The Medical Implications of Nuclear War, Institute of Medicine.

National Academy Press, Washington, D.C.

# Possible Fatalities from Superfires Following Nuclear Attacks in or near Urban Areas

THEODORE A. POSTOL, PH.D.
Stanford University, Stanford, California

## INTRODUCTION

During the period of peak energy output, a 1-megaton (Mt) nuclear weapon can produce temperatures of about 100 million degrees Celsius at its center, about four to five times that which occurs at the center of the Sun.

Because the Sun's surface is only about 6,000°C and it heats the Earth's surface from a range of more than 90 million miles (about 145 million km), it should be clear that such a nuclear detonation would be accompanied by enormous emanations of light and heat.

So great is the amount of light and heat generated by a 1-Mt airburst, that if one were to occur at a high enough altitude over Baltimore, observers in Washington, D.C., might see it as a ball of fire many times brighter than the noonday Sun. Even if such a detonation were to occur near dawn over Detroit, out of line of sight because of the Earth's curvature, enough light could well be scattered and refracted by atmospheric effects for it to be observed as a glare in the sky from Washington, D.C.

This intense light and heat from nuclear detonations is capable of setting many simultaneous fires over vast areas of surrounding terrain. These fires, once initiated, could efficiently heat large volumes of air near the Earth's surface. As this heated air buoyantly rises, cool air from regions beyond the vast burning area would rush in to replace it. Winds at the ground could reach hurricane force, and air temperatures within the zone of fire could exceed that of boiling water

The ferocious hurricane of fire would also be accompanied by the release of large amounts of potentially lethal toxic smoke and combustion gases, creating an environment of extreme heat, high winds, and toxic agents in target areas.

Although the smoke from these fires has been the subject of considerable attention, as it is possible that significant climate effects could result from its sudden injection into the upper atmosphere, there has been no comprehensive evaluation of the implications of these fires for those in target areas.

In this paper, the potential implications of these fire environments on casualty estimates is assessed.

The standard model for calculating deaths and nonfatal injuries from hypothetical nuclear attacks assumes that the same casualty rates will occur at each level of blast overpressure as that which occurred at Hiroshima. This methodology, which will henceforth be referred to as blast effect, or simply blast scaling, is the standard methodology used by government agencies to estimate casualties in nuclear war.

The preliminary analysis presented in this paper indicates that if fire effects are included in assessments of possible fatalities from nuclear attacks using megaton or near megaton airbursts in or near urban areas, about two to four times more fatalities might be expected relative to those which might be expected from blast scaling calculations.

This enormous increase in projected fatalities is partly a result of the very large expected range of superfires, which would extend well beyond that in which large numbers of blast fatalities would be expected, and partly because of the high lethality in the blast-disrupted and fire-swept environments within the burning region.

The very great uncertainties in the speculated differences between blast and fire scaling are due to the great uncertainties in the radius of the potential fire zone, as well as to uncertainties in the exact nature of the environments within these zones.

Another feature that emerges from the analysis is that the projected number of injured requiring medical treatment would be drastically reduced relative to that projected by blast scaling, as many injured that would otherwise require treatment would be consumed in the fires. This is consistent with the findings of German review commissions[1] which were set up during World War II to evaluate the effects of large-scale incendiary raids against their cities and with the findings of the U.S. Strategic Bombing Survey after World War II.[2] Both reviews found that the ratio of fatalities to injuries was much higher when the effects of incendiaries, rather than high explosives, was the major source of damage from air raids.

