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(Supersedes CPG 2-1A3 dated May 1982, which may not be used)

ATTACK ENVIRONMENT MANUAL

Chapter 3

What the planner needs to know about Fire Ignition and Spread

FEDERAL EMERGENCY
MANAGEMENT AGENCY

FOREWORD

WHAT THE EMERGENCY PLANNER NEEDS TO KNOW ABOUT THE NATURE OF NUCLEAR WAR

No one has gone through a nuclear war. This means there isn't any practical experience upon which to build. However, emergency management officials are responsible for preparing for the possibility of nuclear war. Intelligent preparations should be based on a good understanding of what operating conditions may be like in a war that has never occurred. If the planner lacks such understanding, the emergency operations plans produced probably won't make sense if they ever have to be used.

The Attack Environment Manual has been prepared to help the emergency planner understand what such a war could be like. It contains information gathered from over four decades of study of the effects of nuclear weapons and the feasibility of nuclear defense actions, numerous operational studies and exercises, nuclear tests experience, and limited experience in wartime and peacetime disasters that approximate some of the operating situations that may be experienced in a nuclear attack. In short, it summarizes what is known about the nuclear attack environment as it could affect operational readiness at the local level.

The data on the effects of nuclear weapons used in this manual have been taken from the 1977 edition of "The Effects of Nuclear Weapons" (ENW), compiled and edited by S. Glasstone and P. J. Dolan and prepared and published by the United States Department of Energy. Copies are available for purchase from the U.S. Government Printing Office. The ENW is the most widely available authoritative source of weapon effects and is in many public libraries across the country. For these reasons it was chosen as the source data in this manual.

This Attack Environment Manual supersedes CPG 2-1A1 through 2-1A9.

LIST OF CHAPTER TITLES

PREFACE TO CHAPTER 3

This description of the fire environment following nuclear attack provides basic information needed to plan realistic actions to reduce fire casualties and loss of property. It presumes that the reader is familiar with the material in chapters 1 and 2 of the manual. Knowledge of the material in subsequent chapters is not a prerequisite; however, reference is made to pertinent issues in the chapters on fallout, the shelter environment, and emergency operations.

Anyone making a study of the results of the air attacks of World War II on industrial and population centers is struck by the realization that fire effects accounted for much of the damage and loss of life. And, while nuclear explosions add new dimensions to the potential for urban destruction, fire remains a threat of first order. The nuclear bombs dropped on Hiroshima and Nagasaki at the close of World War II demonstrated the great fire-starting potential of nuclear explosions. While nuclear weapons have changed since 1945, and U.S. cities today are considerably different from Japanese cities at the close of World War II, we can expect many of the same principles to apply. Even much of what was learned from the conventional incendiary bombings during that war is applicable to planning for nuclear attack.

Information is presented in the form of "panels," each consisting of a page of text and an associated sketch, photograph, chart, or other visual image. Each panel covers a topic. This preface is like a panel with the list of topics in chapter 3 shown opposite. If the graphic portion is converted into slides or vugraphs, the chapter or any part can be used in an illustrated lecture or briefing, if so desired.

The examples given in this chapter typify nuclear explosions in the range between 500 KT (that is, 1/2 MT) and 1.5 MT. Whenever the generic term "megaton" is used without numeric quantification in the text it refers to yields in this range, which represent much of the strategic arsenal of the Soviet Union today. Since the distances from Ground Zero (GZ) at which similar incendiary effects occur for this whole range of yields are only about 20 percent more or less than that from GZ of the 1-MT explosion, it is usually sufficient to illustrate this range of yields with the effects of the 1-MT-yield case alone. Airburst are described in this chapter because they tend to maximize incendiary effects. A burst height of 5,000 feet has been used for most examples.

Following the first two introductory panels, the next 15 panels deal with subjects of basic phenomenology, covering the thermal pulse and its transmission to ignitable materials and exposed people (3 through 7), fire starting (8 through 11), and fire spread (12 through 17). Next, the consequences and implications of the fires--especially mass fires--are described in panels 18 through 26, ending with an illustration of the fire effects of nuclear attack on a major industrial city of the United States. Panels 27 through 36 consider fire survival prospects of the urban population, discuss the potential for fire control and incendiary damage limitation, and offer some planning options to minimize the dynamic of protracted threat of nuclear fires and their possible climatic effects. Finally, panel 37 suggests additional reading for those interested in more information.

CONTENTS OF CHAPTER 3

WHAT THE PLANNER NEEDS TO KNOW ABOUT FIRE IGNITION AND SPREAD

FIRE IN A BLAST-DAMAGED ENVIRONMENT

Fire effects and the planning of emergency actions to counter them need to be viewed in a context of how severely damaged different parts of the urban community are by the direct effects of the nuclear explosion--particularly the blast damage. We recognize a rough division into three regions of blast severity:

Region 1. Close to Ground Zero (GZ)--12 psi or greater: Buildings are collapsed and fires may be numerous, but the overall intensity of the fire is limited by the massive destruction and relatively slow rates of burning and spread of fires in debris.

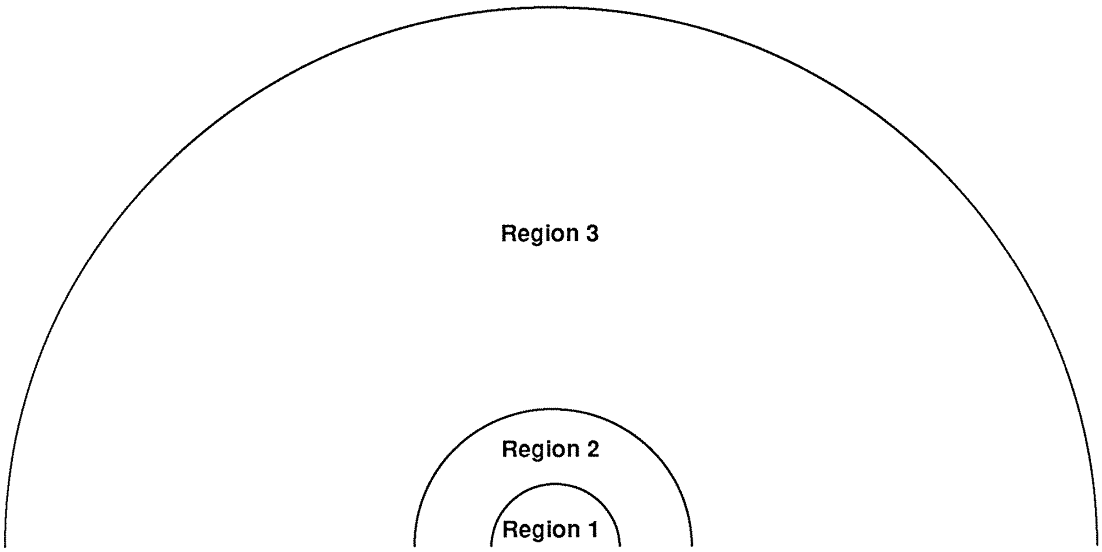
Region 2. Farther from GZ--12 to 4 psi: Buildings are severely damaged, but some remain standing; fires are numerous. In some cases these standing buildings burn rapidly, spreading fire to neighboring buildings that initially escaped fire starts. In tall buildings where lower floors are shielded by surrounding structures, fires are initiated directly by the thermal pulse only in upper floors. Here, the lower floors may become involved through spread of fire downward (a slower process than spread upward) or by subsequent spread of fire from neighboring buildings.

Region 3. Still farther from GZ--4 to 1/2 psi: Fewer buildings are collapsed, but many roofs and weaker walls are caved in and doors blown out of their frames. Fires are scattered and entire city blocks (many of them) escape initial fire starts.

Because of widespread major damage, conventional firefighting will be virtually nonexistent. Reasons include: (1) damage to equipment and injuries to firefighters; (2) streets blocked by debris; (3) disruption of water mains and the electric power grid; (4) lack of suitable emergency communications; (5) the threat of blast and thermal effects from additional weapons; and (6) the threat of radioactive fallout. As a result the highly damaged regions 1 and 2 (constituting 6 percent of the fire-affected area from a single weapon) may be expected to suffer essentially complete burnout and heavy loss of life (exceptions of record at Hiroshima are cited in panel 32 as potential guidance to planners). Though one cannot accurately predict where the damage regions will be located, judicious considerations by planners may identify the potential target areas (see next paragraph) where evacuation would be prudent and the preferred evacuation routes to use. In region 3 (94 percent of the area affected by a single weapon), damage and debris is noticeably less, while fires are expected to be numerous but scattered and sporadic. These conditions afford an opportunity to limit the impact of fire (see panel 33).

Consistent with chapter 2, the facing page depicts the effects in the three regions when a 1 MT weapon is exploded at a height to deliver a peak overpressure of about 40 psi over the largest possible area. This height of burst represents an attack to achieve optimal blast damage to semihard, critical facilities (shipyards, factories, transportation centers, communications centers, etc.) with no regard to minimizing its impact on the civilian population. (The height chosen is not the height of maximal fire damage.) The boundaries of the three regions are circles, with their centers at GZ (directly below the exploding weapon); the radial distance (its "reach") and corresponding range of overpressures are tabulated for each.

THREE DAMAGE REGIONS RESULTING FROM
1 MT WEAPONS EXPLODED 5,000 FT ABOVE GROUND*
(12-mile visibility)



Region	1	2	3
Reach (mi)	2	4	17
Area (sq mi)	12.6	37.7	885
% Total Area Involved	1.4	4.2	94
Overpressures (psi)	>12	4 to 12	0.5 to 4
Expectations:	Collapsed buildings Numerous fires Slow fire spread in rubble Fluence >>40 cal/cm^2	Severe bldg damage Numerous fires Rapid fire spread (inter & intra bldg) Many fires started in upper floors Slower vertical downward spread Fluence ≥40 cal/cm^2	Few bldgs collapsed Roofs cave in Doors & windows blown in Fires scattered Fluence ≥40 cal/cm^2

* Specialized terms and units of physical measurement unique to this chapter are listed in the Glossary (panel 37).

THE FIRE THREAT

Although the experiences of Hiroshima and Nagasaki have provided the only direct evidence of the threat of fire started by nuclear weapons, later studies of the threat of the resulting mass fires have provided us with a basis for extrapolating to effects of today's larger strategic-yield weapons. The scale of effects can be much greater and the simultaneity of fire starts will enhance fire intensity with the potential to induce storm-like winds.

Mass fires are not unique to nuclear attack. Mass fire observations from a number of pertinent circumstances generate useful conclusions about the phenomena. Particularly important sources of information are the fire raids of WWII; extensive observations of nonnuclear catastrophes, such as those produced by major forest fires and by earthquakes in Japan; and simulations--conducted to make direct measurements of the urban threat (thermal output and combustion products in relation to fuel loading and "street widths"). These studies of events have provided real-world examples of mass fires comparable in size and/or intensity to those expected from nuclear attack. It is important to appreciate that 80 percent of the population at direct risk in situations typical of the worst mass fires of WWII (Hamburg, Germany) survived in basement shelters, and no fire deaths were reported in blast shelters.

Fires of all types pose threats to human survival, buildings, and other essential resources. Fire threats to life take many forms. In any fire, a major--often dominant--cause of death is inhalation of toxic combustion products; carbon monoxide is deadly even in low concentrations; smoke is a frequently cited killer; and modern plastics introduced a new threat. The visible components of smoke also contribute to fatalities. Escape from a burning building is difficult or even impossible because of poor visibility. Burning to death is often a secondary result of entrapment or debilitation by inhaled toxicants. In mass fires, people also succumb to heat, respiratory system burns (caused by inhaling hot air and caustic gases), and suffocation. The conditions in a "firestorm" can be so hostile that people are unable to survive even in the middle of wide streets and open, park-like areas.

In a nuclear war, an additional threat is untimely displacement of people out of burning shelters into the streets either after radioactive fallout arrives (approximately 1/2 to 1 hour following a nearby surface burst) or in the face of subsequent explosions. Whenever delayed explosions occur, people out of doors can be injured or killed by the thermal pulse of the nuclear fireball.

A variety of factors may play a role in large urban fire development resulting from nuclear attack. The adjacent figure summarizes these factors; some are well understood but others are not. Subsequent panels discuss the better understood aspects.

NUCLEAR FIRE-THREAT FACTORS

Attack Conditions	Yield; height of burst; single/multiple burst
Thermal Irradiation	Atmospheric transmission; shadowing; window transmission; dust/smoke obscuration
Primary Fires	Ignition thresholds; abrupt flashover; occupancy fuels; ventilation effects
Blast Effects	Secondary fire initiation; flame blowout; structural damage, debris effects
Dust Generation	Blast scouring; structural collapse, dust suspension times, transmissivity loss
Fire Growth and Spread	Radiative, convective, fire-brand spread; fire-wind interaction; breakup/merging of separate fires; onset of mass fires
Fuel Consumption	Fire intensity; power-density history; mass-fire behavior, firestorm phenomena
Smoke Generation	State of fires; ventilation, combustibles, fire intensity, temperature; fuel compactness
Smoke/Dust Lofting	Concerted power density; mass-fire/firestorm onset; atmospheric turbulence; fallout/rain out
Damage/Longterm Impact	Structural damage; resource damage; productivity loss; replacement index; collateral effects, casual-ties, infrastructural damage, recovery constraints

PANEL 2

THE THERMAL PULSE

Most people understand that the blast wave of a nuclear explosion can start fires by disrupting and damaging gas and live electrical lines, operating wood stoves, fireplaces, household appliances, and industrial equipment. Few, besides weapons-effects specialists, comprehend the fire-starting capability of the thermal pulse or "heat flash" emanating from the fireball at the speed of light following nuclear detonation.

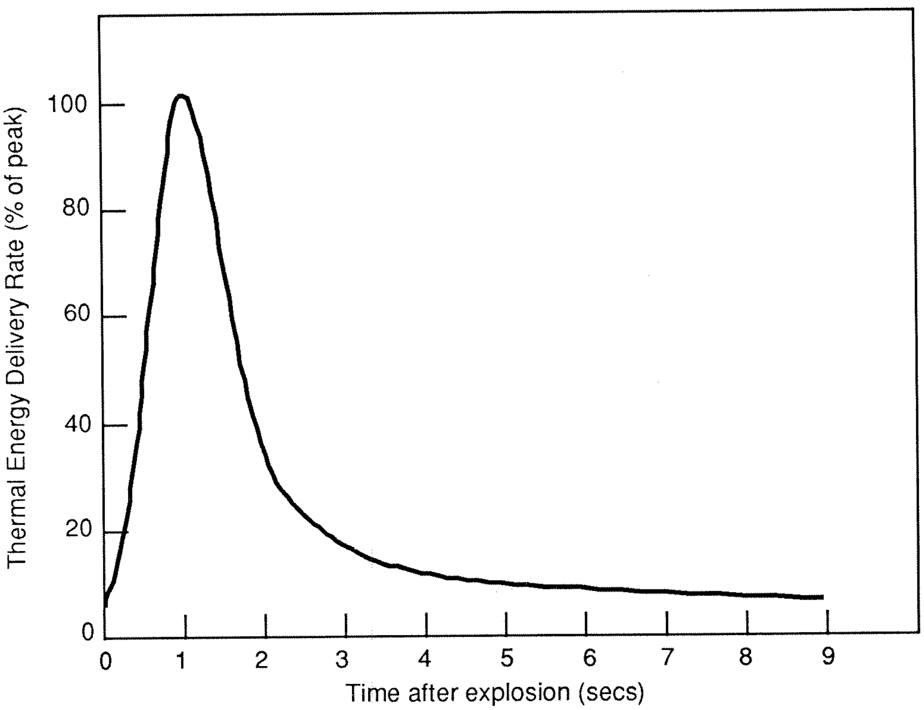
When a nuclear explosion occurs, an enormous amount of energy is released suddenly and deposited in such a small mass and volume that extremely high temperatures are created. All bodies radiate energy, the character or "frequency" of which is directly related to their temperature. At the temperature of ordinary flames, radiation is principally in the infrared; the exploding nuclear weapon is so much hotter than ordinary flames that 80 percent of the energy is initially radiated as invisible X-rays. These are quickly absorbed in the surrounding air, heating it to form the visible fireball. The fireball, in turn, reradiates about one-third of its energy as visible and infrared or "heat" radiation.

Heat sources can be quantified in terms of the radiant energy delivered, e.g., over an area at some fixed location or distance. This particular measure (often called the thermal fluence), with units stated in calories per square centimeter (cal/sq cm), may be delivered in short or long periods and at varying rates (as illustrated on the adjacent page). The rate of delivery by the source (in cal/sq cm per second) is called the thermal flux; and, together with the total energy delivered, it has an important role in determining the degree of damage to the surfaces it strikes. The degree of damage depends on the damage threshold amount and the delivery time frame. As with other forms of radiation, less damage will ensue if the threshold amount for damage is somehow delivered over a longer time span.

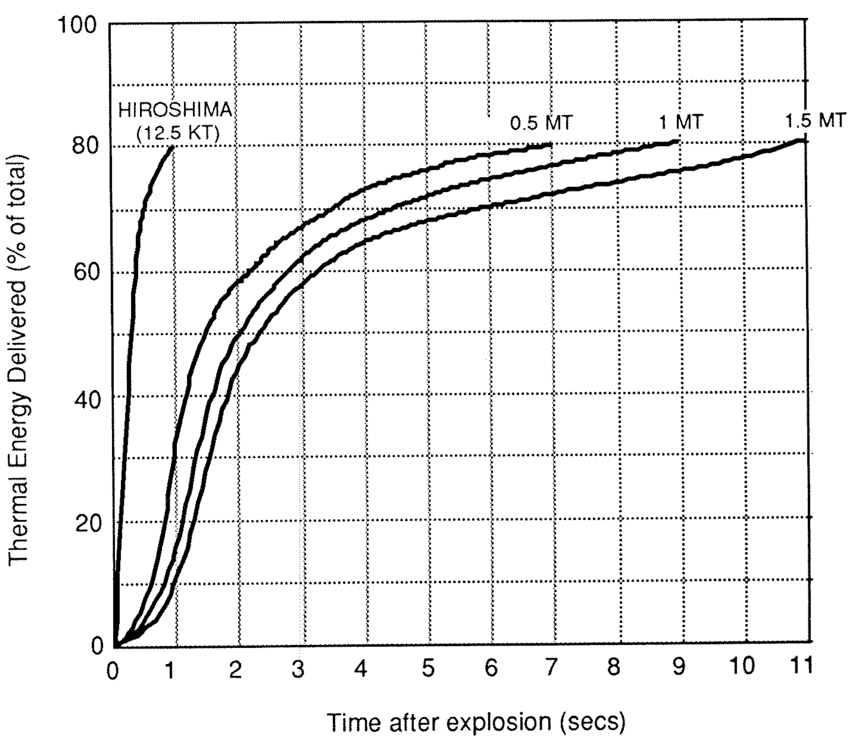
Because strategic nuclear weapons always deliver their thermal energy very rapidly (in seconds) and in a consistent fashion, the rate of delivery is less critical in comparing weapons. Thus, thermal damage levels for nuclear weapons sources are proportional to thermal fluence. Rate effects show up, then, as slight differences in damage thresholds with weapon size.

The adjacent illustrations show that the entire thermal radiation process from nuclear weapons is over in seconds and indicate 1-3 seconds is the critical time span for damage from the thermal pulse. Peak output occurs at about 1 second for megaton size weapons (upper illustration--which shows the variation in thermal flux with time) while the majority of the output is emitted in less than 3 seconds (lower illustration--which shows the cumulative output versus time). This output also defines the percent of the thermal fluence delivered at a fixed location versus time. The lower three curves give evidence that, as the yield of the weapon increases, the rate of delivery of a given thermal fluence slows (albeit at greater distances). Hence, it is more likely that people would have time to take evasive actions to mitigate the thermal pulse effects following detonations of megaton weapons than was the case for the Hiroshima-size weapon of WWII.

THERMAL PULSE OF A MEGATON YIELD AIRBURST



ACCUMULATED THERMAL ENERGY FRACTION



PANEL 3

MODIFICATION OF THERMAL EFFECTS BY ATMOSPHERIC CONDITIONS

The nuclear thermal pulse has been discussed in panel 3 in terms of the weapon output behavior, but the intensity of the energy delivered at a distance depends also on conditions of the atmosphere through which the pulse must pass. Smoke and smog reduce the transmitted energy, much as they do with sunlight. Some of the energy is absorbed by water vapor, water droplets, carbon dioxide, and air pollutants particles; but the main effect of the atmosphere is to scatter and reflect, redirecting the path of the thermal energy radiating out from the fireball.

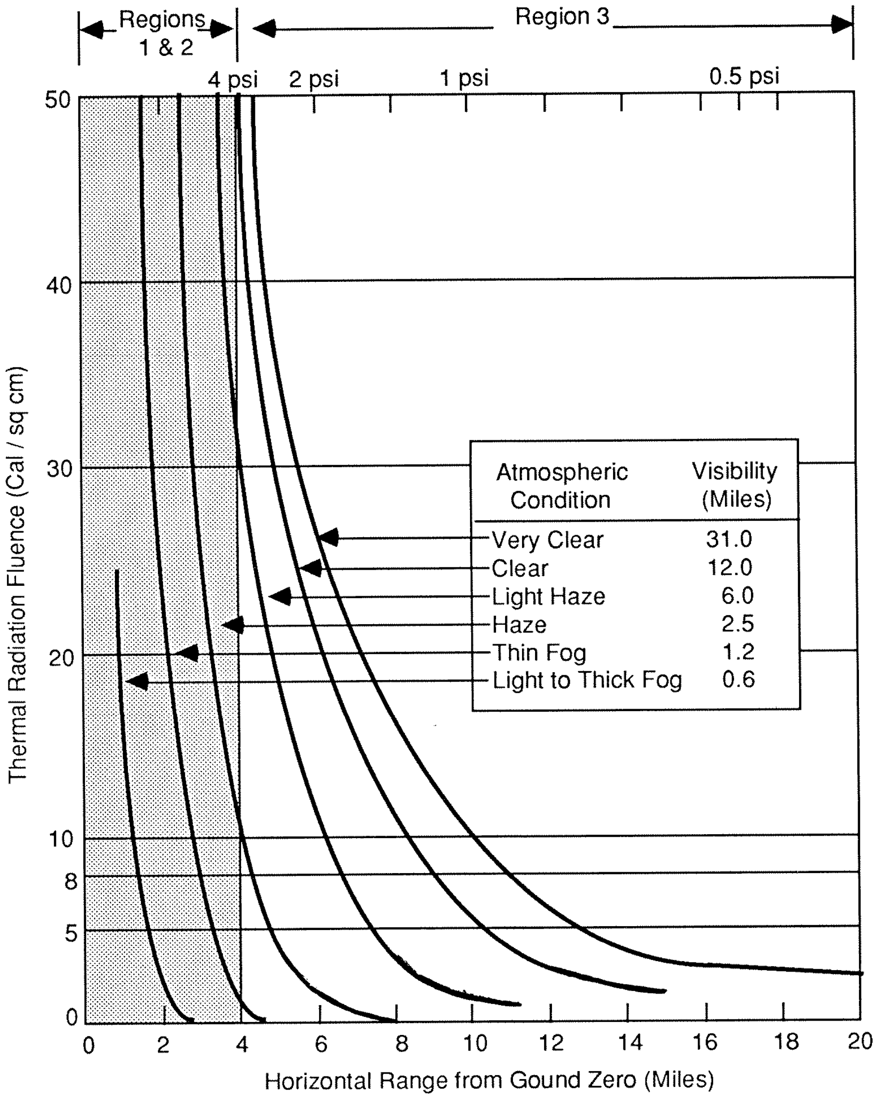
As the figure shows, this atmospheric redirecting of the thermal pulse can shorten (by a factor of 1 to 10) the distances from GZ where hazardous levels of thermal exposure can be experienced. For example, haze can cut in half the distance (reach) at which a serious burn would be expected on bare skin as compared to clear-day exposure (compare the "haze" and "clear" curves).

