source of hazard to life that requires due consideration in civil defense planning. To provide information regarding this source of hazard in a timely and efficient manner, it is clear that the fire parameters considered in the present study should be judged with respect to importance in estimating fire casualties. This consideration can limit the type and degree of detail required in fire models and it can also influence the kinds of distinctions that are made between fire phenomena. For instance, distinctions between fire storms and other types of mass fires must be viewed according to significance in terms of casualties, destruction of structures and industry, and modes of protection.

While much of the popular literature contends that survival is impossible in the fire storm area, the historical evidence indicates the contrary. However, survival in the fire storm area was very much dependent upon what people did and where they were when the fire reached a critical intensity. Survivors were rare among those remaining in buildings, less rare in basement shelters; however, many left these places during the fire buildup phases and found safe refuge both inside and outside the fire storm area. On the other hand, essentially all people survived who were in well constructed concrete bomb shelters. The number of fatalities resulting from the fires then, in the general sense, is a function of the time-rate of fire intensity buildup, the size and configuration of the fire area, the time-rate of movement of population, and the distribution and capacity of adequate shelter within the fire storm area.

Survival in severe fire areas was very rare in conventional buildings and basement shelters because inhabitants generally were forced out of burning structures in from 10 to 30 minutes or were killed in basement shelters by heat and toxic gases. Entry of people into basement shelters after fires had reached fire storm proportions hastened the process by allowing entry of gas, smoke, and heat.(26)

Survival in bomb shelters was almost 100 percent in the fire storm areas. In Hamburg, bombproof shelters of heavy concrete construction protected all shelterees even when such shelters were located in narrow companionways between burning structures.(26) These structures were forced to keep ventilation blowers off to prevent excessive ingress of smoke; however, they were not sealed from the atmosphere and not generally provided with supplementary sources of oxygen. Survival in lightly constructed shelters close to buildings was generally very low. In the Tokyo fire of 10 March 1945, evidence indicated that earth and timber-covered excavations close to structures were useless as protection from fire effects.(49)

Movement through the streets is possible during the early buildup phases of a fire storm. About three-fourths of the people initially in basement shelters in Hamburg apparently saved themselves in this way.(19) However, as a fire storm increases in intensity, movement through streets becomes impossible. People leaving shelters in Hamburg in later phases were seen to collapse before they were able to reach the end of the block.(26) Blocking of passage of streets may result either from plume closure overhead, or from heat radiated directly from burning structures on both sides of the street.(19) Heat radiation and inhalation of toxic gases unquestionably produce fatalities. Autopsies made on persons killed in the Hamburg fire storm indicated serious inhalation damage.(5) Also, the Hamburg fire reached air temperatures estimated at 1400 degrees Fahrenheit, which would be sufficient in itself to cause burning of clothes in the vicinity of the fire (439 degrees F for ignition of cloth).(5) Many people were killed by temperatures below those required to ignite cloth, however.

Survival in large open areas within fire storm areas is possible. In Hamburg, evidence indicates survival frequently occurred in open spaces greater than 300 meters in diameter.(26,16) Oxygen was clearly available in the larger open areas, possibly because of downdrafts over such areas.(Protection in such areas is not necessarily assured, however. Smaller areas and small streams and canals often proved to be traps. In Tokyo, during the great Kanto earthquake and fire of 1923, fire whirls swept across some large open areas, killing many who would have survived the more usual fire hazards.(11) No mention has been found of fire whirls in the literature on the severe German fires, however.(26,50)

Differences in vulnerability and initial conditions in the target areas make direct comparisons of the several fire storms difficult. However, a gross comparison of fatality statistics is instructive. Fatality levels for fire storms and for the Tokyo conflagration of 1945 are given in Table 8. All these fires resulted from incendiary raids. The nuclear attacks at Hiroshima and Nagasaki are not included because no estimate can be given of the number of fire deaths, since the fire areas were largely within the blast damage region.