In this paper, the following will be discussed. First, the blast and incendiary effects that would accompany the detonation of a 1-Mt airburst will be described. A baseline estimate of the radius of potential incendiary effects from the airburst will then be established; and the distinctive characteristics of the resulting giant area fires, high winds, and unusually high average air temperatures will be described. Evidence is presented to show that contrary to what has been previously believed,[3,5] attacks on lightly built-up, sprawling American cities, where the amount of combustible material per unit area is relatively low, could well result in extreme conditions somewhat comparable to those of the firestorms experienced in Japan and Germany during World War II. Estimates of noxious gas concentrations then will be made using data presented in the previous section, and it will be shown that the combination of these toxic agents within the fire zone are likely to be lethal to all unprotected individuals. Anecdotal and medical observations from World War II firestorm experiences will be reviewed, and a very crude cookie cutter model will be discussed. It is argued that more sophisticated models are unjustified in view of the large uncertainties in possible fire radius but that the simplicity of this model still allows a preliminary assessment of the importance of fire effects. The currently standard blast effect scaling method will be reviewed and compared and contrasted with the fire effect scaling method. Projections of casualties using both blast and fire scaling will then be presented for airburst antipopulation attacks. This establishes a reference case for the comparison of casualty projections by both methods and for different target sets. It will be shown that blast scaling may underestimate fatalities from airburst attacks in or near urban areas by factors of about two to four. Casualty projections are then compared for the antipopulation reference attack and a very limited anti-industrial attack, which is not designed to kill large numbers of people. However, the inclusion of superfires in casualty predictions indicates that this more limited attack might actually result in about two to three times more fatalities than that predicted by the government for the antipopulation attack. This serves to underscore the need for a better understanding of these weapons effects.

## INCENDIARY EFFECTS OF NUCLEAR WEAPONS

In this section, the events associated with the detonation of a 1-Mt airburst are described. Because the weapons' effects of interest here, blast and thermal radiation (heat emanating from the fireball), do not change drastically with yield and because many of the weapons in today's arsenals are of comparable yield, this discussion will provide background information that will allow the reader to construct a picture of an urban target area following a nuclear attack.

When a nuclear weapon is detonated, an enormous amount of energy is released in an extraordinarily short interval of time. Nearly all of this energy is initially released in the form of fast-recoiling nuclear matter which is then deposited into the surrounding environment within hundredths of millionths of a second.

Unlike a comparable chemical explosion, in which almost all the explosive power is in expanding gaseous bomb debris, more than 95 percent of the explosive power is at first in the form of intense light. Since this intense light is of very short wavelength (it is soft x-rays), it is efficiently absorbed by the air immediately surrounding the weapon, heating it to very high temperatures creating a "ball" of fire.

Because the early fireball is so hot, it quickly begins to violently expand, initially moving outward at several millions of miles per hour while it also radiates tremendous amounts of light and heat. This rate of expansion slows rapidly, and by the time the fireball begins to approach its maximum size, its average speed of expansion is no more than 5,000 to 10,000 miles/h (about 8,000 to 16,000 km/h).

During the course of its expansion, almost all of the air that originally occupies the volume within and around it is compressed into a thin shell of superheated, glowing, high-pressure gas. This shell of gas, which continues to be driven outward by hot expanding gases in the fireball interior, itself compresses the surrounding air, forming a steeply fronted luminous shock wave of enormous extent and power (see Figure 1A).

By the time a 1-Mt fireball is near its maximum size, it is a highly luminous ball of more than 1 mile (1.6 km) in diameter. At 0.9 second after detonation begins, it is at its brightest. Its surface, which masks the much hotter interior of the fireball from the surroundings, still radiates two and a half to three times more light and heat than that of a comparable area of the Sun's surface.

By taking into account atmospheric attenuation (12-mile [about 19.3-km] visibility), at a distance of 6 miles (about 9.7 km), it would be 300 times brighter than a desert Sun at noon; and at 9 miles (about 14.5 km), it would still be 100 times brighter. Thus, extensive fire ignitions would accompany such an airburst over an urban/industrial area.

Figure 1 shows the development of a 1-Mt airburst detonated at an altitude of 6,500 feet (about 2 km) at five distinct points of time during the process.[6]

At 1.8 seconds (Figure 1A), the fireball is no longer expanding very rapidly, although it is still like a giant luminous and buoyant bubble in the Earth's atmosphere. It has already passed the time of maximum brightness, and the shock wave has broken away from it, already reaching a range of more than 0.5 mile (about 0.8 km) from its point of origin.