The scattering process also causes much of the thermal fluence--as read from the graph--to impact a fully exposed surface from all directions. That means that a major portion of the thermal fluence comes from the whole sky, not directly from the fireball. In fact, less than half the fluence on a fully exposed flat surface outdoors comes directly from the fireball when the distance is equal to the visibility. Accordingly, in a light haze (6-mile visibility), an unshielded outdoor surface located 6 miles from GZ, where it would be exposed to nearly 9 cal/sq cm, would receive only about half that amount via a direct path from the fireball. So even a shielded person (lower sketch) could be exposed to more than 4 cal/sq cm of scattered-in thermal pulse, enough to cause first-degree burns to bare skin. The real benefit of scattering lies in the reduction of thermal fluence on the interior surfaces of rooms (where building-destroying, life-threatening fires are most likely to start) because the radiation is intercepted by roof and walls. These shielding effects and their impact in reducing thermal pulse fire starts are discussed further in panels 6 and 7.

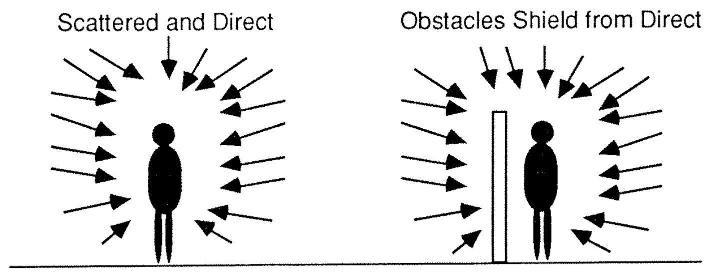
Both snow on the ground beneath the fireball and clouds above it would increase the thermal fluence levels shown. A 50 percent increase could be expected in either case, while the presence of both could more than double the values. Clouds below the fireball reduce thermal fluence in much the same way as haze and fog. Light clouds can be equated to thin fog, heavy clouds, to heavy fog.

In this chapter, we will consider the heat effects transmitted in clear atmosphere because this represents a severe case--though not necessarily the most severe for which to plan. Emergency planners should be aware that the hazard could be greater, but more likely would be less, than the illustrations indicate.

ATMOSPHERIC EFFECTS ON THERMAL FLUENCE FROM A 1 MT WEAPON



ATMOSPHERIC SCATTERING EFFECTS



EFFECTS OF THERMAL PULSE ON EXPOSED PEOPLE

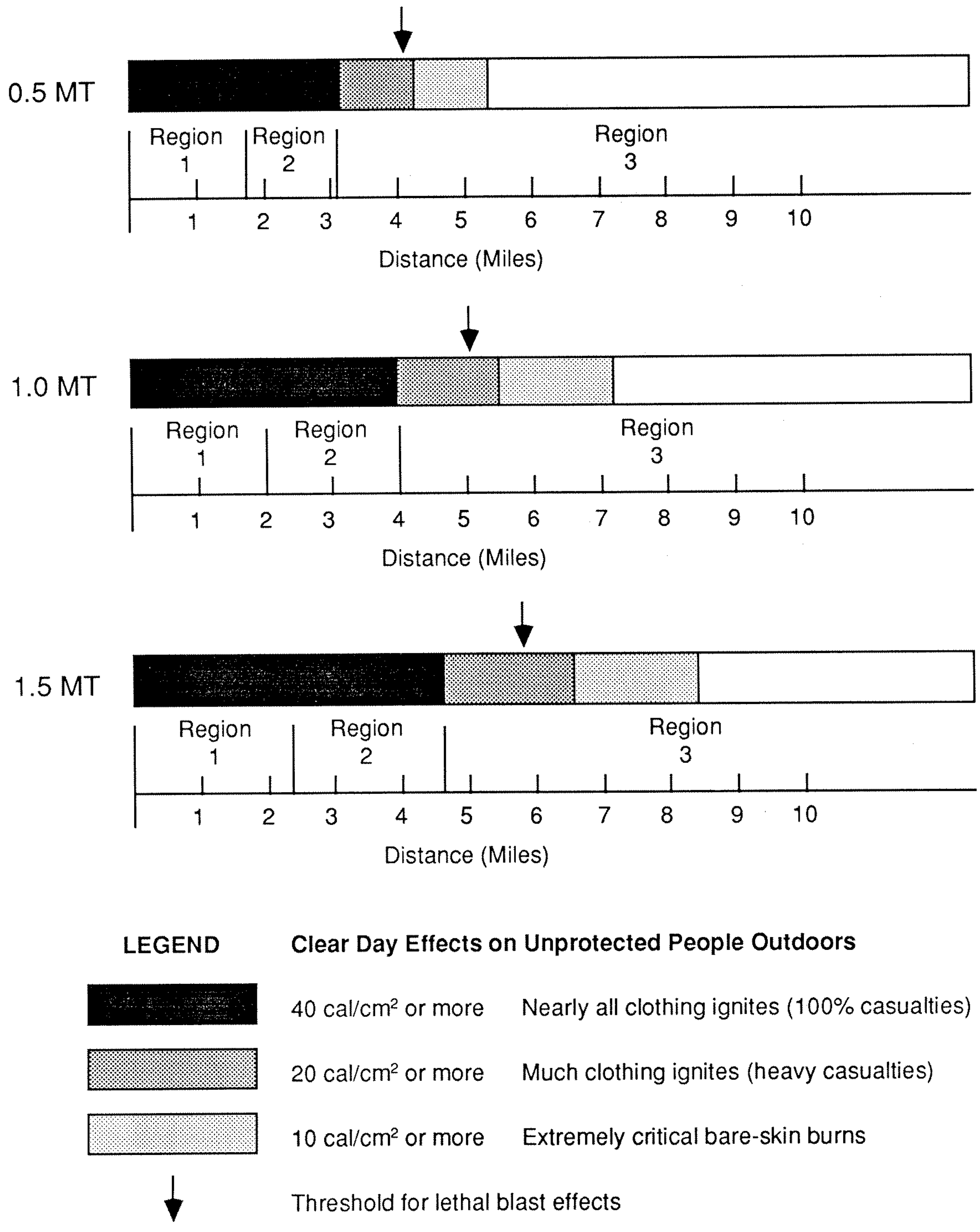
In panel 3, thermal fluence was introduced because it provides a useful quantifiable characteristic of the source that may be delivered to an exposed area at some distance. In panel 4, the effect of the atmosphere was discussed in terms of the effect it can have on the thermal fluence that is delivered; i.e., both directly and indirectly (via scattering). Here we discuss some of the effects of the actual thermal fluence exposure experienced.

The adjacent figure relates some specific damage levels to the weapon that creates them. For 0.5, 1.0, and 1.5 MT weapon sizes, the figure depicts "clear day" (defined as 12-mile visibility) "reach" (ground range or distance) at which several critical thermal fluences will be delivered to a completely exposed (unshielded) surface that is perpendicular to the direction of the radiant heat flow. The reaches shown indicate the maximum distance of the thermal fluence for clear-day conditions. It is important to understand that thermal fluence varies continuously with distance (as indicated in the panel 4 graph) between the maximum reaches we have selected to show here. Also shown on the adjacent figure (as arrow heads) are the ground ranges corresponding to the threshold for lethal impact; per chapter 2, this occurs in the vicinity of 3.3 psi for these megaton weapons. Consequently, it is apparent that the thermal pulse can cause deaths at distances beyond those of the lethal blast wave threat.

For the case at hand, in the range of 0.5 to 1.5 MT weapons, 40 cal/sq cm corresponds roughly to 4 psi (the approximate location of the transition from region 2 to region 3). At this fluence, nearly all types of exposed clothing would ignite causing certain fatality for people caught without any shielding. (Of course, exposed people may also be subjected to various levels of blast, blast-propelled missiles, and gamma rays at such a location.) At 10 cal/sq cm, which corresponds roughly to the 2 psi level (in region 3), third-degree burns would be experienced on bare skin. Third-degree burns on a majority of the body's surface can be lethal and require specialized treatment in any case. At 7 to 8 cal/sq cm, which corresponds approximately to the 1.3 psi level (also in region 3), bare skin would receive second-degree burns. Second-degree burn onset may be regarded as the threshold of serious burn injury. At 5 cal/sq cm, which corresponds very closely with 1 psi, anybody caught in the open without shielding can expect first-degree burns on bare skin. First-degree burns are painful but do not blister; they are somewhat like a sunburn.

Full exposure is rare due to a variety of shielding effects. Some important effects that can reduce exposure are discussed in the next two panels. Panel 6 describes shielding effects of intervening solids and of shadow zones created by natural objects outdoors; panel 7 describes screening and shielding effects as observed from indoors.

SELECTED CRITICAL THERMAL FLUENCE REACHES



PANEL 5

THERMAL SHIELDING

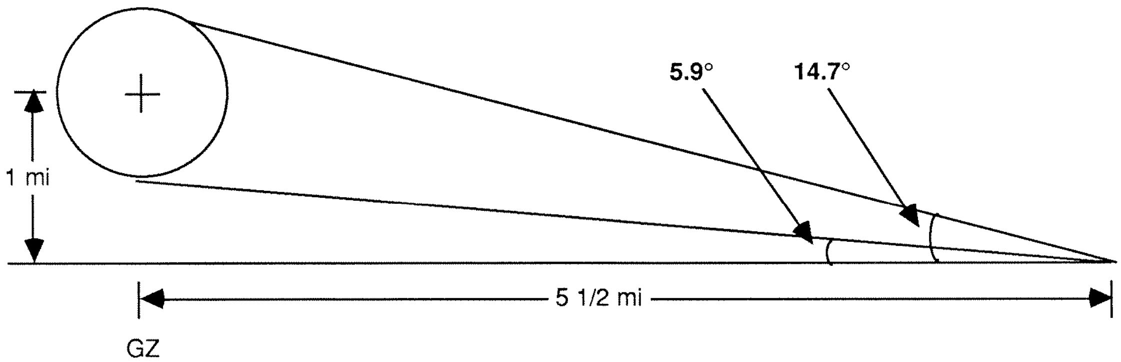
In most places, buildings, trees, hills, and other objects are likely to block out various fractions of the thermal pulse. Virtually any opaque material in the path of the direct radiation will reduce the intensity of the thermal pulse. Such shielding will have its main effect before the blast wave strikes, because the thermal pulse is so brief (panel 3) and its radiation travels at the speed of light. Therefore, unless the shielding object burns away prematurely, it will remain in place to intercept the thermal radiation from the fireball. Even if the shielding should burn away, the burning process will contribute to the clouds of smoke and/or steam that obscure, intercept, and absorb thermal radiation. Rarely, then, would any location in an urban area experience the thermal pulse unaltered by the surroundings; hence, it is likely that less than the full possible thermal fluence transmitted through the atmosphere (panel 4) would be received.

More particularly, however, at distances from GZ where a person outdoors would probably survive the other direct and immediate effects of the explosion, he or she also would have a good chance of being shielded from the thermal pulse, as the adjacent sketch shows. In fact, exposure to the full intensity of the fireball's thermal radiation is much less likely than is complete or partial shielding. If the burst occurs nearer the ground, the shielding effects could be greater and more extensive then illustrated. Conversely, greater heights of burst would tend to reduce shielding effects.

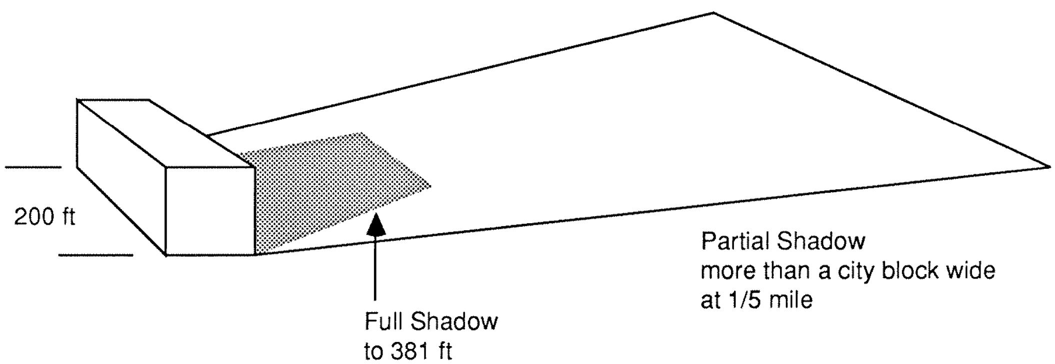
Overall, shielding probabilities play an important role in the assessment of the thermal pulse threat. Consequently, thousands of observations have been made in typical locations in many cities to estimate the likelihood that vulnerable room furnishings and other ignitable fuels would be exposed to the heat radiation of the fireball. This information is required to calculate thermal-pulse fire starts. Starts are discussed in more detail in panel 8; shielding implications are discussed in panel 7.

AN EXAMPLE OF FIREBALL SHIELDING

Ground Level Fireball Angles at 5 1/2 miles (in Region 3)



Ground Level Shielding by an 8-Story Structure at 5 1/2 miles
(building height: 100 ft)



SHIELDING INDOORS

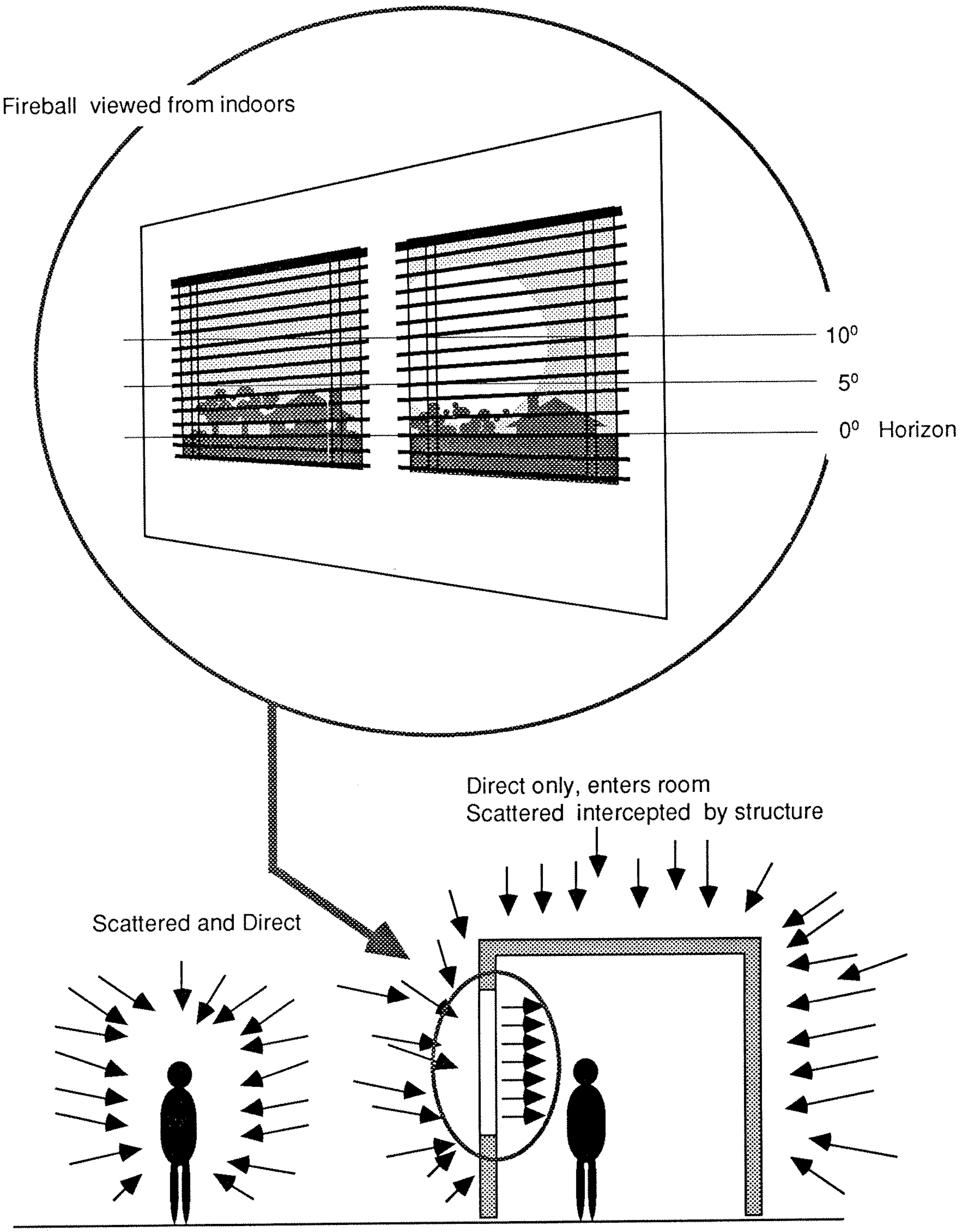
The figure opposite illustrates the fireball of a megaton airburst as it would appear at the peak of the thermal pulse when viewed through a window from inside a residence located--in region 3--between 5 and 6 miles from GZ. Notice that those opaque objects that combine to reduce the fireball exposure of the room and its contents are of two kinds: (1) items close to the observer--venetian blinds, window frames, and sashes; and (2) items far away from the building, comprising a "visual horizon" that rises above the earth's natural horizon--trees, telephone poles, signs, steeples, and other buildings.

In the illustration, the visual horizon--which often varies between 5 and 10 degrees above the natural horizon--obscures nearly one-third of the fireball; while window coverings and the side of one window, itself, reduce the transmitted fluence even further. In clear weather, when full outdoor exposures would be 23 cal/sq cm at this distance (the panel 4 graph using 12-mile visibility), the in-room exposures in this instance would certainly be less than 8 cal/sq cm because of the scattering effects. The exposure could be less than 4 cal/sq cm, depending on the number of panes and kind of glass (also how clean the glass is) and weather insect screens are present. Remember, most of the thermal pulse is delivered before the blast wave strikes and blows away the window coverings. Because thermal pulse fire starts are expected to originate predominantly in rooms, the number of fires may dwindle rapidly beyond the 3 psi ground range.

Farther from GZ, the fireball (at the same stage in its development) does not reach as high above the natural horizon and tends to be somewhat more obscured by the visual horizon. Note, however, that the illustration is for a ground-floor room, the shielding would often be much less in the upper stories of tall buildings.

Some compensation for the loss of visual-horizon shielding in upper stories of tall buildings is provided by the increased likelihood of total shielding of, and by, neighboring buildings. As panel 6 showed, buildings cast very long shadows. Besides, tall buildings are typically in areas of high building density where building separations are a mere fraction of these shadow lengths. If building heights, on average, are five times greater than the average building separation distances (e.g., a moderately built-up area), the average building's façade would be 90 percent shadowed by its neighbor anywhere in regions 2 and 3! Additional implications of shielding effects that have been observed, particularly the items close to the observer, are discussed in panel 33.

INDOOR SCATTERING AND SHIELDING EFFECTS



PANEL 7

IGNITIONS DUE TO THERMAL PULSE

The unique fire-starting mechanism of a nuclear explosion is spontaneous (and nearly simultaneous) ignition of a wide variety of natural and manmade materials exposed to the heat flash from the nuclear fireball. This can occur over an area many miles from the explosion, as far away as dry leaves and litter can ignite--about 5 or 6 cal/sq cm thermal fluence. The panel 4 graph shows fire starts over 9 miles from a megaton airburst in clear weather.

Ignition thresholds vary for different materials. For example, "tinders"--thin, porous, or lightweight materials--require less energy (thermal fluence) to ignite them than do thicker, more dense materials such as sound construction lumber (wood siding and trim). Plastics vary significantly in their reaction to heat. Some will ignite and burn vigorously; others may emit dense smoke, melt, flame transiently without sustaining ignition, or cease flaming for a time but sustain a smolder. Many combinations of these responses are possible, even in a single object. The amount, type, and combination of plastics in a room can affect the severity and spread of fire.

Detailed surveys of the materials inside and outside buildings in several U.S. cities show that building fires are not likely to occur from ignition of tinder fuels alone unless the ignitions occur inside the rooms of the buildings. Even then, the fires have a good chance of dying out without spawning a building fire if there are no tinder fuels close to other burnable room contents that would provide an array of thin and thick fuels in which a fire may grow.

Closer to GZ, such limitations apply less and less; and (as the sketch opposite implies) when thermal fluences reach about 20 cal/sq cm, fires may be directly initiated in the majority of room contents. Whenever this majority includes such furniture items as beds, couches, and upholstered chairs, a damaging fire is nearly certain.

Still closer to GZ, the thermal pulse may start room fires by another mechanism--the "ENCORE effect," i.e., when sufficient energy is transmitted through the window into the room to generally raise the temperature to a "flashover" condition before the blast wave strikes*. More will be said about flashover in panel 11.

Note that the figure shows the proportion of window coverings ignited at any exposure fluence to be less than the room items similarly exposed. Window coverings can either increase or decrease the possibility of a fire starting in a room. Lightweight fabric curtains may ignite easily and spread fire to other items, while metal venetian blinds are virtually incapable of ignition. Thus, window dressing and coverings can play an important role in fire starts. Panel 33 provides some operational implications.