Table 8

FATALITY ESTIMATES FOR MASS FIRES

City	Fire Fatalities	Population in Fire Area	Percent Fatalities	Population	Percent Fatalities (Unprotected)*
Hamburg†	40,000(16)	280,000	14. %	1,760,000	22%
Dresden	135,000 (?)	980,000	>13.	633,000	>13
Kassel	8,790	91,000‡	9.6	228,000	>10
Darmstadt	8,000	48,000‡	16.7	109,000	>17
Tokyo§	84,000	1,000,000‡	8.4	5,000,000	> 9

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* Among those in conventional structures or basement shelters, i.e., does not include those in well constructed shelters.

† Attack of July 27-28, 1943.

‡ Figures given for number of "homeless" following given raid.

§ Tokyo was an area fire, and not a fire storm. Others were all fire storms.

The incendiary raids are of interest, since most of the fatalities were caused by fire. The raids differ from a nuclear attack in that they required generally 1 to 3 hours to deliver.(49,50) However, in the attacks listed, the fire in most cases built up rapidly during the first 30 minutes of the attack. The total number of fatalities given in the table varies by a factor of 10 or more, and the death tolls are highly uncertain because official surveys of the attacks were not made. The Tokyo raid of 9-10 March 1945 might therefore have been the attack resulting in the highest total number of fatalities, and this attack was not generally considered a fire storm. More uniformity is noted if allowances are made for differing populations, sizes, and distributions. Fatalities as percentage of the people that might have been in the target area are shown. With the exception of Dresden and Hamburg, the number in the target areas was taken as the number of homeless following each raid.(49,50) In Dresden, since most of the city was involved in the raid of 13-14 February 1945 (about 87 percent of structures destroyed), the total estimated population in the city was used. This included the 630,000 resident population and an estimated 350,000 refugees.(24)

On this basis the percentage fatalities is seen to vary from about 8 percent in Tokyo to about 17 percent in Darmstadt. A further correction can be made from the estimate of the number in the fire areas who were safe in the bomb shelters. The last column of Table 8 gives the estimated percentage of fatalities in Hamburg(16,26) among those not in good shelters. The Hamburg figure is raised to about 22 percent if only those initially in conventional structures or basement shelters are considered. Similar estimates could not be made for other German cities since the fraction of the population in good bomb shelters was not known. However, the protected fraction was probably smaller than for Hamburg since that city had better bomb protection than most German cities. There were very few suitable shelters in Tokyo. The final estimates for fire storm fatalities are all within a factor or two of each other, ranging from about 10 to somewhat over 20 percent of the unprotected population at risk.

The levels of fatalities in these fires was heavily dependent upon the amount and distribution of refugees and on the movement characteristics of the population at risk. For instance, in the Tokyo fire, while the initial fire area was 8 square miles(16) and the total 15 square miles,(16) hardly any place in the most densely populated district (Asakusa-Ku district) was more than 1/4 mile from refuge (either the Sumida River or other areas). Also, most people began leaving as soon as they saw that the fire was "out of control."(49) In Hamburg a substantial portion of the people in basement shelters apparently waited until the fire storm had built up before attempting to move, and of course many continued to remain in shelters. Also, neither population nor authorities were acquainted with fire storms. They had coped with all previous fires and therefore had a false concept regarding safe procedures until conditions had become unbearable. By then it was too late to make it to the outside. Consequently, with respect to fatalities perhaps the most important question is: What are the conditions that could give rise to a mass fire sufficiently widespread and intense to prevent movement of unprotected population to areas of refuge? Such areas of entrapment [illegible] occur in any mass fire although in most incendiary [illegible] and naturally caused mass fire, the rate of development is sufficiently slow that population fatalities are relatively low.* From the evidence of the Tokyo fire, however, it would appear that such areas of entrapment are not exclusively associated with fire storm phenomena. In the initial fire area following the fire raid on Tokyo in 1945, many of the same phenomena were reported: rapid buildup, complete burnout, impossibility of surviving in the streets, high winds, ineffectiveness of fire fighting, etc. Consequently, for purposes of determining fatalities a more general question would be: What factors favor the development of fire entrapment areas following nuclear attacks and what are the characteristics of such areas that limit the probability of survival of the population in them?