When the primary shock wave from the explosion reaches the ground (see Figure IB), a secondary shock wave is generated by reflection. The primary and secondary shock waves then propagate outward along the ground, forming a single vertical shock wave called the reinforced Mach front (see Figure 1C). The overpressure in this shock is roughly twice that of either the primary or the secondary shock.

By judicious choice of height of burst, it is possible to maximize the area over which this Mach front delivers a predetermined level of destructive overpressure. For the choice of burst height in this example, the area over which 15 pounds per square inch (psi) or more occurs has been maximized.

Figure 1C shows the situation at roughly 11 seconds after detonation. The shock wave would be about 3 miles (about 4.8 km) from the point on the Earth's surface over which the detonation occurred (this point is called ground zero), and the peak shock overpressure would be 6 psi. In the next 5 seconds, the shock would reach a range of 4 miles (about 6.4 km) and decay to a peak overpressure of 5 psi.

Figure 2 shows the sequence of events as they might occur at a wood frame house at a distance of 4 miles. Since the shock wave would take 16 seconds to arrive at the 4-mile range, when the detonation begins, a bright flash of growing intensity would be observed at the house within tenths of seconds. Because the shock wave would take a long time to arrive, this is the only initial indication of a detonation (see Figure 2A). Hence, sounds and noise levels around the house, at least at this moment, would be relatively unaltered.

The fireball, of course, continues to grow in brightness. Within 1 second, it is at its maximum brightness, appearing 800 to 900 times brighter than a desert Sun at noon. The tremendous rate of arrival of radiant power would result in the effusion of black smoke from the front of the house,as paint would be burned off the wood surfaces (see Figure 2B). If the building has interior household materials in it, and they are in the line of sight of the fireball, they would explode into violently burning fires almost instantly.

Fifteen seconds after the peak in the thermal pulse, the shock wave arrives (see Figures 2D, 2E, and 2F). Unlike a shock wave of comparable peak overpressure from a high explosive bomb, which persists for about 0.1 second as it passes, this shock wave persists for nearly 3 seconds. As a result, it is accompanied by winds of more than 150 miles/h (about 241 km/h). The shock wave therefore would first strike the building and then envelope it in a region of high-pressure air and high winds. The building