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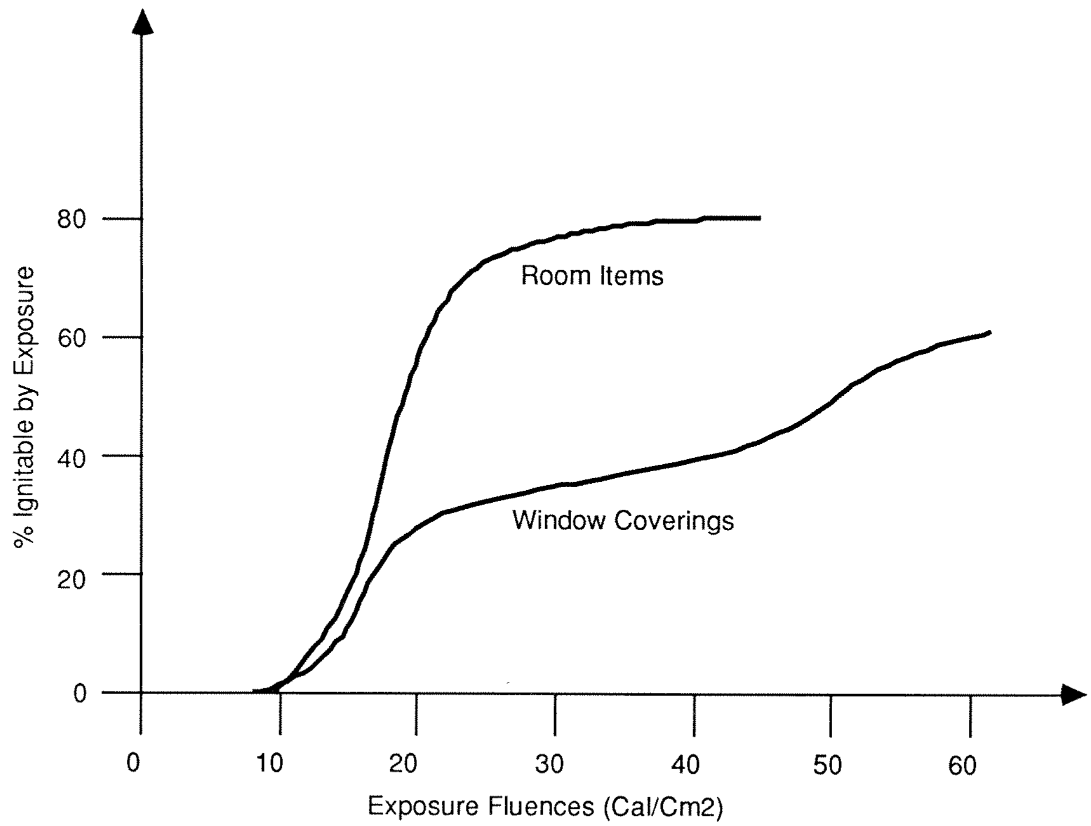
* This phenomenon was first observed at the ENCORE nuclear event in 1953.

THERMAL PULSE IGNITION PROBABILITY



Probability of ignition of a major room item or window covering vs exposure fluence from the fireball of a 1-MT explosion. This incorporates the results of field surveys of combustibles in U.S. cities during the 1960's.

EFFECT OF THE BLAST WAVE IN SUPPRESSING FIRES

Several of the atmospheric nuclear tests provided clear evidence that many ignitions by the thermal pulse (primary-fire starts) were extinguished--or at least suppressed for a while--by the blast wave that followed. Experiments conducted by simulating effects of nuclear explosions have revealed how this comes about.

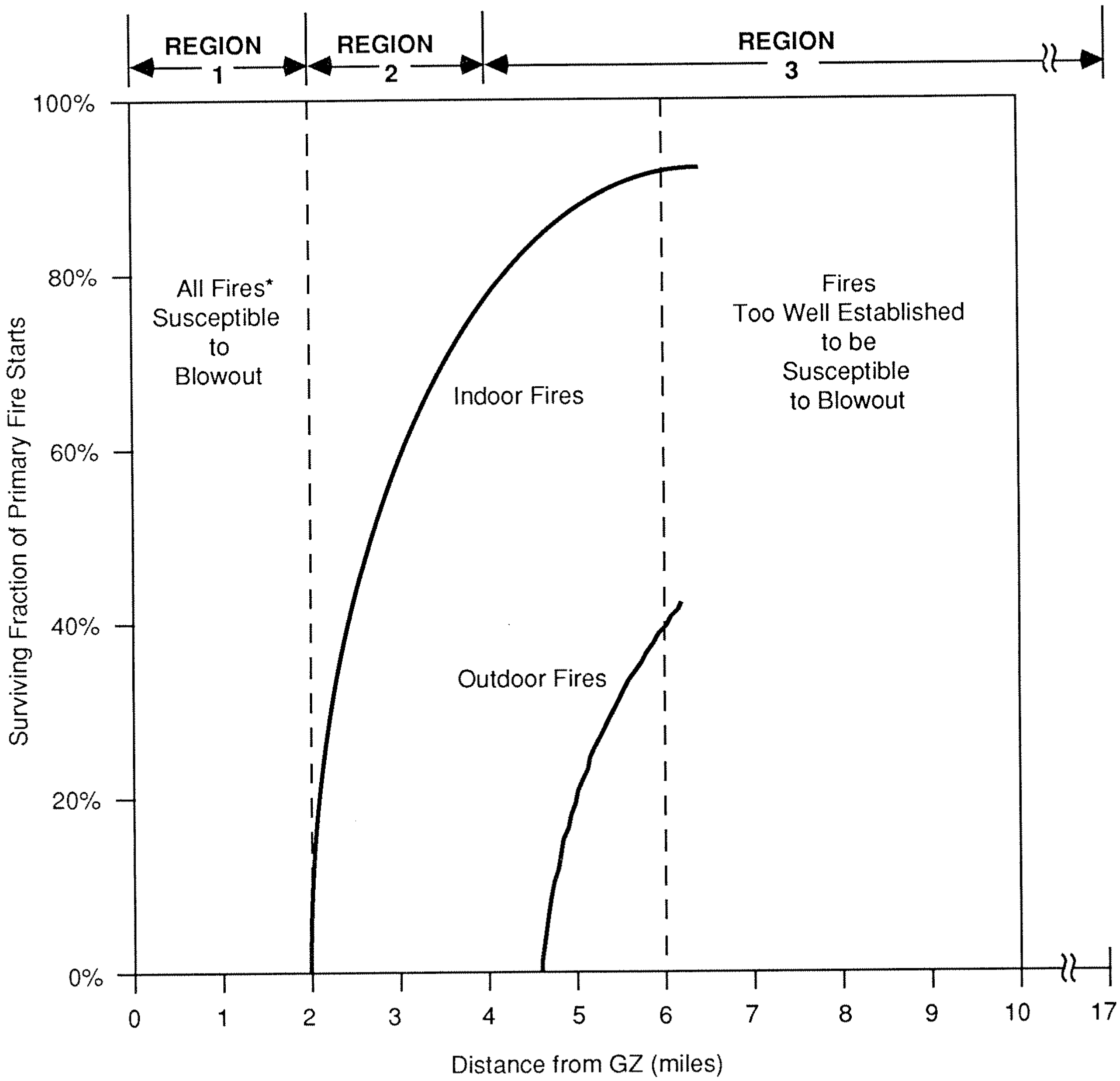
For example, when many urban fuels preburn to critical stage before the airblast strikes, their fires cannot be blown out regardless of the strength of the blast. The critical period for preburn to preclude blowout appears to depend on fuel-element thicknesses, much the same as ignition thresholds do. Thicker fuels are harder to ignite but once ignited--and having been allowed to burn longer than thin fuels--are more difficult to extinguish.

When the blast wave arrives before this critical stage of preburn is reached, active combustion may or may not be interrupted by the blast wave, depending on both its strength and on the duration of intense air flow following the shock. As the figure opposite shows, the critical preburns for common residential room contents correspond to airblast arrival times at distances of about 2 to 6 miles from the GZ of megaton air burst. Beyond about 6 miles, the blast wave arrives too late to have any suppressing effect.

Within the 2 to 6 mile range, suppression depends on what has ignited and whether it is indoors or outdoors. Survival of fires indoors is more likely than equivalent situations outdoors because indoors the intense air flow behind the shock is impeded by encountering walls that rapidly stagnate the flow. This will occur even though the walls may eventually fail. The effect on fires of this particular flow condition is apparent in a comparison of the two example curves that describe how fire survival increases as airblast strength decreases with distance from GZ.

These results indicate that many primary ignitions will be either extinguished or temporarily suppressed by the blast that follows the thermal pulse. The effect can be important out to distances comparable to primary fire reach in clear-to-hazy weather. Fires started by the ENCORE effect, however, may not be susceptible to blowout by even the strongest of air blasts. For the other cases, remission of the fire threat may be only temporary because items of furniture such as mattresses and sofas made with traditional cellulose-based materials--as well as many newer materials--can smolder for a while, then rekindle to flaming combustion over periods of a quarter-hour to an hour or more. Despite the obvious fact that this temporary respite is of little practical merit from the standpoint of the overall area likely to be burned without attempted fire control, blast wave suppression can provide a period for self-help survival activities. Such activities may be of value in all three regions (see Hiroshima examples in panel 32).

FIRE STARTS THAT SURVIVE THE AIR BLAST



* Except "Encore"

PANEL 9

EFFECT OF THE BLAST WAVE IN STARTING FIRES

Although the blast wave can have beneficial effects in blowing out some "primary fires" (those ignited by the thermal pulse) before they have had time to fully develop, the blast wave can also be the cause of fires because of the structural damage it does to buildings.

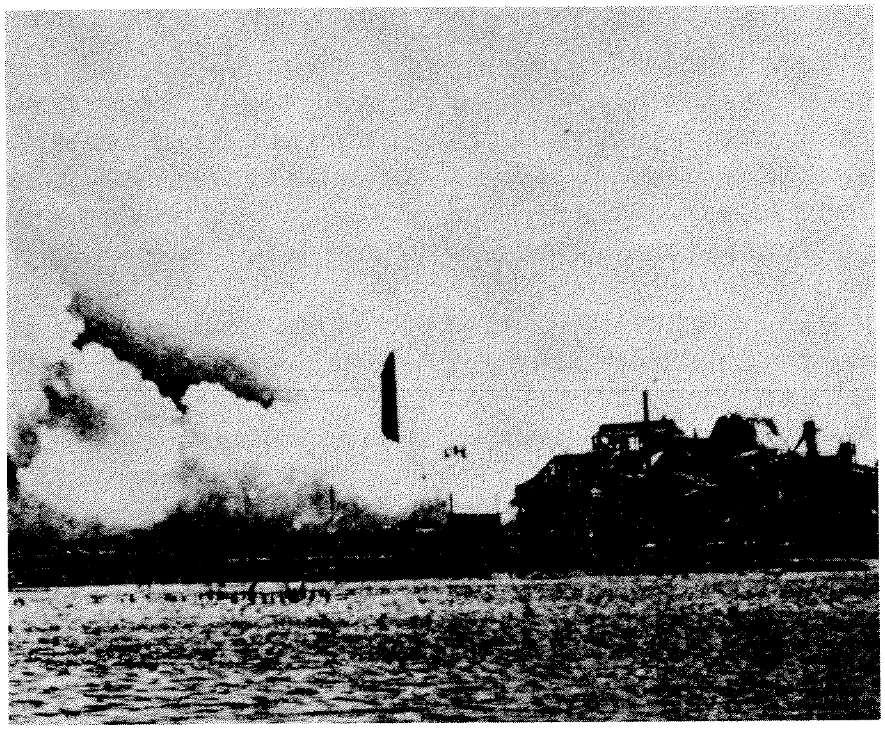
Flying debris and building collapse due to the blast wave can short out electrical equipment and rupture gas lines, setting off "secondary" fires in some circumstances. The causes of fires in structurally damaged industrial operations are nearly as varied as the nature of the various operations themselves, ranging from the rupture of hot furnaces to the release of reactive chemicals.

Data regarding the frequency of blast-produced fires are limited to studies of Hiroshima and Nagasaki, certain World War II bombings, and some large peacetime explosions. (Application of statistics relating to fires resulting from earthquakes and tornadoes to an estimate of blast-related fire frequency is considered deceptive because the mechanisms by which such natural events produce damage is different from that of blast.) The sparse data available indicate that up to six significant "secondary" fires can be expected in each million square feet of building floor space in damaged areas (perhaps only half as many in residential areas). Thus, in an area 25 percent built-up with 2-story buildings, one might find about 80 building fires per square mile due to this cause wherever blast damage is substantial. Blast-caused fires could therefore be an important factor in region 3. Secondary fires may be comparable in number to fires started by the thermal pulse at distances between 5 and 9 miles from GZ of a low airburst in clear weather (see panel 20) and could predominate there in surface burst cases.

Secondary fires may far outweigh primary fires whenever poor visibility inhibits thermal radiation transmission regardless of burst height. In many cases, secondary fire risks can be readily identified in advance and precautions taken (shutting off gas supplies and electrical power) to minimize them. Secondary fires have characteristics similar to the more familiar accidental fires in peacetime. The range of ignition types will yield a distribution of fire growth rates.

Planning fire prevention measures and fire-watch actions can have important damage-control returns. Blast damage will also likely cause failures in fire protective devices and features--such as detectors, automatic sprinklers, fire doors, and structural compartmentation--which will make the premises more vulnerable to fire than under normal conditions. More will be said about fire protection and fire control in panels 31 and 32.

EXPLOSION-CAUSED FIRE



South Amboy Explosion

ROOM FLASHOVER

This panel and the next four panels deal with the growth of a small fire, from the ignition of tinder and other ignitable items, into a room fire; the spread of fire between rooms in damaged and relatively undamaged buildings, engulfing entire structures; and the spread of the fire from one building to others. Factors that affect fire spread between buildings, such as burning times and fire intensity, are addressed later.

The panel 8 discussion implied that damaging fires from thermal pulse exposures are most likely to result from starts inside rooms. That is not to say that ignition of tinder automatically causes a room fire. Isolated small quantities of fuel, such as a newspaper or window curtain, may be completely consumed with no further spread of fire to other room contents. Usually, ignition of major items such as upholstered furniture, rugs or beds (whether ignited directly by the thermal pulse or by spread from a tinder-item start) will result in room flashover.

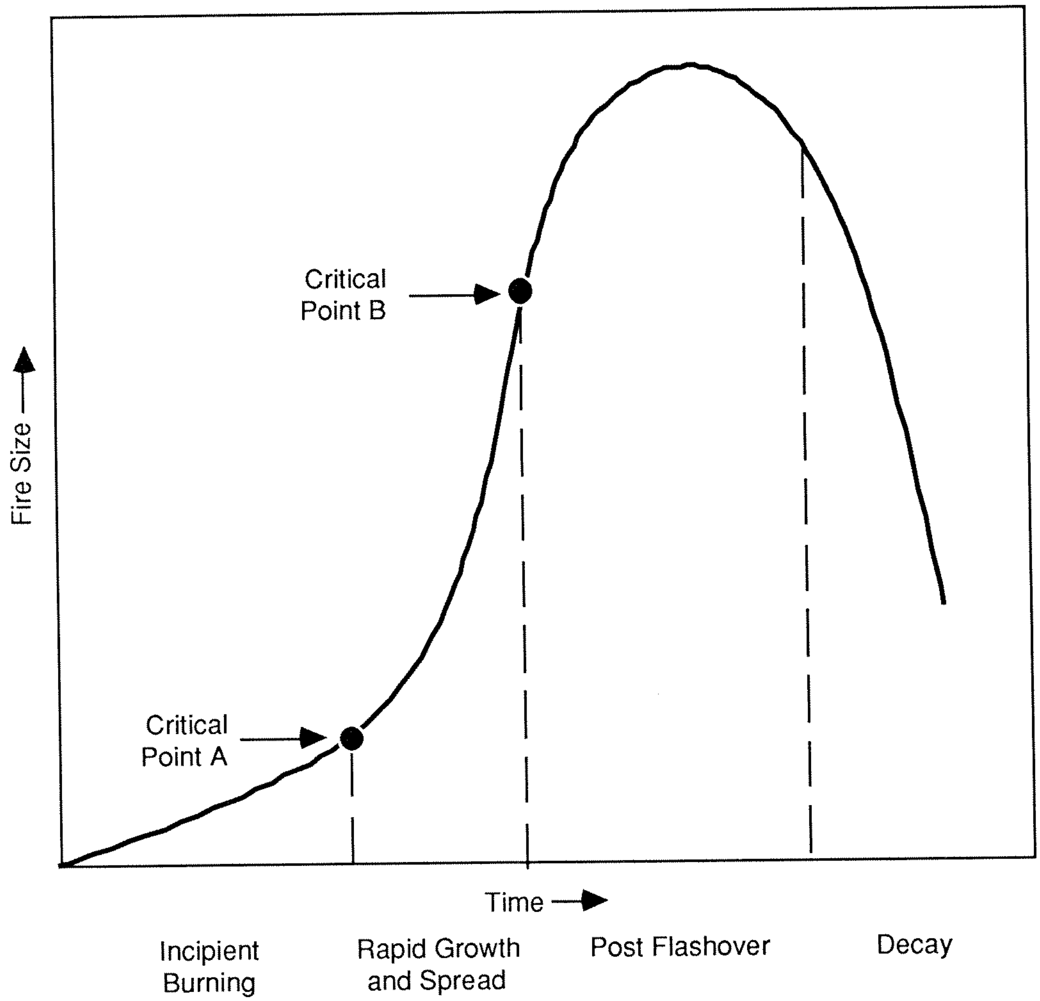
Flashover is a critical transition--often abrupt--during the growth of a room fire when previously uninvolved combustible suddenly ignite from the heat buildup. When this occurs, the whole room appears to burst into flames at once. This endpoint in the room fire-growth process is very important for several reasons. Following flashover, flames can emerge from openings (including windows, ducts, and doors) making the fire visible to people outside. From this stage in the fire's growth, the room fire has become a clear and immediate threat to the building and its occupants; spread of fire to adjoining rooms soon follows. Anyone who has not yet escaped from the room is unlikely to survive. While some simple self-help measures could have been effective before flashover, now self-help firefighting is no longer feasible.

How much time before flashover are we talking about?

The growth time to flashover depends on several things, but none is so important as the rate of heat buildup in the room. This, in turn, depends on what the room contains as well as how intense the thermal pulse is. Primary fires in region 3 should develop slowly from tinder starts. Self-help makes a lot of sense here. In still-standing buildings of region 2, some fires in major items ignited by the heat flash may be blown out by the airblast, only to rekindle at a later time if self-help action does not prevail. Once flaming ignition is sustained in any major item of furniture or other substantial fuel array, flashover can be expected in as little as 3 to 5 minutes.

Typically, residential rooms have mixed furniture upholstery, rugs, and mattress types with a steady trend away from natural to synthetic materials. In office occupancies, much the same applies, but the conversion to synthetics is more nearly complete. Some modern materials, inherently or as a result of treatment to retard flame or to make them smolder or cigarette-ignition resistant, are notably more thermal-pulse ignitable than their traditional counterparts. These materials often release heat more rapidly, thereby shortening times to flashover. Overall, these changes in the composition of room contents reduce the time available for self-help fire protection.

FIRE GROWTH AND FLASHOVER IN ROOMS



Critical Point A:

(1) Flame heights 5-6 ft.
(2) Fire growth rate accelerates.
(3) Signals entry into rapid fire growth stage

Critical Point B:

(1) Onset of flashover
(2) Enhanced room to room burning
(3) Burning rate controlled by ventilation
(4) High production rates of smoke and carbon monoxide

FIRE SPREAD WITHIN RESIDENCES

This series of photographs of the burning of wood-frame residence test structure will illustrate the course of events in a region 3 dwelling set on fire by thermal-pulse exposure following flashover of the first room. In all of the tests conducted, windows were removed and doors opened or removed to simulate light blast damage.

The first photograph, taken 12 minutes after the fire was started, shows the situation shortly after flashover of the fire-start room. The fire has penetrated into the attic space above the room. At 20 minutes after fire start, the fire has spread rapidly throughout the attic space, part of the roof is ablaze, and rooms adjoining the fire-start room have flashed over.

The third photograph shows the building totally involved at approximately the time of peak burning, as measured by the heat received by radiometers located outside the building. At this time, 27 minutes after ignition, the roof has burned through and collapsed. Roof collapse is often associated with the peak radiation from a burning structure. The final photograph, taken at 40 minutes after ignition, shows the building with essentially all the fuel above the floor level burned away.

The maximum burning rate for this test occurred at about 26 minutes after ignition, and the vigorous burning period lasted approximately 20 minutes. In other test fires, including furnished and instrumented residential buildings of two or more stories, vigorous burning periods ranged from 10 to 30 minutes, depending on what the wind conditions were, whether the fire-start room was upwind or downwind, and whether the fire start was on the second (or higher) story or on the ground floor.

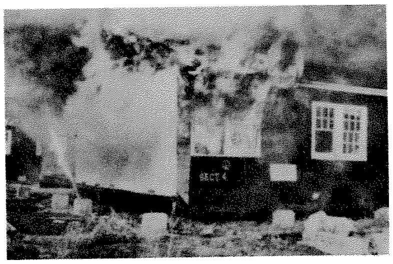
The use of unprotected foamed plastic materials, such as insulation in residences, may increase the fire growth rates beyond levels stated above.

A useful generalization that comes from this unique experimental program is that the fire tends to double in volume every 3 to 7 minutes after the initial flashover under conditions of moderate wind or upward spread. Thus, if rooms are nearly the same size, an adjacent room will flash about 5 minutes after the first. Five minutes later, perhaps four more rooms are engulfed, and shortly thereafter an entire dwelling could be fire involved.

Since most full-scale tests have been conducted with only a single building burning at one time, little directly applicable experimental data are available for evaluating effects of adjacent structural fires on internal fire spread. In a few tests, closely spaced pairs of buildings have been simultaneously burned, as have multiple arrays of building models. Measurements taken during the tests indicated a moderate increase of burning rates. This was presumably due to local fire-induced wind effects, equivalent roughly to effects of the stronger ambient (existing) winds in single-building burns. The subject of fire-induced winds will be discussed further in panel 26.

For very low winds or in cases where upward spread cannot occur, the doubling time is longer--from 9 to 14 or so minutes. As reduced shielding favors thermal-pulse fires in the upper floors of tall buildings, such conditions indicate a factor of two or three slower rate of fire growth in areas of taller buildings in which fires start in the upper stories. Panel 14 addresses fire spread in tall buildings.