One possible method for the prediction of possible fire entrapment areas is to determine those areas in which the clothing of people attempting to escape through the streets would be ignited in a short time, assuming that most of the structures in the area are on fire. Using techniques presented by M. Law,(27) we can readily calculate the distance between buildings that must be exceeded to make escape possible. Calculated values for this escape distance for several building heights are given in Table 9.

The estimates given in Table 9 assume that those attempting to escape will be wearing cotton print fabrics, that 50 percent of the surfaces of the burning buildings will be radiating heat, and that the buildings are long with respect to their heights.

A comparison of the estimates in Table 9 with actual conditions at Hamburg is interesting. The streets in the Hamburg fire storm area frequently ranged from 45 to 60 feet across, which would have made them lethal areas during the fire storm by the heat radiation criteria. People in a small park in Hamburg, about 300 meters in diameter, survived; and an area of this size could be expected to have a core that would be relatively safe from heat radiation. The possibilities for predicting fire areas of entrapment with the help of techniques like those used in the preparation of Table 9 warrant further investigation.

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* There are exceptions, such as the great Kanto Fire and earthquake in 1923 where 107,000 were killed.(11)

Table 9

MINIMUM STRUCTURE SEPARATION DISTANCES PERMITTING ESCAPE - WITH REFERENCE TO THE HEAT RADIATION HAZARD

Building Heights (feet)	Distance Between Structures That Must Be Exceeded To Make Escape Possible (feet)
20	40
30	57
40	67
50	83
60	96

The occurrence of fire entrapment areas is a matter that can be determined much more easily than occurrence of fire storms, since the former is much less dependent upon atmospheric parameters. Considering the important parameters identified in Section IV, it appears that areas of entrapment are related primarily to the density of fires and to fuel loading. Determination of lethality of the fire would require knowledge of the uniformity with which fires occur over the area, the rate of fire intensity buildup, the number and distribution of areas of refuge, and the behavior pattern of the population.

IX RECOMMENDATIONS FOR FUTURE WORK

It is recognized that the civil defense need for a better understanding of fire storm phenomenology and behavior is based on need to develop information about the hazards to persons and property to assist in the specification and development of useful countermeasures. Ultimately, however, this need is not restricted to fires classed as fire storms but to all classes of fires. Fundamental to such research also is the need for a better knowledge as to the fire storm effects on people, structures, and industry, the likelihood that fire storms could be created in the United States by nuclear detonations, and the interaction between fire and radiation hazards.