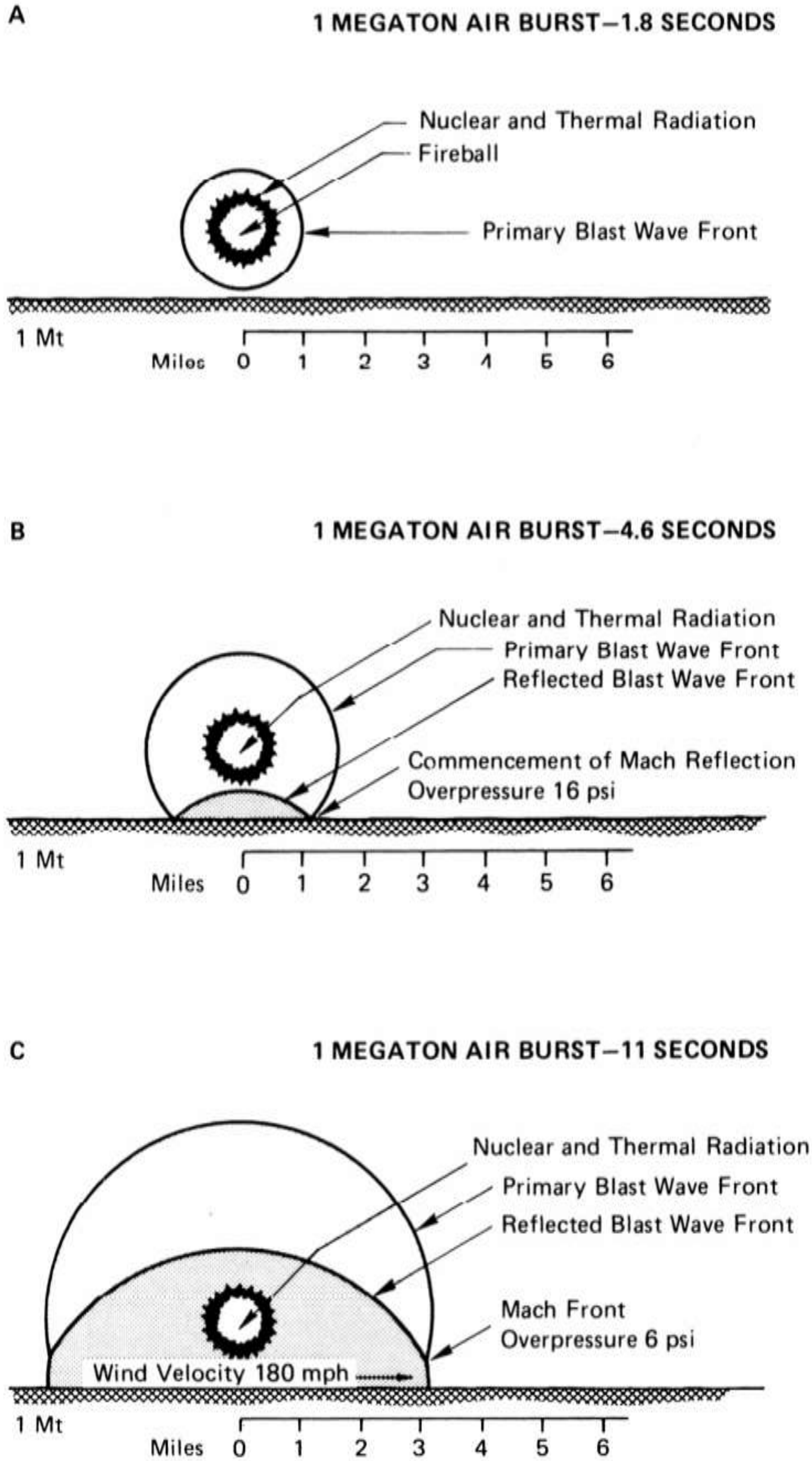
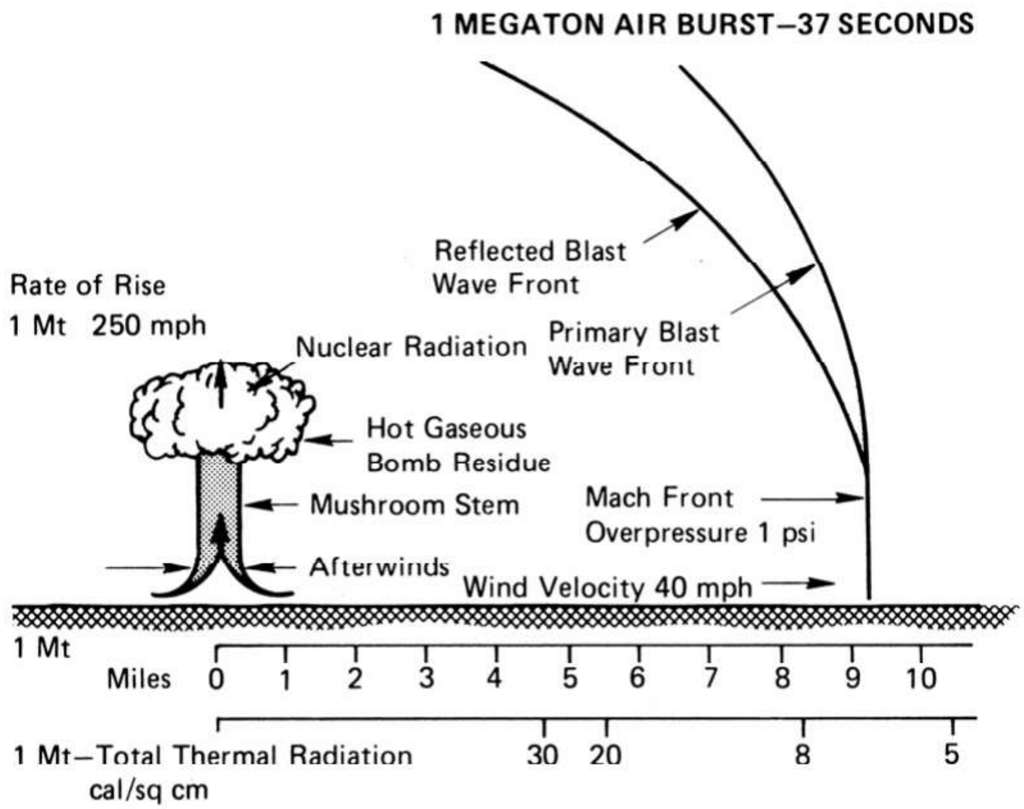