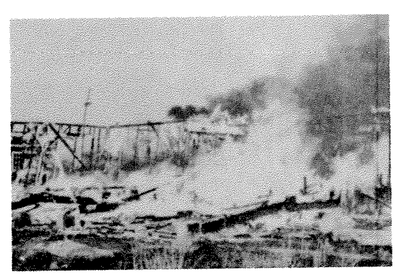
FIRE SPREAD IN A BURNING BUILDING



12 Minutes after ignition

20 Minutes after ignition

27 Minutes after ignition



40 Minutes after ignition

FIRE SPREAD IN DAMAGED RESIDENCES

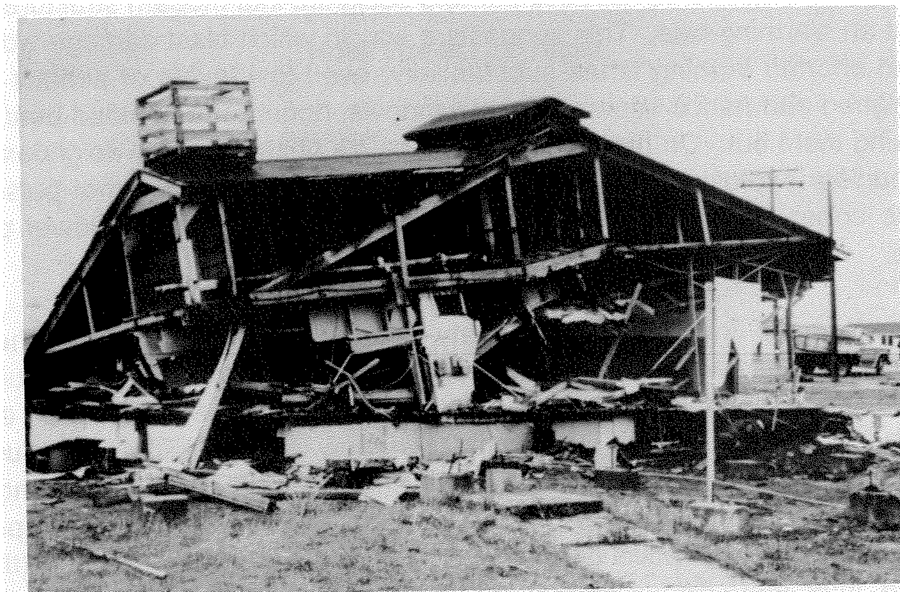
Only a few fire experiments have been performed in which buildings have been damaged as they are expected to be in region 2. The upper photograph shows a test structure identical to the one shown in the previous panel except that the roof has been deliberately collapsed onto the floor on one side of the building. The lower photo shows the damaged structure totally involved in flame.

In this experiment, the time required for the flames to spread from the ignition site to the far end of the building was about the same as that observed in the undamaged building when flame spread occurred through the attic. In this partially collapsed building, however, the rapid spread was not just through the attic but throughout the whole volume. As a consequence the entire building was involved sooner, and the fire peaked very rapidly. The vigorous burning period was only 7 minutes long, and the rate of fuel consumption at peak burning was about twice that of the less damaged structure (the test structures described in the previous panel wherein the windows and doors were removed).

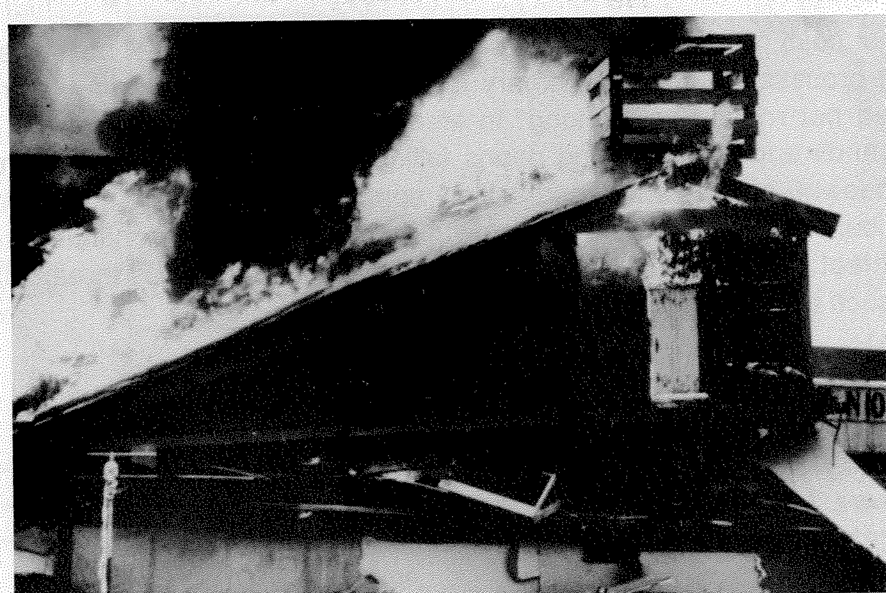
Two other experiments were conducted in which dynamite was used to damage wood-frame houses prior to burning them; these gave vigorous burning periods of 9 and 12 minutes. On the basis of such limited evidence, it would appear that a 10-minute estimate for the vigorous burning period of residences is a reasonable approximation for structures damaged in the 3-to-5-psi radius of a nuclear explosion.

Other experimental fires in more completely collapsed buildings--representative of residential buildings in the remainder of region 2, subjected to more than 5 psi and generally reduced to rubble or debris--exhibited much slower rates of fire spread and a much reduced burning intensity. These fires were reminiscent of the mass-fire zone of Hiroshima.

FIRE SPREAD IN A DAMAGED BUILDING



Damaged Test Building



Burning of Damaged Building

FIRE SPREAD WITHIN TALL BUILDINGS

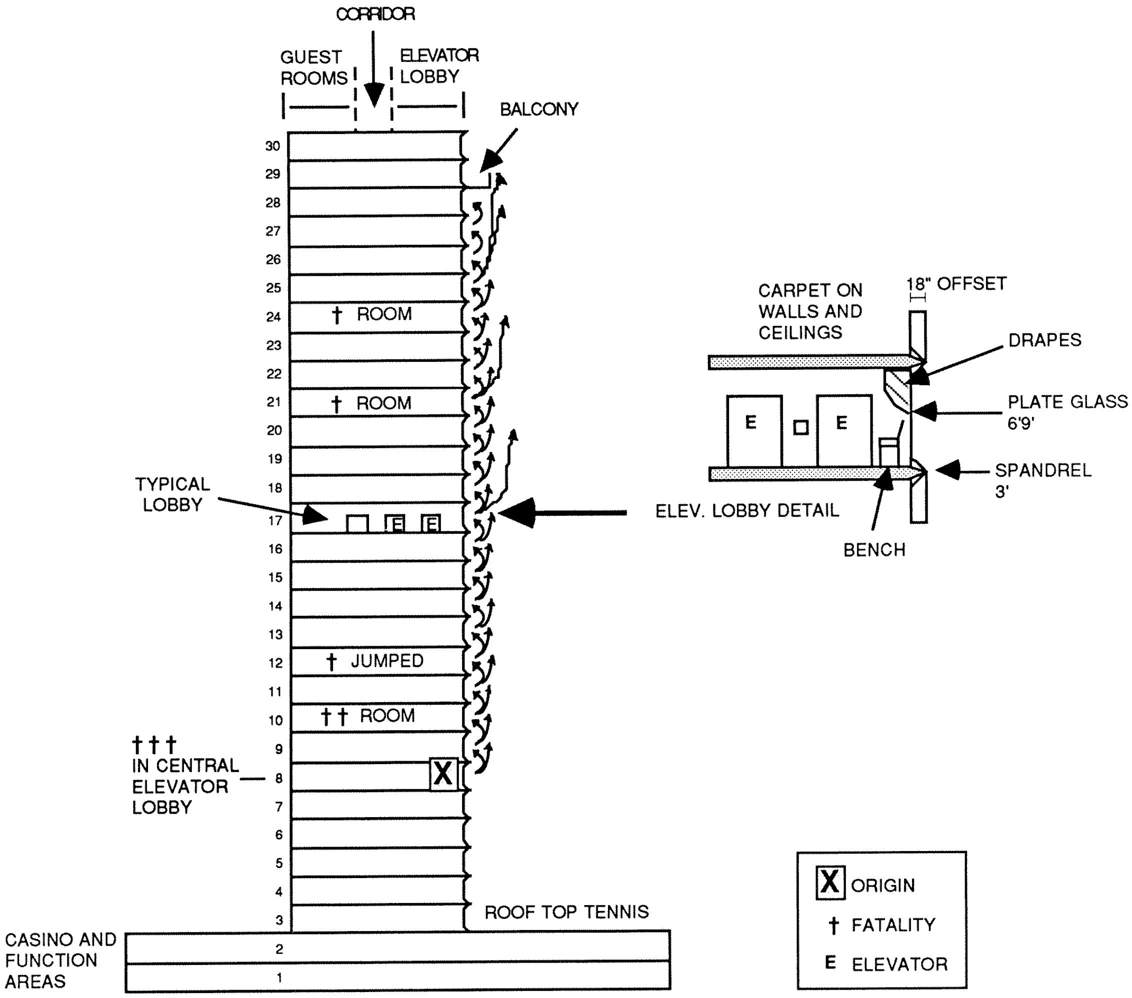
Our knowledge of fire spread in larger buildings is mostly derived from observing peacetime fires in undamaged buildings. Much of the resource in test and experimental fires also is limited to structures that have not been previously damaged by blast and therefore do not relate well to nuclear attack. It is clear from recent experience that pathways of relatively easy fire spread, circumventing the fire-resistive barriers designed into modern structures, often allow fires to grow at an alarming rate. This suggests a way in which blast damage would speed up fire spread and shorten burning times substantially; even low levels of airblast damage can defeat the designed endurance separations of windows, doors, and nonload-bearing partitions simply by blowing them out. On the other hand, because of shielding by neighboring buildings, many of the nuclear-explosion fires--mainly those started by the thermal pulse--would be confined to the upper floors and forced to spread downward, a much slower process than upward spread.

Several major hotel fires of recent notoriety have surprised observers by their rapidity of spread upward (see the adjacent figure). These have typically found routes through ventilation systems and similar unimpeded passageways, or flames leaving the windows on one floor light off new fires on the next floor above by entering a window in the outside wall. Such fire jumps can occur in minutes. The frequent pattern is a fire start on a lower floor in common-use space or a utility such as a kitchen from which the fire has access to the less impeded passageways. Such fires are more representative of secondary (blast-caused) than primary (thermal pulse caused) fire and, thus, more representative of fires in the tall buildings of region 3 than of region 2. The threat to building occupants can be extreme. This emphasizes the importance of taking advance precautions to prevent such fires, even though their incidence may be many times less than the primary fires in region 2.

One further point on rates of fire spread pertaining mostly to the tall buildings of region 2 is that, while the process initiated by primary ignitions in upper floors may be relatively slow starting, it need not remain so for long. In time, through building-to-building jumps (some involving firebrands and other burning debris falling and/or being blown into the streets and lower-story windows), new fires will increasingly spread upward accelerating ignitions that will involve whole buildings. This rapid fire growth poses a threat to continued survival of the occupants, a threat that requires either immediate evacuation to a less threatening location or prompt action such as that described in panel 32.

PROGRESS OF FIRE SPREAD

Hotel Fire in Las Vegas



Section A-A of East Tower

FIRE SPREAD BETWEEN BUILDINGS

Initiation of fire by the direct effects of the nuclear explosion and the early growth of those fires within the buildings of origin represents only part of the total fire problem. Fire spread between buildings will add heavily to the ultimate incendiary damage, especially in region 3 where so many buildings and whole city blocks may escape initial ignitions.

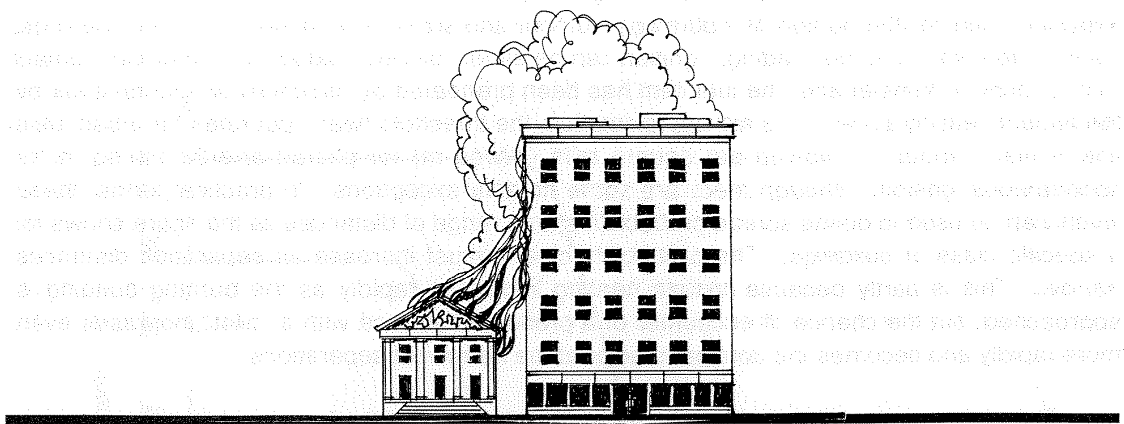
There are three distinct mechanisms by which fires may spread from burning buildings to buildings not yet ignited--all of which are aided by wind, especially in the downwind direction. The first, called "convection," consists of heating nearby combustibles by either direct flame contact or hot gases of an active fire until sustained ignition occurs. This is very short-range mechanism of interest mainly for closely adjoining buildings or those sharing common walls. Convection is the main means of fire spread within buildings and is of concern in peacetime fires where a taller building may be at hazard from its smaller neighbor (upper sketch). As we have seen, it is far more likely in nuclear attack that ignitions will be confined to the upper floors of the taller buildings.

The second means of fire spread is "radiation." The flaming mass of a burning building radiates heat which, in sufficient quantity, can raise the temperature of exposed elements of nearby buildings to the kindling point. Through this mechanism, the flaming building causes ignitions much like nuclear fire ball does--though on a smaller scale. In this instance, the rate of heat input--usually expressed in watts per unit area rather than the total fluence (in calories per unit area)--determines whether ignitions occur to spread the fire.

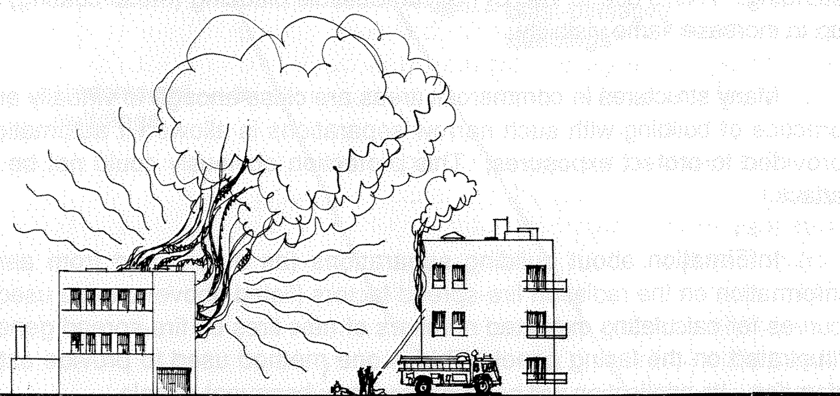
The threat of fire spread through radiation is common in peacetime fires. "Control of exposure" is a major firefighting measure--playing a hose on the exposed surfaces of nearby structures to cool them below the kindling temperature. This activity is shown in the middle sketch. Fire spread by radiation is discussed in panel 16.

The final means of fire spread is by windborne "firebrands". This spread can be very long range, allowing fire to jump over wide firebreaks and start new fires far from the origin of the brand. Unlike the previous two mechanisms of fire spread, "spotting" with firebrands can readily start fires in the many blocks of region 3 that were untouched by the initial fire starts. Firebrands are discussed in panel 17.

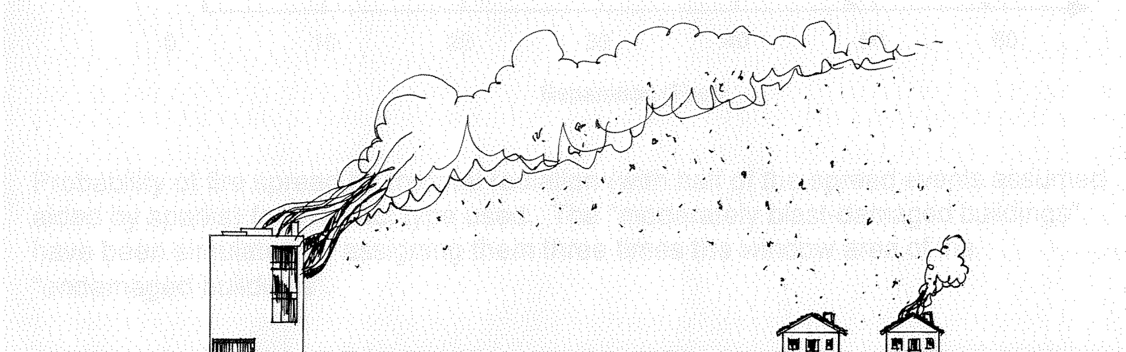
FIRE SPREAD BETWEEN BUILDINGS



Fire Spread by Convection



Fire Spread by Radiation



Fire Spread by Firebrands

FIRE SPREAD BY FLAME RADIATION

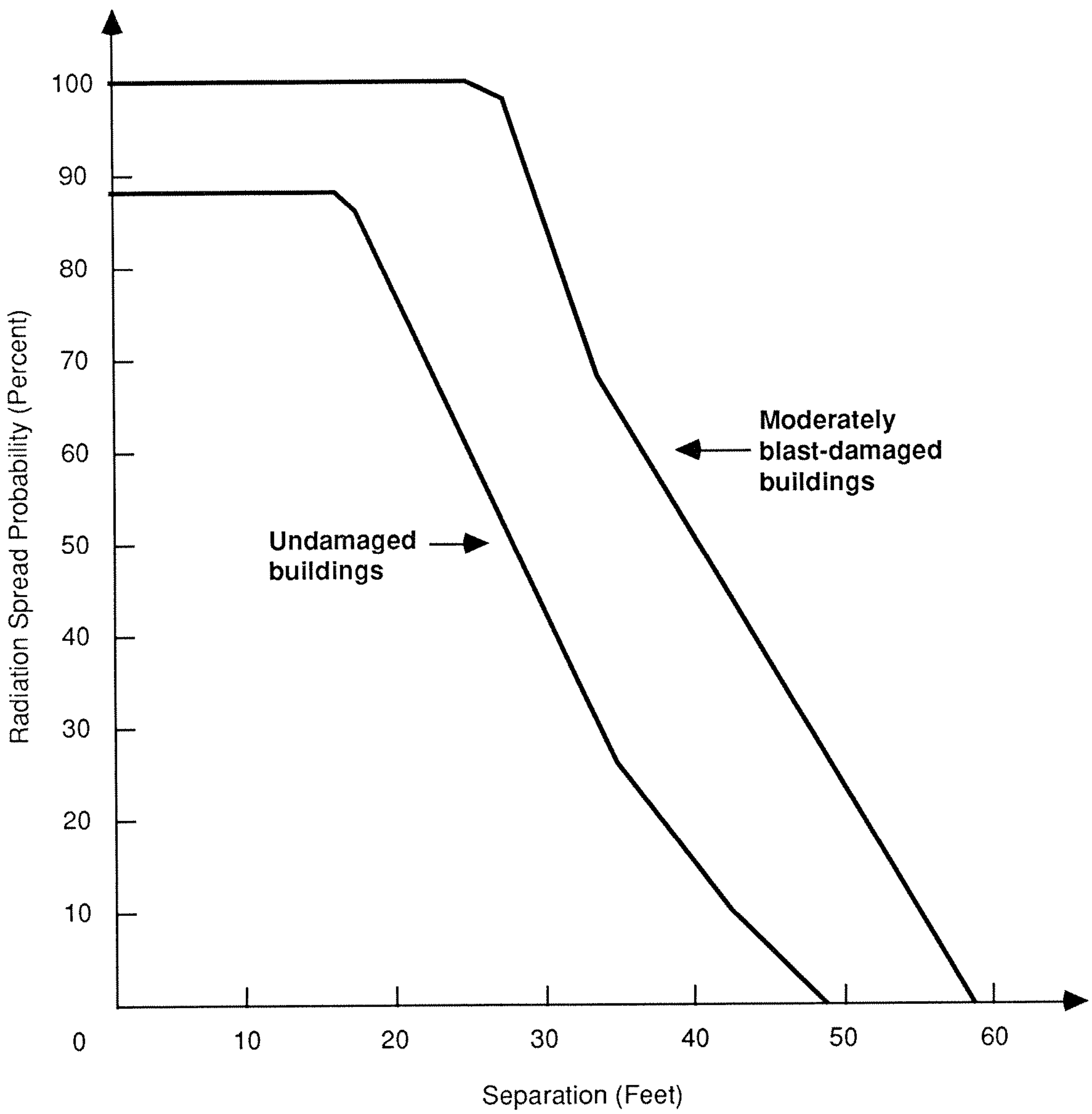
The main mechanism for spread of fire over short distances, as in the case of spread among neighboring buildings in the same block, is thermal radiation heating of fuel items to their point of ignition. The primary factors affecting fire spread by radiation are the dimensions of the exposing building (the portion of it burning), number and sizes of windows and other openings, construction type, and fuel loading. Ignition can be either "piloted" (aided by momentary contact with a spark or flamelet after the fuel item has been preheated by radiation) or spontaneous by the radiant heating alone. To a fair approximation, the threshold heat input rates for urban fuels are similar: about 17 kilowatt per square mile (kW/sq m) for piloted and 33 kW/sq m for spontaneous ignition, although there are some notable exceptions. In practical terms, these levels can be used to define spread probabilities for a range of distances as the figure shows for a specific class of buildings. The probability clearly must increase as separation distances narrow. This is partly because radiant heating increases rapidly as the burning building is approached, but the chance of encounter of a preheated surface with a "pilot" increases even more rapidly and becomes the dominant factor at the narrowest separations.

The higher probabilities for blast-damaged buildings reflect the increased radiating areas--as well as increased exposure of ignitable surfaces--of buildings moderately damaged but still standing. This is due to loss of noncombustible cladding (metal coating) and a general opening up to increase flame visibility.

Many structures in commercial areas are close enough to virtually ensure fire spread. This practice of building with such narrow separations is allowed if automatic sprinklers have been provided to protect exposures. This protection obviously could not be counted on in nuclear attack.

Information about building separations (as determined from aerial photography) and information on the radiation fire-spread factors (listed above) can be used to develop probability curves for calculating expected numbers of new fires by fire-spread generation. An example is illustrated on the facing panel. This is one method used to provide estimates of ultimate fire damage. Its application will be illustrated in subsequent panels.

THERMAL RADIATION FIRE SPREAD PROBABILITY



Probability of fire spread by thermal radiation (with half of the spread events assumed aided by sparks) for the tract type used. The "moderately blast-damaged buildings" have been simulated by assigning them three times the window area of the "undamaged buildings".

SPREAD BY FIRE BRANDS

Experience clearly shows that wood-shingled roofs are unusually vulnerable to spot fires started by fire brands and that such roofs produce a profusion of brands when on fire. This accounts in large part for the disastrous residential fires that regularly occur in the United States, especially in the southwestern states in summer and fall.