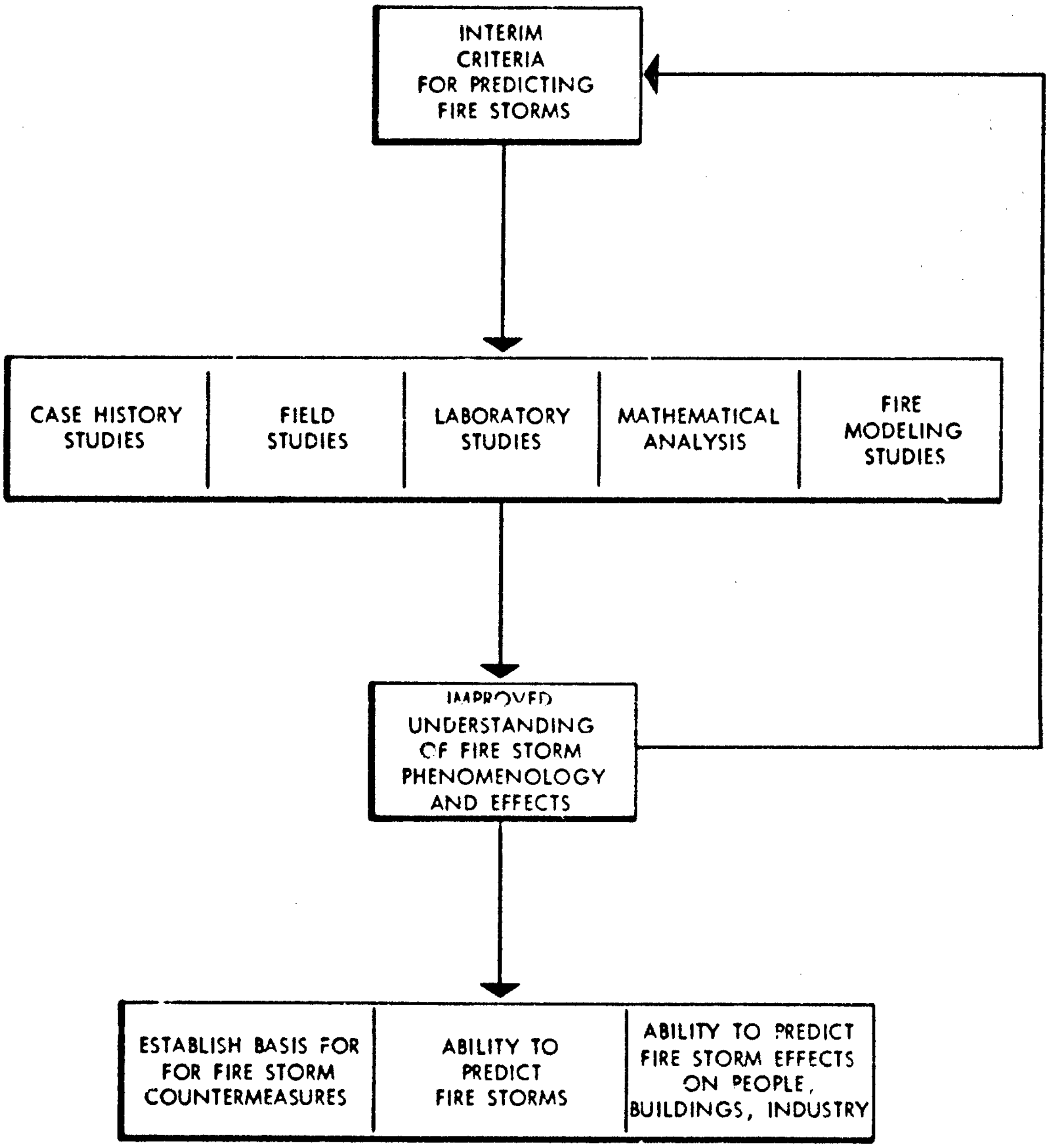
Other associated factors for which further information appears to be needed include: (1) biological responses to a variety of fire environments, (2) description of fire damage to structures and industrial facilities, (3) description of fire debris, (4) effect of fires on the radiation hazards from fallout, and (5) combined effect of fire and fallout on countermeasures.

While small fires in the laboratory and in the field will unquestionably contribute to a better knowledge of fire storms, research aimed at a better understanding of fire storm behavior must go well beyond the concept that fire storms and conflagrations are simply magnified small fires. It is clear that mass fires involve many interactions with atmospheric effects and other factors that are difficult to scale and that may not have been observed in small fires. Fire models of the types discussed in Section IV of this report could be a tool which would ultimately lead to a greater understanding of fire storm and mass fire behavior.

One concept for a fire storm research program is illustrated in Figure 6. The program starts with recognition of the need for improved knowledge of fire storm behavior and interim criteria for possible fire storms. Models are used to enhance understanding of the phenomena, to indicate experimental information required, and to establish a basis for design of a coordinated research program. Increased understanding of fire storm behavior and effects will in turn improve the models and point toward other techniques for studying the problem. Each time the cycle is repeated, the ability to predict the possible occurrence and effects

FIGURE 6

FIRE STORM RESEARCH CYCLE



SOURCE: Stanford Research Institute.

of fire storms is increased. The procedure must be repeated until a satisfactory level of understanding and predictability is achieved.

Most of the unsolved problems of fire storm behavior may be placed in three broad categories. These are: thermal energy release rate, atmospheric factors, and interactions among the various fire storm behavior factors. Major thermal energy release rate factors include fuels, combustibility, topography, configuration, spread, buildup, fire density, size of the fire area, and fire dependence on air flow.

The second major group is concerned with atmospheric factors. Two elements that clearly warrant primary attention are the effects of the wind field and of atmospheric stability. The influence of these conditions on the development of fire storms and mass fires has so far received little attention. An effort of considerable magnitude is required in order to place these factors in proper perspective.