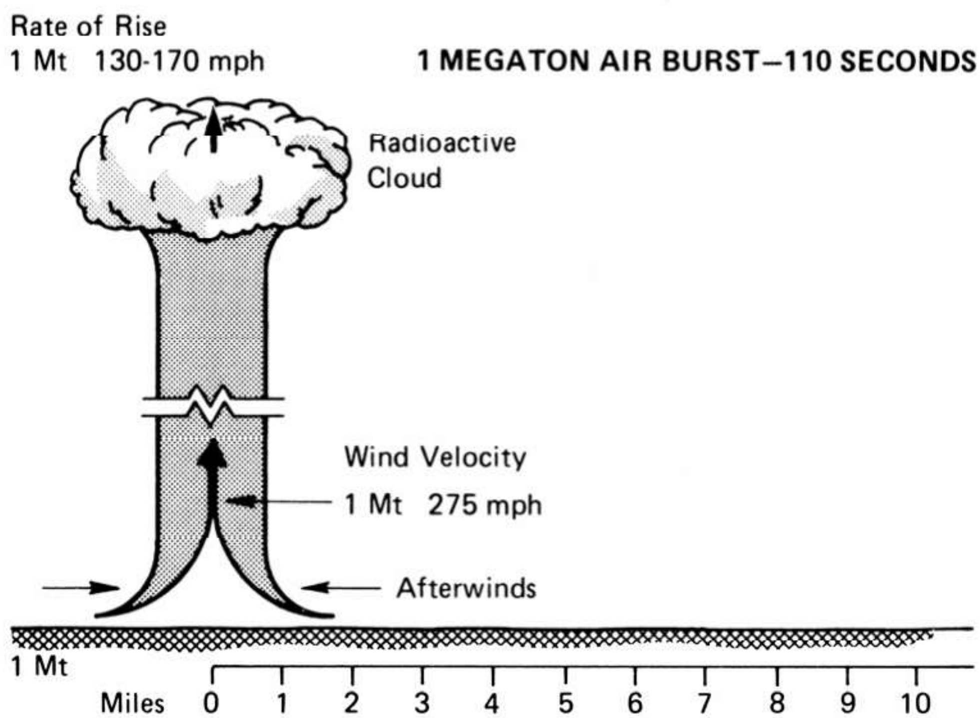