Wood-shingle brands, however, are poor igniters compared to brands from the 1-inch sheathing that is commonly used under a variety of roof coverings and some building sidings. The larger brands from 1-inch sheathing are generally "checked" with deep fissures that maintain the glowing combustion of the brand for a long time, and the size of these brands allows them to survive long windborne trips to remote targets. Production of these brands is greatest at about the time of roof collapse. Since peak radiation occurs before roof collapse when the bulk of the brands are formed, peak initiation by brands from a structure will lag behind peak initiation by radiation.

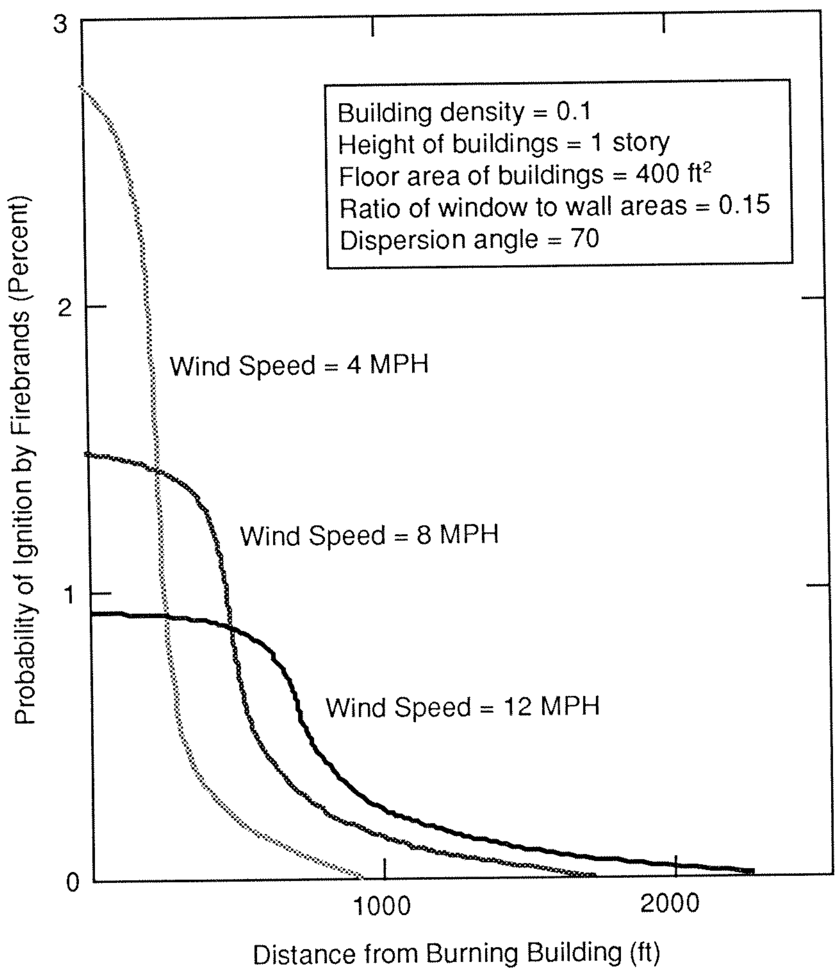
Except for wood-shingled roofs, building exteriors are not particularly subject to brand ignition. Sound milled wood, as in trim and siding, is not susceptible to brand ignition except within about 50 feet of the burning building where the brand acts as a pilot of radiant ignition. Susceptible exterior fuels are paper; canvas; unsound wood; dry vegetation; and unmilled, low-density woods such as split-cedar shakes. On the other hand, many room-content items (upholstered furniture, beds, and ignitable window hangings) are susceptible hosts.

Most fire brands are light in weight, tending to float about as they fall. This gives them the option of going into rooms through open windows. Blast damage can both aid and hinder the process. It can break windows, open doorways, remove curtain walls, and open up resistant roof coverings to expose building interiors to brand showers; but it can also remove roofs, as we saw in chapter 2, greatly reducing the source of brands.

The figure gives a representative example of how firebrand spread probabilities decrease with distance and how they depend, in the downwind direction, on the wind speed. This illustrates both how low firebrand spread probabilities typically are compared to radiation spread probabilities and how far brands aided by wind can reach. The illustration is not intended to be typical of all urban areas.

The number of fires started by fire brands will depend, among other things, on the number of buildings burning at one time and the number of unburned buildings available as hosts. While the chances of spread by fire brands shown here may seem low, it must be remembered that even a single fire started in a city block previously free of fires can then spread within the block by radiation. Brands are therefore a major cause of block-to-block fire spread, with a key role to play in conflagrations. Firebrands are also generated by fires in wooded areas and can contribute to urban fire damage, particularly at the urban/wildland interface so common to southern California communities.

FIREBRAND SPREAD PROBABILITY



LARGE FIRES AND LIFE LOSS

Large fires were inflicted on German and Japanese cities during World War II by air raids in which large loads of bombs were dropped on a selected area within a relatively short period of time. High explosive bombs were employed in some raids and fire bombs in others. Some of the worst fires in German cities were caused by use of both types simultaneously. As the war progressed, the combined use of incendiaries and high explosives increased. In the latter stages of the strategic air offensive against Germany, about 70 percent of the total tonnage dropped was incendiary munitions. Against Japan, the preponderance of incendiaries is noteworthy.

Fires were classified, according to their behavior, as "group fires" if individual fires burned out without merging and as "conflagrations" if a fire front developed that was driven across unburned areas by a prevailing wind. In some German cities, a particularly devastating kind of group fire was developed in which heavily built-up residential areas were ignited simultaneously over an area of several square miles to produce an inferno--labeled by German journalists as a "firestorm."

Japan experienced some very devastating fires too, but no firestorms due to conventional bombing. One of the worst fires in Japan happened in March of 1945 when Tokyo was swept by fires set by repeated conventional bombing with incendiary munitions. In one night, a massive conflagration burned out 16 square miles, taking an enormous toll of lives. In the nonconventional bombing of Japan, Hiroshima is often said to have suffered a firestorm as a result of the atomic-bomb attack on it in August 1945.

Clearly, it is important to recognize that fire deaths could still be high in any nuclear attack despite measures taken to protect the population from blast, initial radiation, fallout, and other threats to life. As the Hamburg and Tokyo studies show, deaths would be particularly high if firestorms or conflagrations were to ensue. For this reason, we have given some specific attention in this chapter to the prospects for firestorms and conflagrations resulting from nuclear attack on or near urban centers. Since the development of conflagrations seems to depend critically on the preexistence of high ambient winds or conditions favoring them, our discussion of conflagration-potential assessment is deferred until the subjects of fire storms and wind effects have been presented.

To set the scene for treatment of firestorms, we draw on historical records. Analysis of the records of the 1943 bombing of Hamburg, Germany, in which one of the worst of the firestorms occurred, indicates that an average of one out of every two buildings was set on fire by the bombs. (In contrast, in the raids on German cities in which ordinary group fires occurred, only one in seven or eight buildings was ignited.) Moreover, postwar analyses have repeatedly shown that these fires burned so intensely that their peak rates of heat release--per square mile of fire area--were in the 600 to 700 million kilowatt range, while group fires were less than half as intense--often much less. Factors that influence the development of firestorms are described in the next five panels.

EXAMPLES OF WWII FIRES

- GROUP FIRE
  Ulm, Germany, Nov/Dec 1944 -- 504 deaths
  -- 1.5% of population at risk
  -- 0.78 deaths/tons of bombs dropped
  Contiguous Fire Areas -- typically one city block or less
  Fire Severity (avg.) -- 100 million kwatts/sq. mile

- CONFLAGRATION
  Tokyo, Japan, 9/10 March 1945 -- 84,000 deaths
  -- 8.4%of population at risk
  -- 50.3 deaths/tons of bombs
  Fire Area -- 16 sq. miles

- FIRE STORM
  Hamburg, Germany, 27/28 July 1943 -- 40,000 deaths
  -- 14% of population at risk
  -- 30.8 deaths/tons of bombs
  Fire Area -- 5 sq. miles
  Fire Severity -- 720 million kwatts/sq. mile

FIRESTORM POSSIBILITIES

The marked increase in loss of life found in "firestorm events" focused attention on the nature of these fires and the necessary conditions for their occurrence. What is generally meant by the term firestorm is a mass fire characterized by high-velocity winds at ground level, a well-developed convection or smoke column reaching high into the atmosphere, and little spread beyond the area that contained the initial fires.

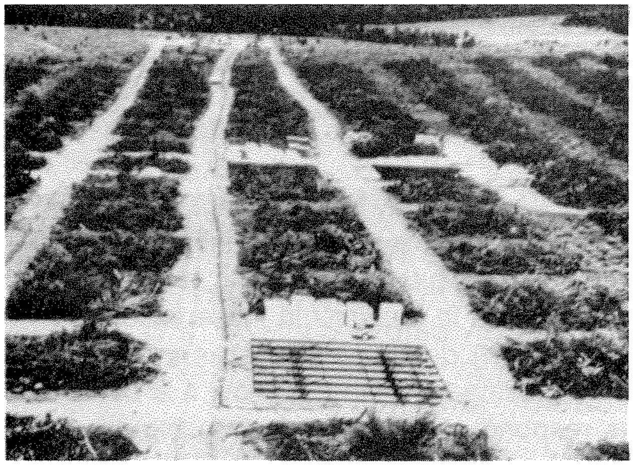
Research has shown that fire-induced inrush wind velocities of firestorms require the high rates of energy release associated with the high fuel loadings that fed these fires. In Germany, ground-level wind speeds of 50 to 100 miles per hour were reported in the firestorm catastrophes, and it was in part due to these storm-like winds that the name "firestorm" was coined. Group fires in Germany had wind speeds less than 40 mph. Peak fire-induced winds at Hiroshima, where fuel loadings were much less than at Hamburg, were estimated to reach 35 mph.

From 1964 to 1975, the U.S. Forest Service and the Defense Department ran a series of mass fire experiments called Operation FLAMBEAU. Other tests of a similar nature were conducted in Australia and Canada and, as recently as 1987, here in the United States. Wildland fuels are often piled up in large arrays representing the amount of fuel usually found in houses and burned to measure the resulting fire environment. The left-hand picture on the opposite panel shows the largest array, occupying 50 acres, before the burn. The right-hand picture shows the array during the burn. Through these tests and other work, it was confirmed that the energy release from a large fire depended on the amount of fuel available, the burning rate of the individual buildings, and the weather conditions at the time of the fire. The figure indicates the conditions thought necessary for production of a firestorm. The presence of debris mixed with noncombustible rubble can affect the outcome, but such variables were not involved in these evaluations.

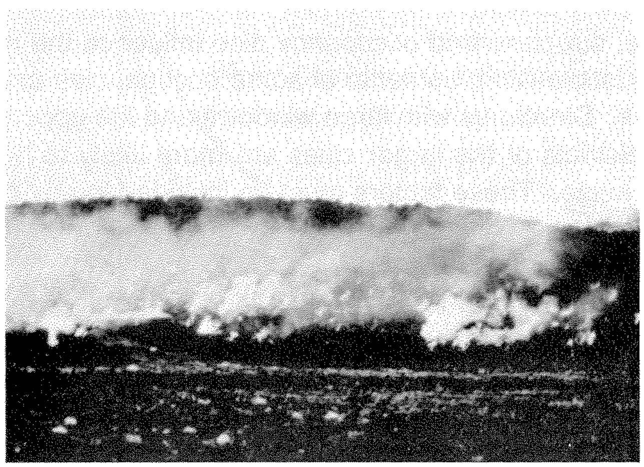
Customarily, some minimum-area requirement is prescribed for firestorm formation, but this has never been based on much besides speculation. It is argued by some atmospheric physicists that inherent instabilities would cause large-area fires to degenerate into separated convection columns that could limit the size of firestorm formation. Until this subject is better understood, we are unable to provide a minimum-size criterion. In the interest of erring on the safe side, we recommend treating all areas of congested construction, regardless of size, as prone to mass fire.

Uncertainties still exist concerning the number of initial fires that will survive the extinguishing action of the blast wave, but it can be assumed that urban targets of nuclear attack will include areas in which half or more of the buildings will be burning within a short time following the explosion, thereby satisfying at least one of the firestorm-start criteria (the 50 percent rule). Tall buildings concentrated in central business districts are notably vulnerable to primary fires, while petrochemical facilities and other industrial concentrations of flammable fluids and related processes are more vulnerable to secondary fires. For firestorms to result (see adjacent figure) both criteria (along with suitable weather) must be met at once in a single area. Panels 21 and 22 examine the prospects for simultaneously meeting the fuel-load criterion. The next panel illustrates by example the number of fires that can be started directly by a single nuclear explosion and how they are distributed over the three regions.

CONDITIONS FOR FIRESTORMS



Flambeau plot before burning



Flambeau plot during burning

Empirical Criteria *

- Greater than 20 pounds of fuel per square foot of fire area.
- Greater than 50 percent of structures on fire initially.

* Based on historical evidence from WWII and experimental studies depicted above.

HOW MANY FIRES START?

As previously noted, damaging building fires started by the thermal pulse are nearly certain to occur at distances where exposures in rooms are sufficient to ignite upholstery fabrics and bedspreads. With some preparation to limit exposure of room contents, the number of such fires can be drastically reduced. More will be said about this in subsequent panels of this chapter. For the time being, we will assume no such precautions have been taken. Even so, partial shielding and the normal attenuation of the thermal radiation by the atmosphere, window glass, screens, and the like will substantially reduce the exposure of room contents. Calculations show that these factors, more than the out-of-doors thermal fluence values shown previously in panel 4, determine how many fires are started by the thermal pulse.

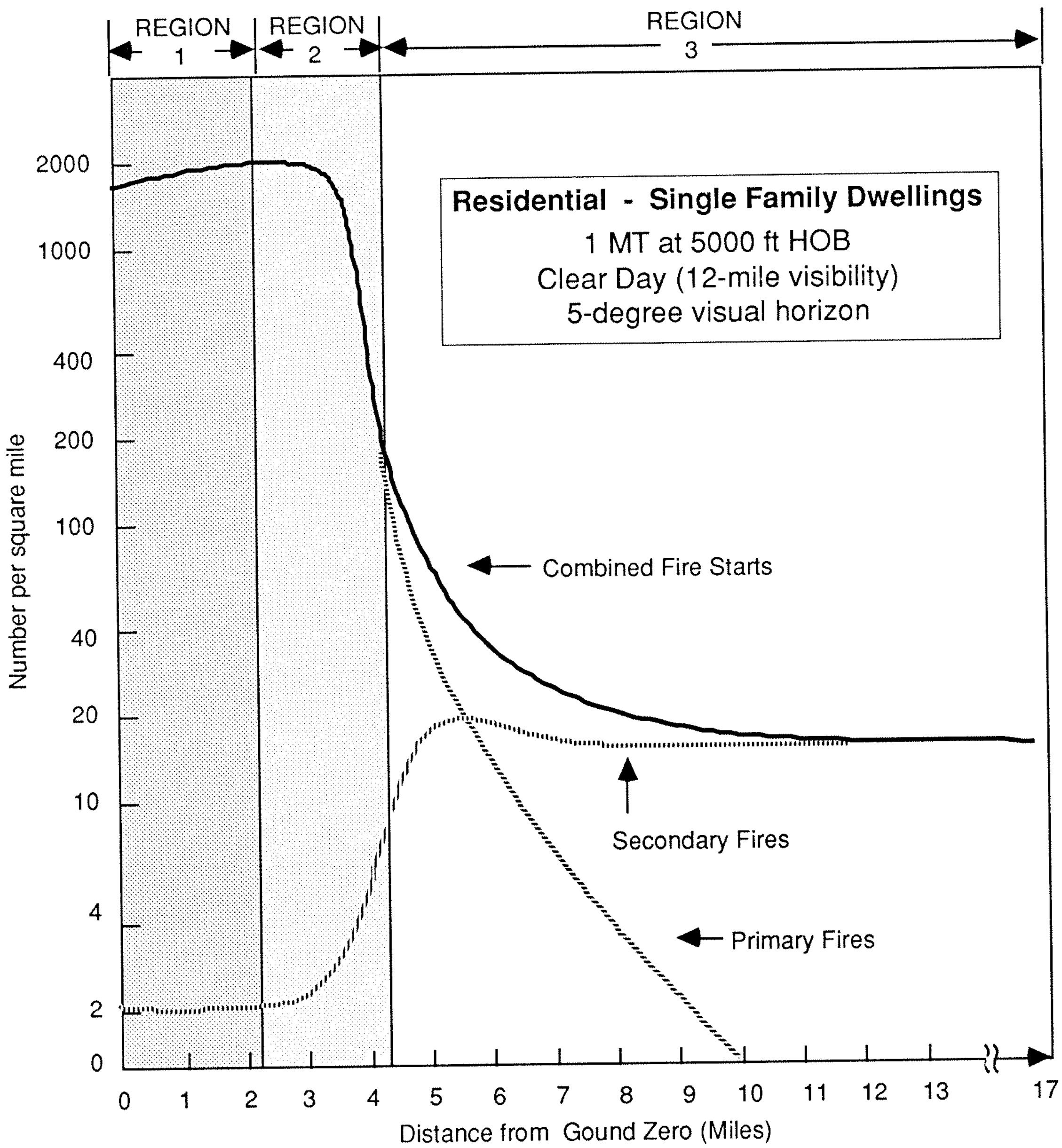
In contrast, secondary fires started by blast damage are directly related to the strength of the out-of-doors airblast because it provides the mechanism forces that cause the breakdown of the electrical system, the discharge of gas or liquid fuels, and the upset stove or the over-design load on an electric motor that leads to the fire. In these cases, the occupancy of the building (that is, how the building is used) determines what is in the building that may become a secondary-fire starter. The building itself (that is, how it is constructed) determines how the building and its contents respond to the blast--producing the breakdown of the electrical system, etc. Therefore, in relation to the airblast peak overpressure, both structure type and occupancy class determine how many secondary fires occur.

To a lesser degree, structure and occupancy also influence the number of thermal-pulse fires. Clearly, the combustible room contents of some occupancies are more abundant and/or more ignitable than others. Structures with large windows and the uppermost stories of the taller buildings in downtown districts of the larger cities are more likely to have their room contents exposed to the full heat pulse. These factors must be included in any careful analysis of urban fire starts.

Single family residences in one-to-two story, wood-frame and masonry houses make up the most common structure/occupancy class of the extensive low density areas of American cities. This structure class is neither the most nor the least fire-vulnerable of the typical classes, but it covers such a large portion of any city that it is a representative example of urban or suburban fire outcome. Outside vegetation is assumed not to contribute to fire starts in buildings. The diagram on the facing page shows fire starts in such a residential area. Primary and secondary fire estimates are shown separately, along with the combined fire starts.

Similar estimates can be made for other structures/occupancy classes if due allowance is given to exposure differences and varying susceptibilities to secondary-fire starts. The results are different in detail, but the conclusions are always the same: even in region 3, the number of fires would completely overtax the capacity of the fire services.

DISTRIBUTION OF BUILDING FIRE STARTS



PANEL 20

URBAN FUEL LOADING

The total amount of combustibles in a building, including both structure and contents, has an important bearing on the potential severity (or intensity) of fires. Each pound of combustibles typically generates about 2 1/3 kilowatt hours of heat energy--often more when modern plastics predominate in the furnishings. The type and quantity of smoke developed is directly related to the composition and number of combustibles available to burn. The characteristics as well as the quantity of smoke are of practical concern because they determine the way smoke interferes with the transmission of thermal radiation through the air; reflect how smoke contains varying abundances of toxic and/or caustic substances to threaten the population and emergency personnel; and impact our evaluation of long-term global climatic effects of nuclear war--the so-called Nuclear Winter concept (panel 36).

It is common practice in surveys of urban fuel loadings to report all combustibles in weight-per-unit-floor-area units adjusted to a common heat-release yield based on the calorific value of wood. That is, if a synthetic material has a 10 percent greater heat release on combustion than the same weight of wood, a fuel load of 1 pound per square foot (lb/sq ft) of that synthetic is reported as 1.1 lb/sq ft wood equivalent. We will follow that practice here so that our values reflect the changes in fuel composition as they affect heat release. Clearly, no such wood equivalent simplification applies to smoke yields and compositions.

An estimated range of fuel loadings in typical building uses or "occupancies" is shown here. Whether a particular structure would have a fuel loading near the high or low end of the range shown depends mainly on the type of construction of the building. For example, the typical combustible contents of residences average about 5 lb/sq ft floor area. Wood construction adds an average of 15 lb/sq ft for a total of 20 lb/sq ft, while masonry construction has less combustible material, bringing the total to only about 15 lb/sq ft.

The combustible contents of office and commercial space range from 6 to 17 lb/sq ft floor area. Combustible contents of industrial and storage buildings vary quite widely depending on the nature of the operations involved.

ESTIMATED FUEL LOADINGS

	FUEL LOAD PER STORY (pounds / sq ft of floor area)*	TYPICAL STORIES (No.)	RANGE OF BUILDING FUEL LOAD (pounds / sq ft of building plan area)*
Residential (Single Family)			
Wood Frame	18-24	1 1/2	27-36
Masonry	14-18	1 1/2	21-27
Mobile Home	18	1	18
Residential (Multifamily)			
Garden Apartments (Fire Resistant)	9-11	6	54-66
Garden Apartments (Frame)	13-19	3	39-57
Tenement Apartments	10-30	10	100-300
School / Institutional	5-10	2	10-20
Office / Commerce			
High-Rise Offices	8-10	20	160-200
Ind. Park / Shopping Mall	8-10	2	16-20
Wholesale / Warehouse	20-80	6	120-480
Industrial			
Light Industry	6-20	2	12-40
Heavy Industry	4-10	1	4-10
Petrol. / Petrochemical	40-50	2	80-100

* Wood Equivalent, Including the building plus contents, distributed over an area equal to the average building "footprint."

BUILDING DENSITY

Another important factor in fire growth, spread, and intensity is the density of construction. Building density is usually expressed as the fraction of the total built-up area (including streets and yards) that is under roof, because it is readily estimated from aerial photographs. Typically, the building density in residential areas ranges from about 10 percent to 25 percent. In commercial and downtown areas it can run up to 40 percent and more. Industrial and storage areas can vary widely in building density. Those with very high density are often referred to as "massive industrial" areas.

The combination of building density and fuel loading per square foot of building "footprint"* gives the fuel loading per square foot of overall fire area (referred to here as "fire load"). The firestorm area of Hamburg was about 45 percent built up, with buildings having a fuel loading of about 70 lb/sq ft. This would mean a fire load of about 32 lb/sq ft of fire area, somewhat more than the 20 lb/sq ft estimated as the minimum necessary for firestorm conditions.