The final and possibly most important group of problems is that group which will define the interactions among the thermal energy release, atmospheric factors, the convection column, and induced surface and upper winds. It is necessary that these interactions be understood, particularly insofar as they influence the development of induced winds and the convection column. In fact, it is the interactions and feedback that make the problem so difficult, and "causes" and "effects" often cannot be clearly separated. The fact that one "effect" may also be part of the "cause" of its own "cause," which in turn may be related to other of its "causes," limits the extent to which individual factors or relationships may be fruitfully studied.

Recommendations for specific tasks that would assist in achieving a capability for predicting the occurrence of fire storms may be helpful in planning a step-by-step program. A list of such recommended tasks is presented below. This listing is not a complete one, but does represent our view of the more important tasks that seem evident at this point in the research.

Primary Ignitions

> Provide methods for estimating the range and frequency of primary fires from nuclear detonations of varying yields, heights of burst, and atmospheric conditions.

Secondary Ignitions

Provide methods for estimating the range and frequency of secondary fires from nuclear detonations of varying yields and heights of burst.

Fuel Loading

Investigate the minimum fuel loading and configuration required to support a fire storm, and investigate relationships between these two factors and the burning rate.

Study fuel loadings of World War II fire storms.

Obtain data on fuel loadings in U.S. urban and wildlands areas.

Configuration

Explore probable effects of target configuration on fire storm development. Consider various geometrical shapes.

Obtain information on expected fire behavior as a function of fuel arrangement and spacing.

Combustibility

Explore relationship of combustible properties of materials to initial fire density, fire spread, change in fire intensity with time and total energy released, and energy released by the fire.

Study effects on combustibility resulting from various types of materials, recent humidity and precipitation history, and temperature.

Topography

Investigate effects of topography on convection column development. Show how topography can influence fire spread (fire breaks, hills, etc.)

Size of Area

Study probable lower size limits for fire storm areas, using fire modeling studies, considering possible effects from countermeasures, etc.

Investigate upper size limits for fire storm areas, based on induced winds and convection processes, topography and distribution of fuels in the United States, etc.

Spread and Buildup

Determine lower limits for change in fire intensity with time and total energy released (as a function of spread, fuel density, initial fire density, etc.)

Study fire propagation and spread methods and rates. Explore limits.

Investigate relative contribution of convection and radiation on fire propagation rate.

Fire Density

Study relation of initial fire density to burst height, weapon size, etc.

Thermal Energy Release Rate

Investigate the range of thermal energy release rates that would support a fire storm.

Study the relationship of energy release rate to combustible gas flow, radiation, and reaction rate; and identify the processes that limit the magnitude of burning rates (rate at which fuel is consumed).

Study the relationship between the burning rate of the fuel and the wind field.

Study the interactions between two or more fires as they affect energy release rates.

Wind Profile

Investigate low level wind fields that will permit or foster development of a fire storm. Consider whether low level wind jets can influence fire storm development (as postulated for "blow up" forest fires).

Review available wind data for past fires of all types.

Investigate how the relationship between wind profile and atmospheric stability might influence fire storm initiation and development.

Atmospheric Stability

Investigate the effects of atmospheric stability on convection column formation and on induced ground winds.

Explore possible influence of inversion layers on fire storm formation.

Review available atmospheric stability for past fires of all types, and investigate whether, aside from other atmospheric effects, some unique atmospheric condition or combination of conditions is needed to "trigger" a fire storm.

Convection Column

Explore relationships among height and diameter of convection column, area of fire, efficiency of combustion process, and interactions between convection currents and burning processes

Investigate how convection columns form in the presence of stable and unstable atmospheres.

Develop relationships between convection currents and fire spread.

Study the conditions under which the convection columns from several separate fires join.

Provide interactions between convection currents and burning processes.

Induced Surface Winds

Investigate relationship between high velocity surface winds and convection column parameter.

Determine whether limited spread of fire storms is result of inrushing ground winds.

Study whether high velocity ground winds can be accounted for without large scale vortex flow.

Criteria

Revise periodically, as better information becomes available, the criteria for predicting occurrence of fire storms.

Investigate the conditions under which fire storms might be expected in urban areas of the United States.

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