By way of contrast, the case of a residential area of 10 percent building density with single-story, wood-frame, detached homes would have a fire load of only 3 lb/sq ft, well below the firestorm criterion. But, as the facing table shows, other cases common to American cities can exceed the criterion.

The remaining factor that must be evaluated as a part of the estimation of fire severity is how fast the fuel would burn or, alternatively, how long it would take for it to burn. This depends on rates of burning, fuel composition and geometry, and the available of the air necessary to support combustion. This is summarized in the next panel.

Actually, we seem to have--from experiences with real building fires--more information on burning times than on burning rates; but, since long burning times imply slow burning rates (and vice versa), burning times can be used to estimate burning rates. Burning times can be divided into three consecutive periods: growth, vigorous burning, and residual burning. In most cases, only the period of vigorous burning is of concern to mass fire forecasting.

The next panel will direct your attention to both burning rates and to the durations of the active burning periods, focusing mainly on the conditions that strongly affect how fast buildings burn.

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* The area of the building foundation plus the area of any overhanging structure beyond the building perimeter.

BUILDING DENSITIES AND THE BUILT-AREA FIRE LOAD

	RANGE OF BLDG. FUEL LOAD (pounds / sq ft of Bldg. plan area)*	RANGE OF BLDG. DENSITY (% of built-up area)	BUILT-AREA FIRE LOAD* (pounds / sq ft of total area)
Residential (Single Family)			
Wood Frame	27-36	10-20	2.7-7.2
Masonry	21-27	10-20	2.1-5.4
Mobile Home	18	10-50	1.8-9
Residential (Multifamily)			
Garden Apartments (Fire Resistant)	54-66	10-25	5.4-16.5
Garden Apartments (Frame)	39-57	10-25	3.9-14.2
Tenement Apartments	100-300	25-50	25-150+
School / Institutional	10-20	5-15	0.5-3
Office / Commerce			
High-Rise Offices	160-200	20-40	32-80+
Ind. Park / Shopping Mall	16-20	5-25	0.8-5
Wholesale / Warehouse	120-480	10-25	12-120+
Industrial			
Light Industry	12-40	5-15	0.6-6
Heavy Industry	4-10	20-40	0.8-4
Petrol. / Petrochemical	80-100	20-40	16-40+

* Assumes roof areas = building plan areas. The error thus introduced is slight.
+ Firestorm Range.

BURNING TIMES OF BUILDINGS

The information of the previous two panels on fire loads is useful in evaluating such aspects of the nuclear-fire threat as firestorm possibilities only if we also have a basis for estimating how fast the available fuel can burn. Some factors that influence how fast a building and its contents burn are:

- Construction type
- Occupancy
- Structural damage due to blast
- Location and severity of fire start
- Wind

Among the important structural variables are the kinds and amounts of burnable materials and the number and sizes of windows and other openings through which the fire will draw air to support it. The original openness of building construction will, of course, be less important in blast damaged buildings.

Occupancy is important because of differences in contents associated with the different ways a building is used. The burnable components of the building's contents along with its interior finish (also dependent on occupancy) contribute to how rapidly fire spreads through its interior spaces and how fast it becomes fully involved. Some of the effects of structure and occupancy, as well as blast damage, are roughly indicated in the table opposite. Location and severity of the initial fire have already been covered in pervious panels.

The wind factor presents special complications to the planner: (1) it is a weather variable that the planner cannot anticipate other than statistically from weather records; and (2) in addition to the ambient wind, the fire itself can induce wind--its strength depending on fire severity, and vice versa. For example, the ambient wind may intensify the fire so much that winds induced by the fire may totally overwhelm the ambient. Such runaway behavior is thought typical of both conflagrations and firestorms. The burning-time data shown opposite are representative of low-wind conditions. It must be remembered, however, that wind does enhance burning rates (see panels 26 and 34).

While the period of vigorous burning often last less than an hour--less than a half hour for many residential structures, it may account for more than 70 percent of the energy released. The vigorous burning period produces a smaller fraction of the total energy release in heavy construction, as the table indicates. The residual burning period may last several hours, with a burning rate that can be less than the heat output of the vigorous burning stage of lighter construction, even though the fuel loading is greater.

In compartmentalized--especially fire resistive--buildings, the concept of building burn times is apt to be misleading. Single rooms or uncompartmented floors still have a recognizable vigorous burn period, but the delay in fire propagation to adjacent compartments or floors may be so long that each has passed most of its period of vigorous burning before the next begins. Tall buildings and large warehouses can burn for many hours, maintaining a large rate of heat (and smoke) release throughout. This would, of course, be less a factor when multiple fires are started in each building, as in region 2.

BURNING TIMES FOR STRUCTURES AND DEBRIS

CONSTRUCTION TYPE	VIGOROUS BURNING		RESIDUAL BURNING	
	Time (min)	Energy Release (percent)	Time (min)	Energy Release (percent)
Light Residential				
Undamaged	20	70	30	15
Damaged	10	70	30	15
Debris	60	75	20	10
Heavy Residential				
Undamaged	25	60	40	20
Damaged	15	60	40	20
Debris	50	70	40	15
Light Commercial				
Undamaged	40	60	90	20
Damaged	20	65	80	15
Debris	80	70	25	15
City Center and Massive Manufacturing				
Undamaged	60	60	120	30
Damaged	45	55	120	30
Debris	120	50	2000	40

MODEL OF A REAL CITY--FIRE START*

Detroit, a representative industrial city of the United States, is the model we have chosen to illustrate incendiary potential of a megaton nuclear airburst. This panel describes our model and the distribution of fire starts resulting from analysis using a research-applications computer program of recent development. We will use the pseudonym "FIRECODE" in reference to this computer program. This computer program assembles for convenient analysis all of the bits of information already presented in this chapter. As output, it provides graphical depiction of the extent and dynamics of the fire threat to a community subjected to nuclear attack. This and the following two panels deal with an example of the output of one such program.

The upper illustration depicts the land use of the city resolved on a 1-square-mile grid (the analysis was done using a square-tract representation with 1/2 mile to the side). Each tract was given a single land-use designation, as shown.

Ground Zero was selected to represent targeting of the automotive-industry center at the western end of the city. The illustrated attack is a single 1-MT explosion at 8530 feet (a greater burst height than in previous examples†) in clear weather. There is a 9-mph wind from the west.

In the lower figure, the central shaded area is region 1, and the larger shaded area is region 2. The area of debris around GZ is effectively region 1 plus a substantial part of region 2 (out to 6 psi). This extensive debris field reflects the preponderance of residential land use surrounding the targeted industrial area, with relatively weak-walled construction being the nearly universal type building here. The ignited area ends abruptly at a radius of about 7 1/2 miles because FIRECODE assumes 2 psi to be the limit of secondary-fire starts (a more recent code projects secondary-fire starts to 1/2 psi). The defining contour of the ignited area represents the locus of points outside of which 99 percent of the buildings are "unburned" (or in a fire-start context, 99 percent escaped fire initiation by direct weapons effects).

No firestorm is anticipated because the central business district is beyond the effective incendiary reach of this explosion. Any other potentially suitable high-fuel-loaded areas are either beyond the incendiary reach or within region 1.

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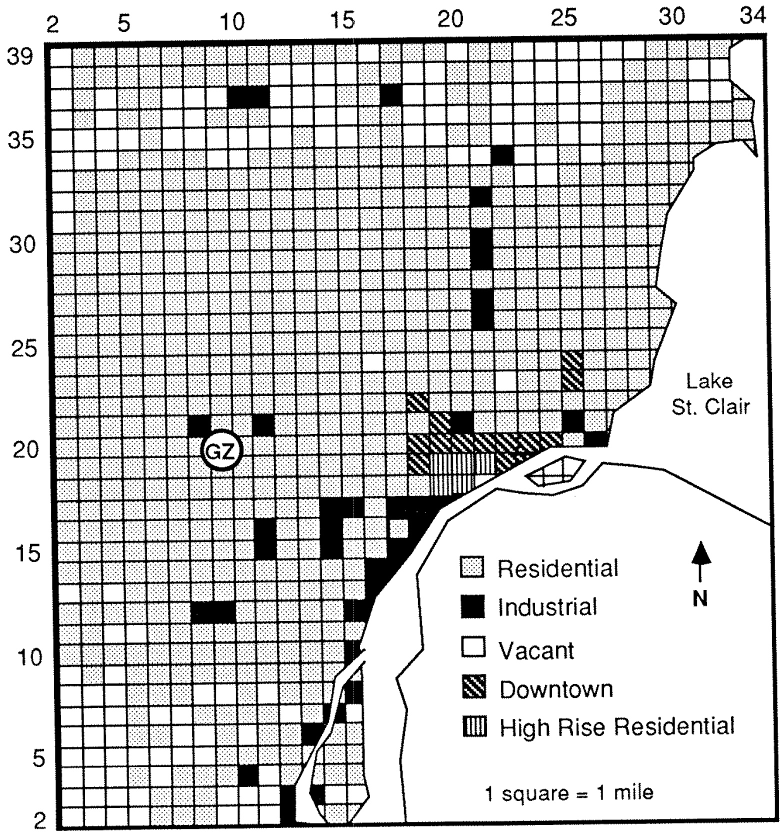
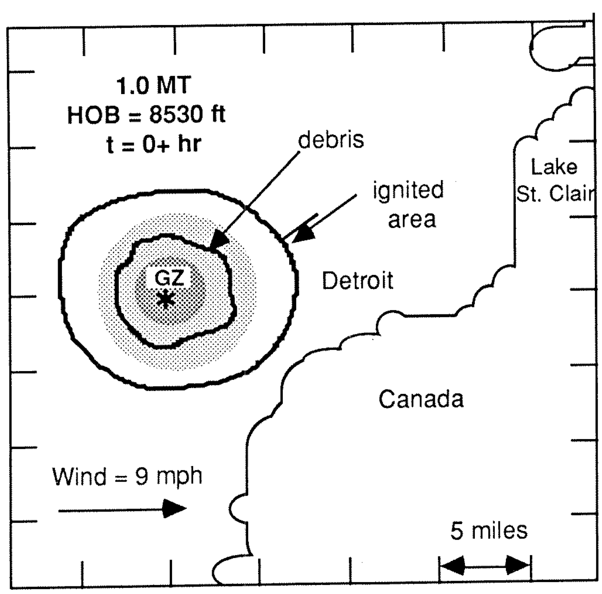
* See panel 27 for the life-saving operations referenced in chapter 7.

† As a consequence, regions 2 and 3 extend farther from GZ, with region 3 reaching to 22 miles.

MODEL OF FIRE START



City of Detroit



Contour of Ignited Area in Detroit immediately after burst.

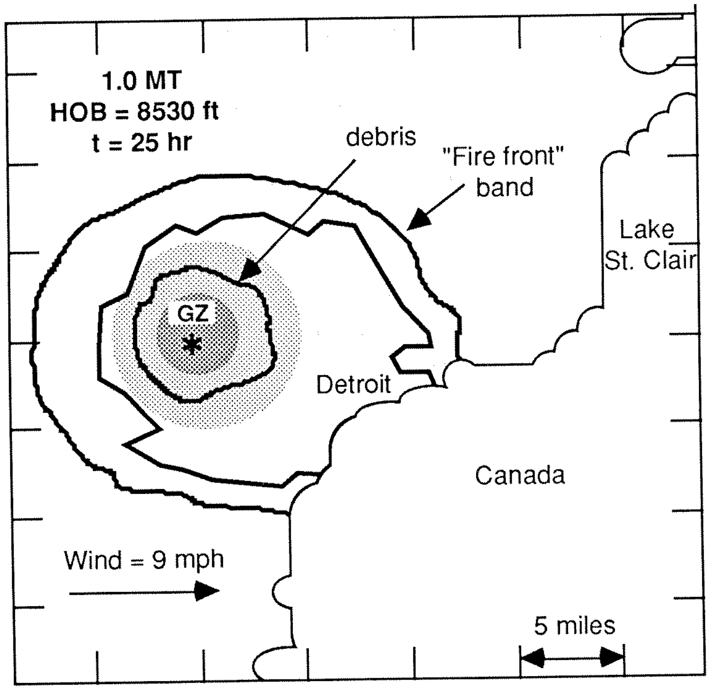
PANEL 24

MODEL OF A REAL CITY--FIRE SPREAD

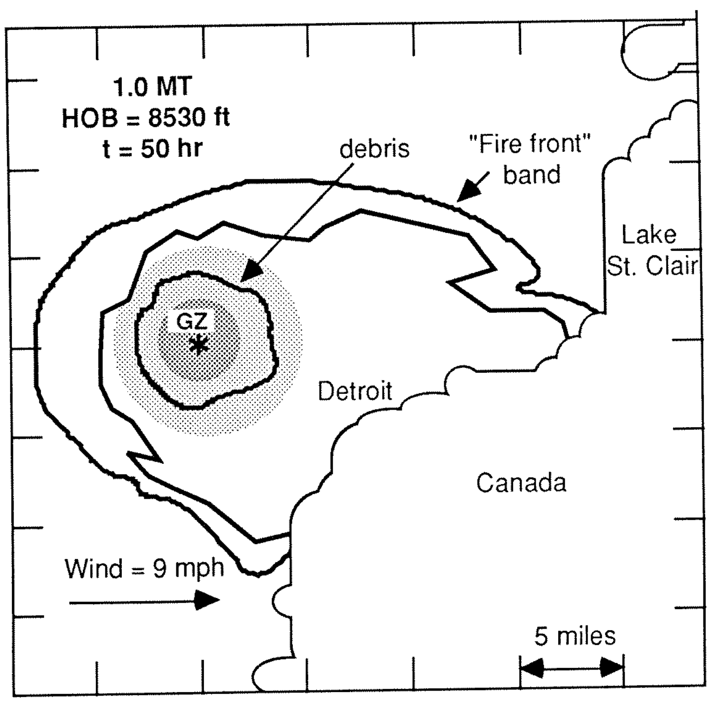
One full day after the attack, much of Detroit and its suburban area is burned out. The fire front has encountered the river. The firebreak effect of this water course is evident, as is the slowing action of a "vacant" area just north of downtown. The "fire front" is the band in which the principal burning is taking place. Ahead of the leading contour, 99 percent of the structures are as yet unburned, and behind the trailing contour (a distance of 1/2 to several miles behind the front) 10 percent of the buildings are as yet unburned. The results of this computer analysis forecast greater than 90 percent destruction over a large portion of the city, including the downtown area and the industrial complexes to the south of the city.

Continually driven by a west wind, the fire front has progressed, by the end of the second day, well to the south along the river and extensively northeast toward Lake St. Clair where further progress will be limited by lack of fuel. After 25 hours, this super-large urban fire is estimated to have burned over 8 million tonnes (about 9 million short tons) of fuel (wood equivalent) with a maximum heat release rate of 2.8 billion kilowatts, peaking at 6 hours after the explosion. At no time, however, does the model take on the characteristics of a firestorm, according to the criteria given in panel 19.

MODELS OF FIRE SPREAD



One day after attack



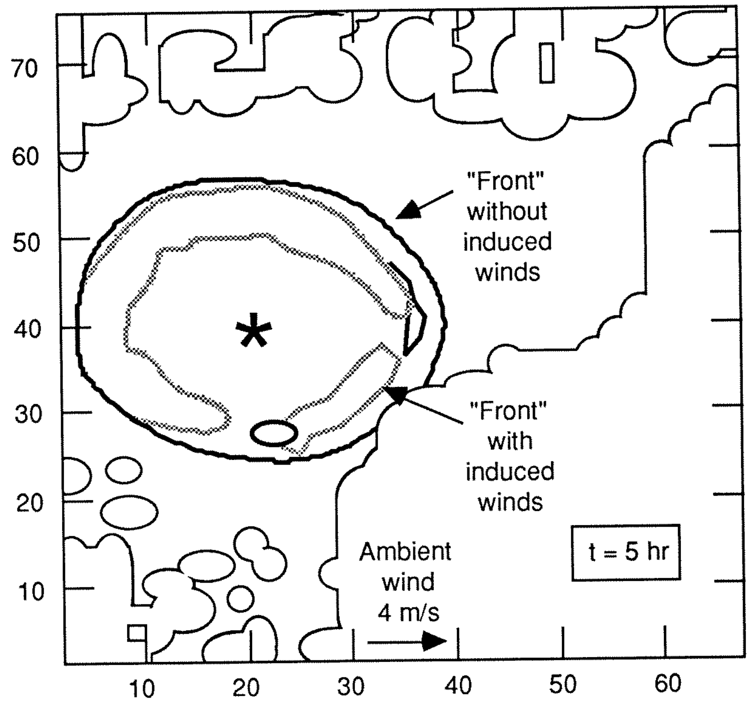
Two days after attack

MODEL OF A REAL CITY--FIRE WINDS

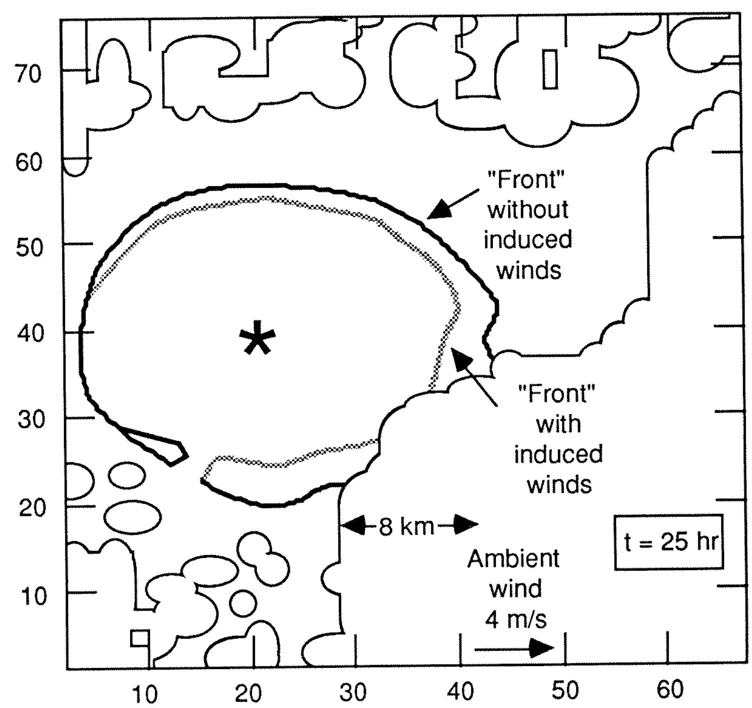
FIRECODE was run to simulate fire-induced winds and to compare results with and without the effects of winds. Figures on the facing page illustrate some of the analytical results. Interestingly, the main action of fire-induced winds under the conditions of this analysis was to retard outward spread. This is at least consistent with the prevalent notion that light ambient winds are readily overcome by the general inflow of fire-induced winds when the fire is large. It seems important to remark, however, that stronger ambient winds--perhaps only slightly stronger--might have turned this situation into a rapidly advancing conflagration. FIRECODE is unable to predict the synergistic effects of combinations of ambient and fire-induced winds. We cannot learn from it anything about conflagration potential except for that of fire spread enhancement by the ambient wind alone and the situation illustrated here in which the effects of fire-induced winds are to inhibit outward spread.

Computer-software codes are currently under development and are being designed to evaluate conflagration potential and other effects--synergistic and otherwise--of fire-induced winds (panel 34 and 35).

MODELS OF FIRE WINDS



Five hours after attack



25 hours after attack

PANEL 26

SURVIVAL IN FIRE AREAS

The traditional community priorities in maintaining fire emergency services are preservation of life, property, and the environment. Under normal circumstances there are rarely so many simultaneous emergencies that current systems and management measures fail. In a nuclear attack, however, fire departments would be overwhelmed because there are likely to be thousands of fires in any given city--much as occurred in the bomber incendiary attacks of World War II. As then, survival in the fire areas would require citizens self-help measures.

Preservation of life in a nuclear-attack threatened area is best served by shutting down utilities and operations and evacuating. Nevertheless, inadequate warning or lack of public resolve could leave thousands in the fire areas essentially on their own. Hence, continued survival following a nuclear explosion would require survivors to immediately assess damage in the shelter structure, check for fire starts, and take whatever actions is appropriate. Without this, there will be many more lives lost to fire and its effects.

Except for those in special blast shelters, region1 will have few survivors, virtually none outdoors. There will be survivors in region 2 even without special shelters (the vast majority of these will have been indoors in structures that survived, though most with damage). Immediate evacuation to region 3 is likely to be required for survival, as firefighting (by professionals or otherwise) will be impractical in region 2. For this circumstance, planners need to consider where surplus shelters exist for potential region 2, and some region 3, evacuees.

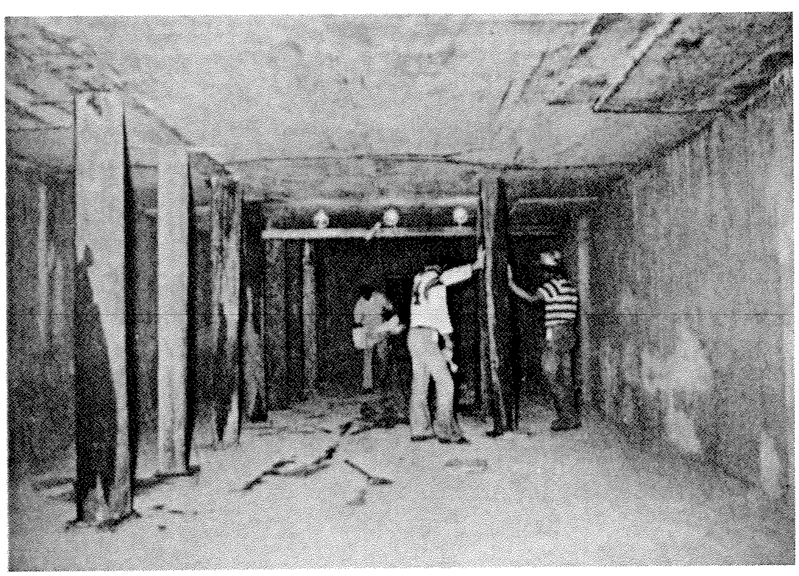
In considering shelters, the planner must take account to the fire threat from the standpoint of: fire ignition, fire spread, sufficient breathable air, escape (with both fallout and fire threats in mind), and rescue. This is in addition to the need to consider continuing blast and radioactive fallout threats (chapter 2 and 6). Fire threat information contained in this chapter provides insights to the task of ranking existing shelter buildings on the basis of fire risk if expedient sheltering should be required.

An ideal shelter is of heavy construction (lots of concrete and steel, so more blast resistant); is a low-rise building to preclude interior ignitions (warehouse type with few if any windows); has a basement with a concrete slab overhead to provide both fire and radioactive fallout protection, as it stands; has clear space around the structure to minimize debris from other structures that are demolished by the blast; and has alternative exits from the basement to facilitate escape and/or rescue. It will also have need of air-treatment facilities for protection from smoke and toxic gases. (Shelters are discussed in chapter 7.) Few buildings will have all these features, but the planner who has given consideration to potential targets will have an easier time identifying suitable compromises. A survey and list of potential shelters must take into account the fire threats enumerated.

PANEL 27

SURVIVAL IN FIRE AREAS

Damage control in simulated nuclear attack fire conditions.



Upgrading shelter suitable for fire protection.

FIRE SURVIVAL IN RESIDENTIAL AREAS

In chapter 2 (panel 12), it was noted that "survival in residential basements is estimated to be much higher than aboveground" (insofar as blast effects are concerned). Structural damage conditions were depicted in three ranges of overpressure--two characteristics primarily within region 3 (0.5 to 4.0 psi) and one characteristic primarily of regions 1 and 2.

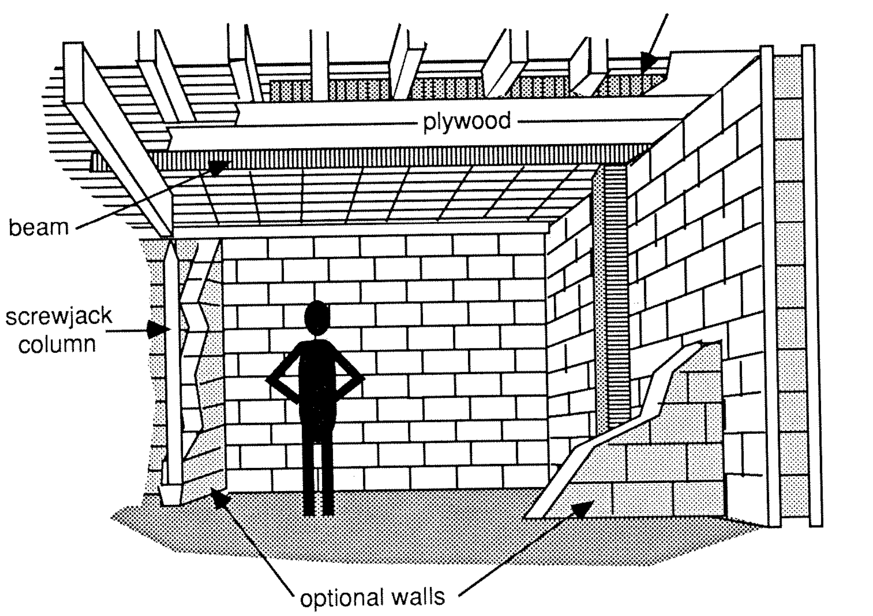
Certainly a home basement shelter may be expected to reduce deaths and injuries from missiles. (Some 100 shards per square foot of exposed surface are anticipated from shattering of windows glass and light plywood even at the 1 to 2 psi overpressures.) Basements can also protect individuals from the direct effects of the thermal pulse. Unfortunately, an unmodified basement will not protect from structural collapse. Hence, this option is tolerable only as a temporary (several minutes) expedient during the thermal pulse and blast phase when no other option is available. The fire threat, or the fallout threat, will be extremely high for anyone who stays out in such unmodified basement shelters. As that is the case, it is best to begin with a better alternative.

Chapter 2 provides reference to FEMA publications, e.g., H-20, "Protection in the Nuclear Age," June 1985, (superseded in July 1988 by "Planning for Survival") for modifications, improvements, and alternatives to shelters in the residential area. Many of these do not take into consideration the total fire threat. Even the most rigorous postattack fire-guard vigil in a residence cannot protect basement shelterees with wooden floors overhead if the residence is in an area of many fire starts or is subsequently swept over by a fire front. Those that survived the mass fires in shelters in World War II were generally protected by concrete slabs overhead or by complete concrete bunkers. Such shelters would also provide fallout protection in the nuclear age. Survivors out of doors in the fire area were generally immersed in water (rivers, large fountains) and had wet blankets to put over their heads. The blankets dried in minutes and require repeated immersing to protect against burns on the head and to cool the air that was breathed. Today, this approach in a mass fire area would provide temporary respite at best and could not be considered a satisfactory long-term solution because of the fallout threat. As survival outdoors or in basement shelters with wood floors overhead is untenable in the intermediate term, it would be better to have suitable protection available at the start.

A substantial shelter designed to protect against blast, fire, and fallout would provide optimum protection. Even a simple shelter is desirable and can be made by digging a trench; laying corrugated metal sheeting, plywood, or solid core doors over it; and then covering it with 18 inches of dirt. (The trench should be as far from all structures as possible to minimize burial in combustible debris.) The soil cover of this type of shelter is the key to protection from the fire and radioactive fallout, but soil is readily scoured away by blast waves from weapons in the megaton range. Therefore, it is important to protect the soil to keep it from blowing off. If the soil is moistened, overlaid with plastic sheeting or canvas, and then covered by sod or some other noncombustible (bricks, concrete blocks) to protect the plastic or canvas, the entire cover will act as a unit. This measure is necessary to safeguard against drying out (by fire) so that another blast wave will not completely scour away the soil.

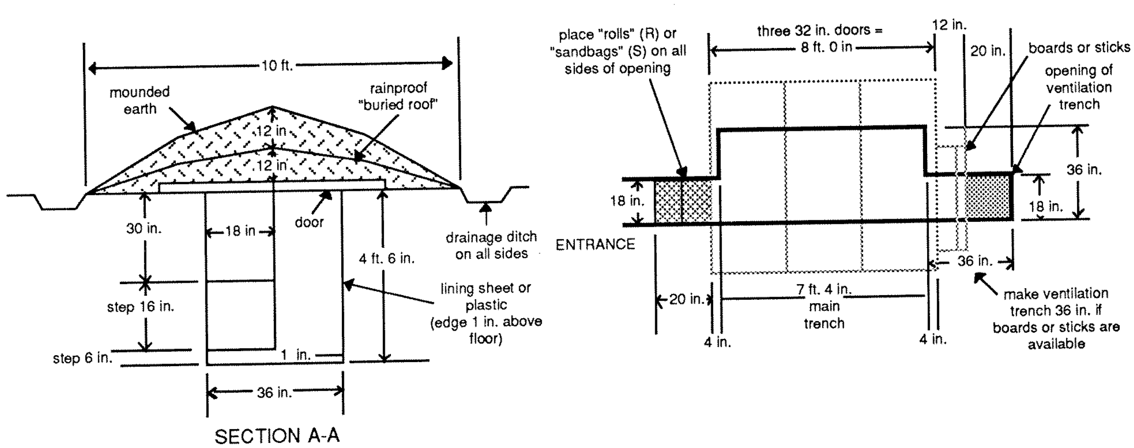
POOR LONG-TERM FIRE PROTECTION
Home Basement Shelter

Ceiling Modification Plan A



Very good fallout and thermal pulse protection; moderate blast protection

GOOD LONG-TERM FIRE PROTECTION
Trench Shelter



Very good fallout, thermal pulse, and last protection

FIRE SURVIVAL IN LARGE BASEMENTS

The basements of large buildings, particularly those described as "good shelters" in chapter 2, are commonly not penetrated by fire. An example from Hiroshima, the Fukoku Building, is shown in the upper photograph. This reinforced-concrete frame building experienced about 20 psi overpressure. Subsequently, the building was gutted by fire, but the fire did not penetrate into the basement. Since Hiroshima basements were not generally occupied as shelters, there is no evidence as to whether heat and noxious gases would have prevented survival inside them.

To gain a better understanding of the life hazard in basements, experiments were conducted in a reusable fire-test facility with two stories and a basement as shown in the lower photograph. The walls were designed to permit openings to simulate various degrees of blast damage. Combustibles were placed in one or both stories to represent the room contents for various occupancies such as residential, office, commercial, etc. The ground floor slab could be adjusted in thickness and in tightness to simulate openings that might be present. Although experiments indicated no serious problem from toxic gases penetrating the basement, the heat transmitted through the floor slab did present a serious problem. The basement, which had a floor slab 5 inches thick, became untenable in about an hour.

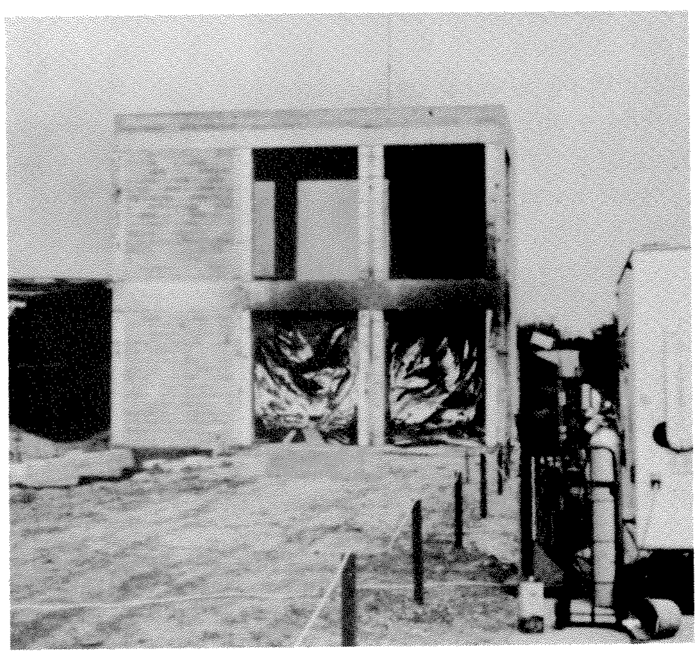
During the World War II raid of July 27-28, 1943, on the German city of Hamburg, about 20 percent of the population was sheltered in bunkers and other structures, specially built for this purpose, that were separate from other buildings. About 80 percent were sheltered in basements of public buildings and apartment houses that had been reinforced, sealed, and ventilated according to regulations of the German government. Survival in bunkers was 100 percent; about 80 percent of those sheltered in basements survived this notorious firestorm. Deaths in the basements were attributed principally to overheating and to carbon monoxide poisoning.

Where large basements are designated as blast or fallout shelters, fire guard teams should be assigned in each shelter to watch for and extinguish incipient fires. Plans should include procedures for orderly evacuation of shelterees to alternative shelters in case fires in the building above the basement shelter become out of control.

In fire-resistive basements, the primary threat to life would be toxic products of combustion, primary carbon monoxide (CO). Fires initiated outside of the basement in debris or the structure overhead will produce large quantities of CO. If, because of local wind conditions or the location of the fire, smoke infiltrates the basement, untenable conditions will develop--sometimes quite rapidly. Particulate smoke can be filtered easily through wetted fabrics. Fire gases such as CO and hydrocyanic acid (HCN), however, are not filtered in this way. Even low gas concentrations can be lethal whenever exposure times are prolonged. The German experience in WWII firestorms cited above indicates that adequate attention to the sealing and ventilation of bunkers to preclude any loss of life to mass fires was successfully achieved a half century ago. There is every reason to believe the same technique would be effective today throughout regions 2 and 3 and part of region 1.

PANEL 29

Fukoku building following the Hiroshima attack and fire



Fire above basement in Gary fire test facility

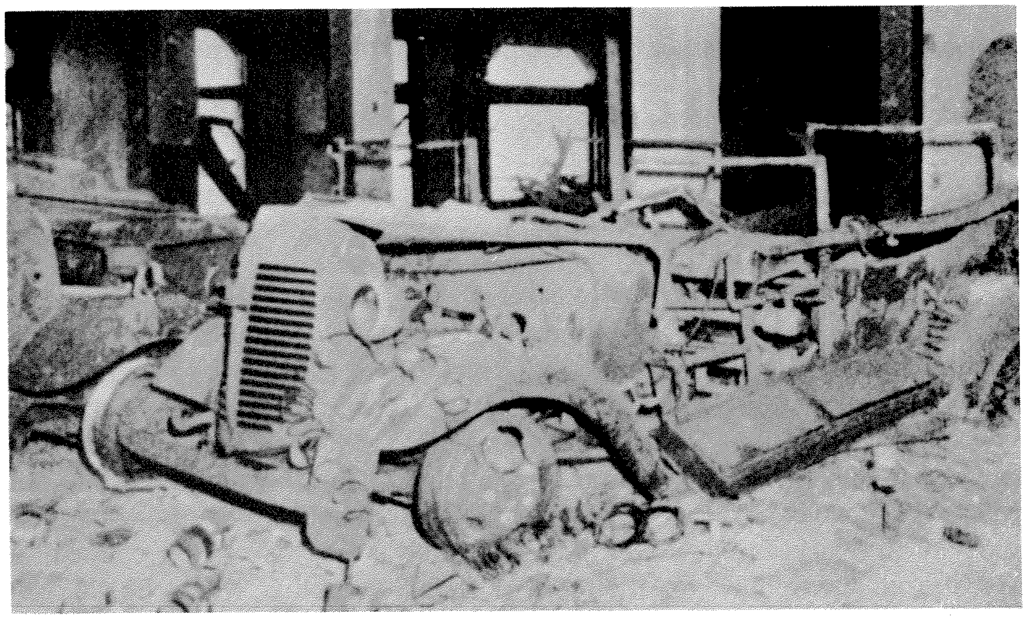
THE EFFECT OF FIRE ON PROPERTY

Nearly all the discussion in this chapter has emphasized the saving of life as the objective of fire defense measures. While this is as it should be, the emergency planner should be fully aware of the damaging effects of fire on community resources and productive facilities.

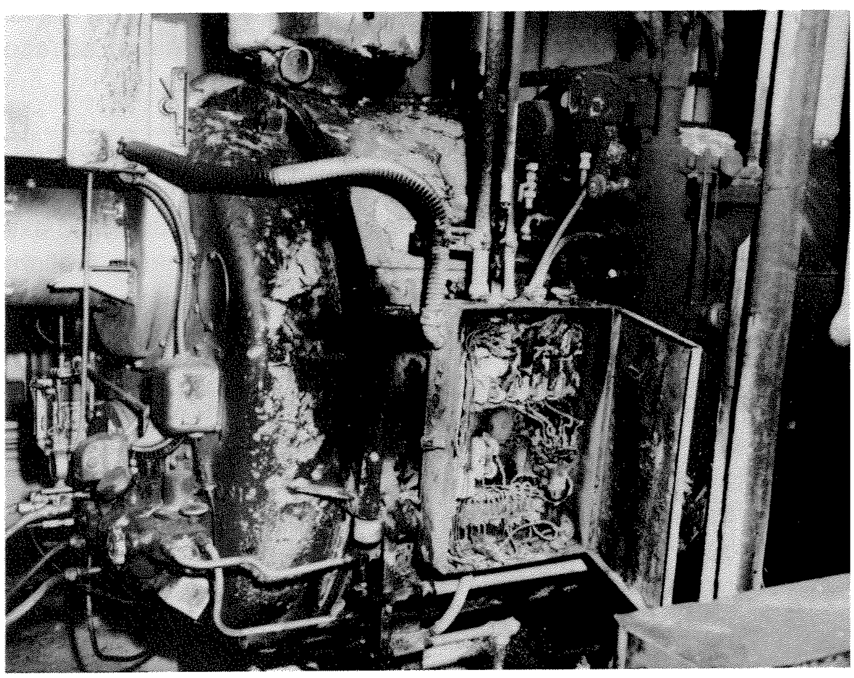
We have seen that fires will occur mainly in the area already damaged by the blast wave. It would be false to conclude, however, that the ensuing fire could add little to the damage that had already occurred. Tests show that blast-damaged equipment, vehicles, and buildings in region 2 (and some in region 1) can retain much of their original value. Many can be repaired and those damaged beyond repair often can be salvaged for parts and materials of value in postattack recovery. If such items were subjected to fire, however, the salvageable remains would likely be reduced to the category of junk, as shown in these photographs.

Historical data have shown that important facilities and equipment, such as electric power substations, pumping stations, and the like, must be completely replaced if swept by fire; whereas, blast-caused damage can often be quickly repaired. Emergency repairs to vital utilities and facilities are an emergency management function. Prevention of fire damage to vital plants and equipment is essential to the achievement of this objective. Special attention should be paid to those facilities that are particularly critical to the community. A possible approach to this problem is identified in panel 31.

FIRE DAMAGE



Hiroshima Industrial Company Building showing destruction of fire trucks in public fire department substation in first story. Building was gutted by fire although it suffered only 14 percent superficial blast damage.



Fire damaged electrical control box.

Photograph courtesy of Factory Mutual Engineering

THE BASIC FIRE DEFENSE PROBLEM

In any nuclear attack in an urban area, there would be so many buildings initially on fire that the established fire service could not handle them, even under ideal conditions. In urban areas, there are typically several thousand buildings in each square mile. The average fire company services about 2 square miles of urban area. If as few as 1 percent of the buildings were set on fire, each fire company would face 30 to 80 simultaneous building fires. Even near the edge of the fire area, established mutual support arrangements would be insufficient to extinguish more than a fraction of the fires.

Clearly, some expanded fire defense capability is necessary to prevent initial fires from growing and spreading. A practical fire defense must be based on a knowledge of how unattended fires develop and spread. Preventive measures prior to attack can have a major impact on the number of ignitions that may occur. Barring the ENCORE effect (panel 8), uncollapsed rooms may not flashover for a few minutes after sustained ignition of major fuels. In many situations, the blast wave will extinguish flames for periods of minutes to hours, providing additional time for preventive actions.

In addition to precautionary measures to minimize fires and fire spread, there appear to be two main planning options available. One is to deploy or maintain professional firefighters and their equipment at critical facilities (see panel 30) where their use in fire defense would not depend on the ability to move through the streets. The other would be to relocate fire companies to staging areas, together with debris-clearing equipment, so that movement to one or more threatened sites might be feasible. Either option, or a combination of the two, might be appropriate, depending on the number of critical facilities in the area and the availability of fire equipment and manpower. Such deployment would have to be contingent on a support team to monitor radioactive fallout for each firefighting team and the availability of adequate fallout shelters within easy reach. Also, planners and government officials must recognize that the fallout hazard may limit or cut short firefighting emergency operations.

On the basis of the information at hand, the elements shown in this chart would appear necessary. In a nuclear emergency, the organized fire companies would be restricted to defense of vital facilities and major firebreaks. Fire prevention measures and extinguishment of incipient fires would depend on auxiliary units and on self-help emergency firefighting among the population. There is a need for fire guard teams in public shelters as specified parts of widespread fire defense capability. Material support needs must also be taken into account.

The firefighting of fire guard teams and self-help firefighters will be restricted to reducing the amount of combustible material in the vicinity of shelters before attack and extinguishing incipient and smoldering fires after passage of the blast wave. Their training will therefore be fundamentally different from that of the organized fire service as they will generally not attempt to fight fully developed fires.

ELEMENTS OF A FIRE DEFENSE ORGANIZATION

PANEL 31

SOME HISTORICAL EXPERIENCES OF NOTE

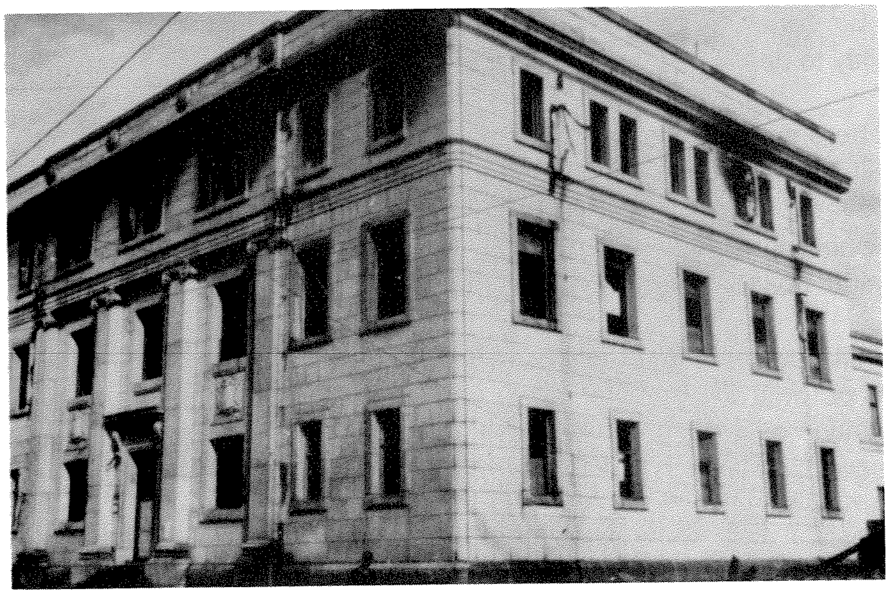
Survivors can suppress ignitions and fires in an area damaged by a nuclear detonation. World War II records from the Japanese experience indicate that this is so.

Hiroshima suffered one of the only two mass fires initiated by a nuclear weapon. Though the citizens did not have any concept of the threat of a nuclear explosion, they were prepared for incendiary fires because a number of Japanese cities had undergone massive firebombings. Incendiary attack preparation consisted of keeping firefighting tools ready: pails of sand, dirt, and water; tongs for picking up firebrands; and a capability to use these tools. There are new factors to consider today that differ from the Hiroshima situation. The risk from fallout while fighting fires is unknown. Megaton weapons would produce much longer duration blast winds. Relatively lower burst heights would result in many times greater blast winds inside region 1. Nevertheless, the incendiary attack preparations proved of value in Hiroshima; in residential areas where there was little professional firefighting capability available, citizen firefighting brought recorded successes.

The upper photograph shows a building, postattack, located in Hiroshima's region 1. It was a three-story, reinforced-concrete building of earthquake resistant design. The building was exposed to an overpressure of 18 psi, which killed about half of the 100 occupants; only four were said to have been uninjured. For whatever reason, no initial ignitions occurred; but after about an hour and a half, a firebrand started a fire in a room on the second floor. This blaze was extinguished with water by survivors, preventing further damage. A later fire on the third floor got beyond control before discovery and burned the floor out without spreading to lower floors. A somewhat similar experience was recorded for another bank building located in Hiroshima's region 2 (see lower photograph). Subsequent fires were extinguished by building occupants with water, and negligible fire damage resulted.

Fires were often temporarily extinguished in postwar American experiments conducted in a special blast/fire facility. Typical furnishings were set afire in rooms and subjected to different blast waves to simulate the decay expected from megaton weapons. It is noteworthy that members of the study team could and did enter the rooms and carry the smoldering furnishings outside where a large proportion of them reignited in periods of minutes to hours later. Such actions do not, therefore, seem out of the question as a means to protect against fire in any of the three regions. Smoldering items need not be carried outdoors, however; it would be faster to throw them out a window, so long as they are thrown clear of debris that could catch fire and threaten the shelter exterior.

BUILDINGS SURVIVING NUCLEAR ATTACK



Bank of Japan building after attack on Hiroshima

Geibi Bank Co. building after attack on Hiroshima

SELF-HELP FIRE DEFENSES

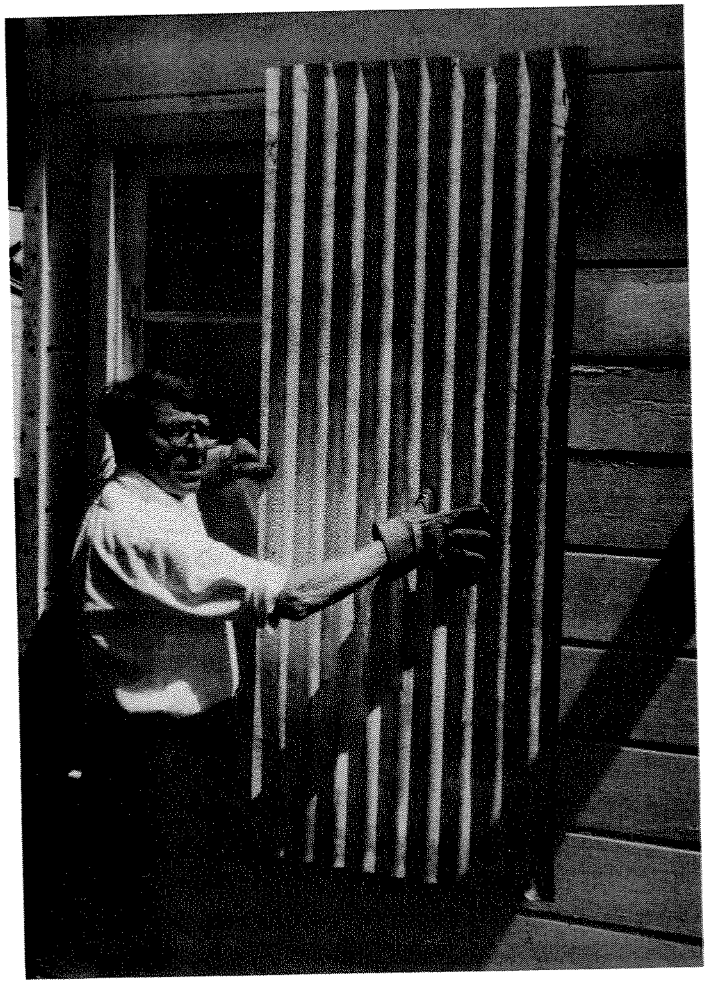
The National Fire Protection Association estimates that only one out of every ten fires that occur annually in the United States is actually reported. In 1986, a total of 2,271,500 fires were reported; about 800,000 were structural fires, 581,500 were residential. How were the other 20 million fires--those unreported--extinguished? No doubt some died out for lack of fuel, and others were extinguished by automatic systems and by emergency response teams and fire brigades with varying degrees of specialized training. Nevertheless, for many millions of fires yearly, it may be construed that the general public extinguishes them, demonstrating an effective capability to deal with incipient fires.

The point here is that the principal opportunities for public intervention in a nuclear attack environment will be with incipient fires and in preventive aspects, both areas where public capability is proven. Panel 1 points out the many reasons that conventional firefighting is unlikely, hence public intervention will be important. The question remains as to where and how this capability might best be applied.

Actions similar to those of Hiroshima residents appear practical in all three regions and could be carried out with minimal risk from radioactive fallout in regions of a building below the top floor. Elimination of combustibles on an entire floor above the shelter area would provide a firebreak and leave higher floors to provide fallout protection for fireguard tours. This firebreak could be made immediately following an attack with minimal risk from fallout radiation.

Successful extinguishment or jettison of smoldering items depends on finding fire starts immediately following the blast. In regions 1 and 2, search for incipient fires in surviving (damaged) structures is within the capability of physically able survivors within those structures with minimal risk (panel 32). Because the fire is dynamic, this will be a continuing task. However, general firefighting activities in areas of demolished structures will not be profitable because extinguishment will be beyond available resources. In region 3, most structures and people will survive the blast and thermal pulse (though some homes will be demolished near region 2). In region 3, the risk of fire remains high, and extinguishment of incipient fires is a reasonable task. Extinguishing a myriad of fires, often without water, will be difficult at best. A possible alternative for avoiding most starts in region 2 and 3 altogether might be achieved through timely implementation of the preventive actions described below. This requires sufficient warning.

Many pieces of advice are offered to the public regarding preventive actions. For residences, most of these are time consuming (cleaning attics, garages, basements, moving everything combustible away from windows, etc.) and will not be effective if the structure does not survive in any case. By far, the most effective options are: (1) turn off all utilities at the main; and (2) use plywood or lightweight corrugated (for strength) metal sheeting to cover all windows. The first option is simple and will prevent the majority of secondary fires in residences. The second option will preclude interior ignitions by thermal pulse, will survive if the structure does, and will still be there in case a thermal pulse from another weapon arrives (whereas aluminum foil and paint covered windows will be shattered as far out as 0.5 psi following the first blast). Plywood and corrugated metal sheeting are practical window coverings that are available nationwide in dimensions far exceeding the window areas in structures.



Corrugated roofing and siding used to protect windows. (Deflection at center less than 1.75-inches when nailed at ends for a 4-ft span of 28 gauge corrugated steel, 0.029 in. thick.)

CONFLAGRATION ASSESSMENT

We have previously expressed concerns about a form of mass fire--different from a firestorm, but no less a threat to human survival--called a conflagration. This wind-driven fire takes on special significance when it develops its own winds to accelerate and reinforce the effects of the ambient wind. At present, we do not have an adequate theory of how this reinforcement comes about, nor can we prescribe its prerequisite conditions. Experience, however, provides clear warnings that certain situations of urban congestion and poor construction practices are conflagration prone.

An assessment of the conflagration potential of various tracts in a city will provide a basis for planning fire defense measures. It will also pinpoint which high-risk shelter facilities should be abandoned as potentially untenable as soon as significant fires are observed in the area.

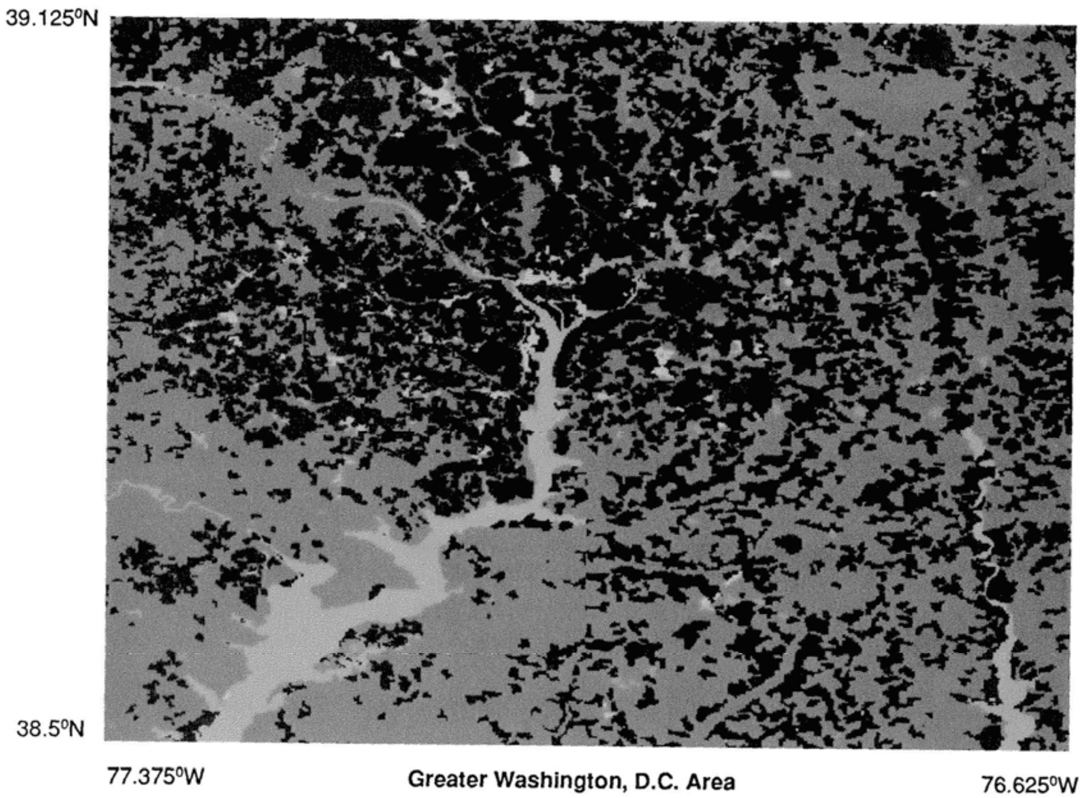
By using a rating method, fire service personnel and others with a working knowledge of fire protection technology and the ability to identify the various types of building construction can make a block-by-block assessment of the fire risk. The hazard rating for each block or group of similar blocks in the city, which is based on the fuel loading and density of construction, represents relative hazard rather than an absolute measure of risk. The higher the block rating, the greater the likelihood of simultaneous burning of many buildings on the block to create a conflagration.

This detailed block-by-block assessment of conflagration potential can form a basis for selecting the shelter facilities to be included in the in-place fallout shelter plans as well as a basis for identifying those tracts that should be avoided when possible or abandoned rapidly, if fires occur. Identification of conflagration areas can help improve peacetime assignment of firefighting personnel and equipment. It can contribute to community planning and urban renewal by pointing to existing substandard structures whose razing would reduce peacetime fire hazards in the city. It should also prove useful in planning for emergency operations in natural disasters, such as earthquakes.

Computer automated methods are now beginning to show their capability to accomplish a similar assessment with a much reduced investment in manpower. These methods may not be as reliable in detailed assessments as on-the-ground surveys because they are based on digitized map data bases derived from aerial and satellite photos. However, they can be updated regularly as the city changes and when the data base improves. Moreover, as the illustration opposite reveals, block-by-block resolution can be achieved.

This illustration (a map of the greater Washington, D.C., area) is resolved into tracts 300 feet on a side--about the size of a city block. The data base provides 250 unique features directly related to land use. Separate attributes contained in the data include measures of building density and size. Other fire-analysis variables are being added as requirements are identified. In the very near future, we can expect software developments that will allow planners to routinely conduct such computer analysis using up-to-the-minute information provided by improved data bases tailored specifically to the needs of fire-damage assessments.

LAND USE MAP



Greater Washington, D.C. Area

Black	=	Open land and residential
White	=	Water/transportation/commercial
Grey	=	Vegetation

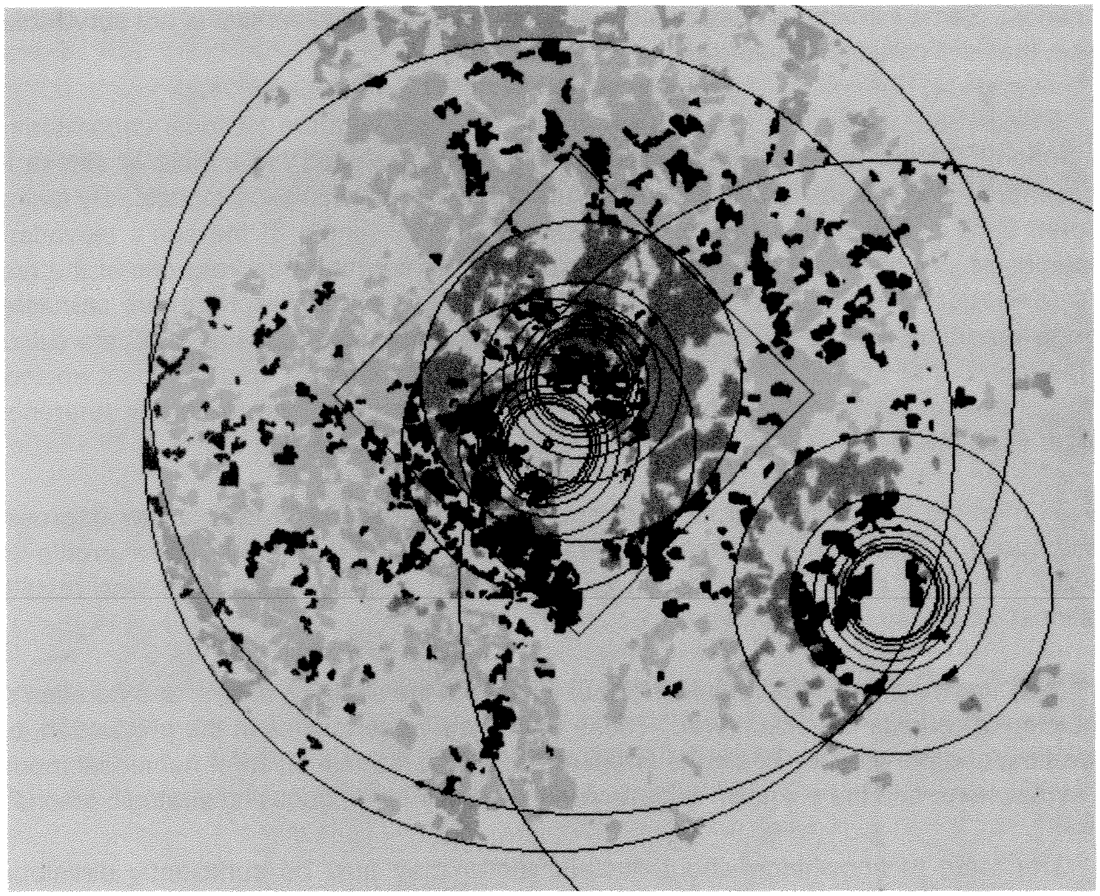
POSSIBLE ATTACKS AND CONSEQUENCES

Throughout this chapter, we have dealt with fire effects and defenses as if your city, unlucky enough to be subjected to the direct effects of a nuclear explosion, had experienced only one nuclear explosion. Such a scenario is plausible and deserves serious emergency planning but is no longer an adequate picture of strategic attack. Today, threatened with multiple warhead missiles, cities must extend their plans to include the consequences of multiple bursts. While targeting policies of any potential enemy nations place no known priority on civilian population centers, neither do they necessarily try to avoid them in plans to destroy strategic targets, both military and civilian. Although the explosion yields of multiburst attacks will often be smaller, with somewhat reduced areas of damage, planning is complicated by the possibilities of delays between bursts; the uncertainty as to how long to keep personnel under cover; and when to begin emergency operations. Planning and control become even more indispensable to making the right decisions and carrying them out.

Most of the material already presented to you is still perfectly valid for multiple burst situations. The main differences stem from the simple fact that, if subsequent bursts hit an already damaged city, some overlap of the effects is bound to occur. Some amelioration of effects may result from dust and smoke caused by an earlier nuclear burst, which can shield parts of the city from the thermal radiation emitted by a later fireball, and thereby limit the number of additional primary fires. But thermal radiation screens erected in anticipation of attack are apt to be lost to the first blast wave, with subsequent bursts, more ignitions can be expected in debris in the streets and leaking fuel from broken mains as well as flammable liquids.

Until recently, we have not had the capability to describe the net effect of replacing a single explosion with two or more, at different times and locations, unless they were postulated to be so far apart that no appreciable overlapping occurred. Now, however, computer models are available to do some parts of the overlap problem with confidence. Here we show output of one such exercise when a three-warhead attack was postulated in the vicinity of the Nation's Capital.

EFFECTS OF A THREE-WARHEAD ATTACK



Greater Washington, D.C. Area

Black	=	Firestorm intensity
White	=	Minor fires
Grey	=	Group fire intensity (panel 11)

NUCLEAR WINTER

In 1983, a study was published on the climatological effects of injection into the atmosphere of hundreds of millions of tons of smoke and dust by a large nuclear war. This study, entitled "Nuclear Winter: Global Consequences of Multiple Nuclear Explosions" (nicknamed TTAPS from the initials of its authors: Turco, Toon, Ackerman, Pollack, and Sagan), predicted temperature depressions of 40° to 60° centigrade (C) for some attack scenarios. Some individuals cited these results as proof that nuclear war is not survivable and, hence, that civil defense is unfeasible.

Since 1983, workers at Los Alamos and Lawrence Livermore National Laboratories and the National Center for Atmospheric Research have reanalyzed the effects of smoke in the atmosphere using increasingly complex 3-dimensional global circulation models. By taking into account such things as the heat capacity of oceans, the angle of the sun's elevation, the properties of smoke, and the movement of the winds, temperature depressions of the order of 15°C (averaged over the temperature latitudes of the Northern Hemisphere) are calculated for large summertime attacks on cities. Temperature depressions as large as 25°C are calculated for the interiors of continents for large attacks in the summertime, causing local episodes of frost. These temperatures are based on more recent models than the study referenced in chapter 6, panel 29.

Wintertime wars would produce temperature depressions of only a few degrees, not substantially different from normal winters. Alteration of the temperature profile in the atmosphere could suppress convection precipitation in a spring or summer war, resulting in additional difficulties for agriculture.

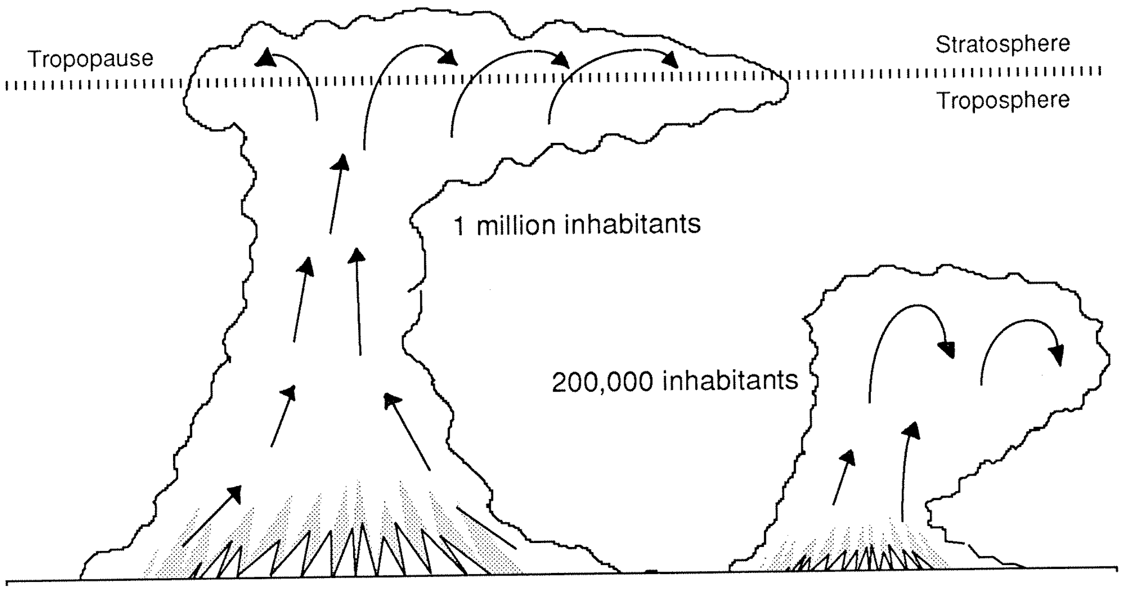
Very large uncertainties remain in the estimates of the severity, extent, and duration of the climatological effects of nuclear war. These stem from uncertainties in the production, optical properties, and persistence of smoke in the atmosphere; the resolution of numerical models of the atmosphere; and the unknown targeting and accuracy of the opposing strategic arsenal.

The state of knowledge about nuclear winter may now be sufficiently developed to conclude:

- Neither cold nor drought is likely to be a direct threat to human survival for a population with the wherewithal to survive normal January temperatures.
- The principal threat from nuclear winter is to food production, which could present problems to countries that are without food reserves.
- Loss of a crop year is neither a new nor an unexpected threat from nuclear war to the United States and the Soviet Union. Both have at least a year's food reserve at all times.

The consequences of nuclear winter could be expected to fall more heavily on the Soviet Union then on the United States. The Soviet Union is at a higher latitude in the center of a larger continent and has a more marginal climate for agriculture.

APPROXIMATE HEIGHTS OF SMOKE PLUMES OF CITY FIRES IGNITED BY THERMONUCLEAR WEAPONS



Scale: 5.3 centimeters equal to 33,000 feet (10 kilometers)

SUGGESTED READING

Fire Protection Handbook, Sixteenth Edition, Section 7, "Fire Safety in Building Design and Construction," National Fire Protection Association, 1986.

Lie, T.T., **Fire and Buildings**, Applied Science Publishers, Ltd., 1972.

Drysdale, D., **An Introduction to Fire Dynamics**, John Wiley and Sons, 1985.

Culver, Charles G., **Survey Results for Fire Loads and Live Loads in Office Buildings**, Building Science Series 85, National Bureau of Standards, Gaithersburg, MD, May 1976.

GLOSSARY OF TERMS AND UNITS

Blowout--Suppression of fire by sudden onset of air flow caused by blast wave. Flames may be only temporarily extinguished in materials that smolder.

Buildings Fuel Load--Weight of total combustibles (both structural and contents) per unit foundation area, expressed here in pounds per square foot (psf).

Building Density--Fraction of built-up land area actually contained within building foundations.

Conflagration--A mass fire moving, under the influence of the ambient (existing) wind, as a front into previously unburned areas (example: Tokyo, 1945).

Fire Load--Average weight of fuel per unit land area, expressed here in psf. Computed by multiplying building fuel loads times building densities.

Fire Winds--Winds in excess of the ambient wind that are induced by fire convection.

Firestorm--A mass fire, commonly stationary, that generates strong, inwardly directed winds, and consumes virtually everything combustible within the effected area (example: Hamburg, 1943).

Flame Radiation--Thermal radiation emitted by a fire. Intensity is often expressed in kilowatts per square meter (see Thermal Flux).

Flashover--Change of state (often quite abrupt) in room fire during growth that results in full fire involvement of all combustibles.

Mass Fires--Fires simultaneously burning over contiguous areas of at least several city blocks in size. Mass fires may be either stationary (e.g., firestorms) or moving-front fires (e.g., conflagrations).

Overpressure--Momentary pressure rise associated with the passage of the blast wave, expressed in pounds per square inch (psi).

Primary Fires--Fires initiated directly by the thermal pulse of the nuclear fireball.

Secondary Fires--Fire initiated by other weapons effects, mainly blast damage.

Self-help--Firefighting (or fire prevention) undertaken by nonprofessional residents.

Thermal Fluence--Thermal-pulse energy per unit area of exposure, expressed here (and by common convention) in calories per square centimeter (1 cal/sq cm = 41.85 kW-s/sq meter).

Thermal Flux--Momentary thermal-pulse power per unit area of exposure, expressed in calories per square centimeter per second (1 cal/sq cm-s = 41.85 kW/sq m).

Yield--Energy released in a nuclear explosion; thus, an index of a weapon's potential to destroy, expressed as kilotons or megatons of TNT.