FIGURE 1 The sequence of events for a 1-Mt airburst detonated at 6,500 feet (about 2 km) altitude are shown in A through E. This altitude maximizes the range from ground zero at which the primary and secondary shock waves coalesce

D




E




to give a 15-psi peak overpressure on the ground (see text). By adjusting the detonation altitude to 11,000 feet (about 3,353 m), the 5-psi distance could be increased from 3.8 to 4.3 miles (about 6 to 7 km), but the 15-psi range would shrink to near zero. Source: Glasstone (1962).[6]

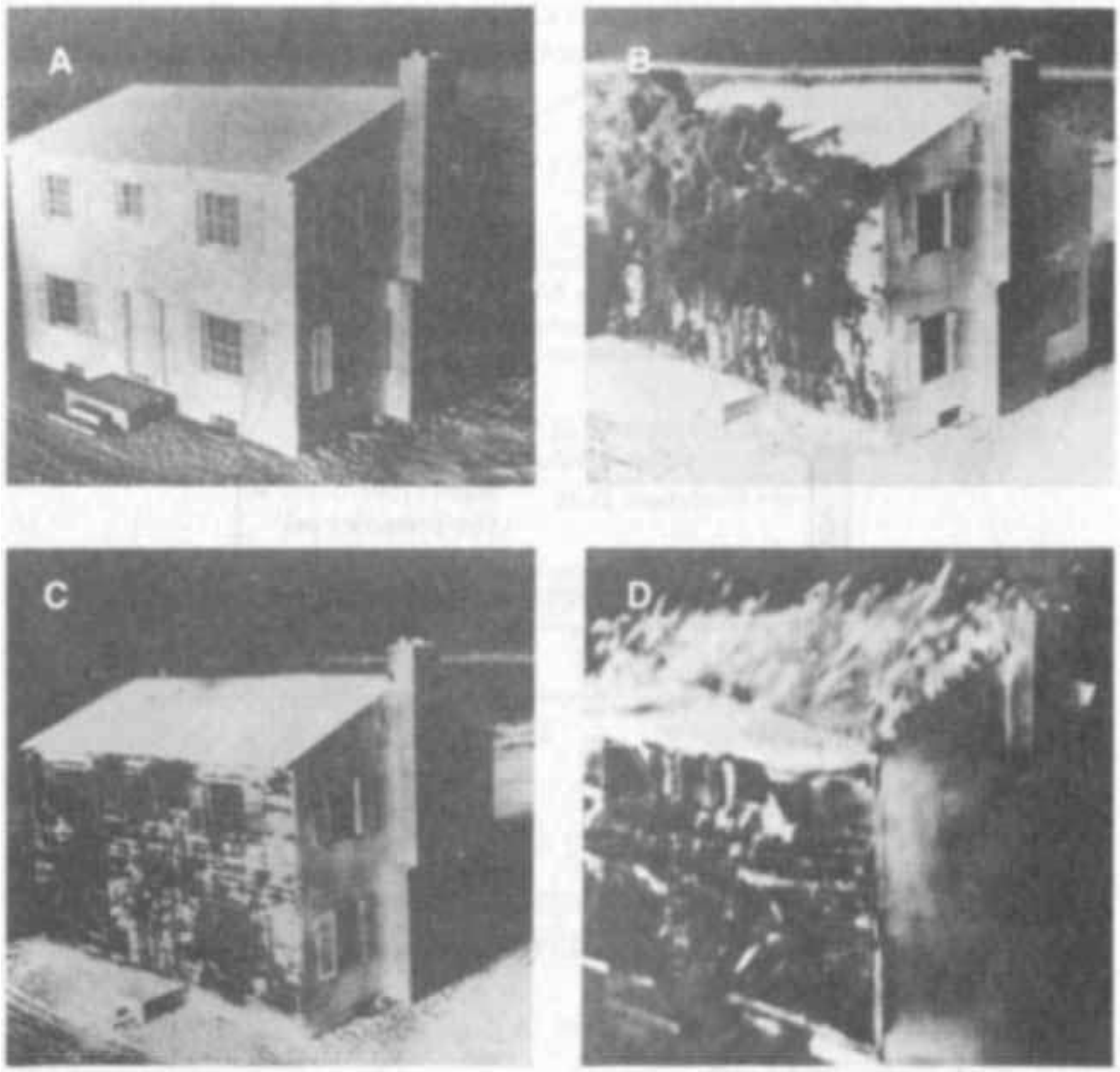
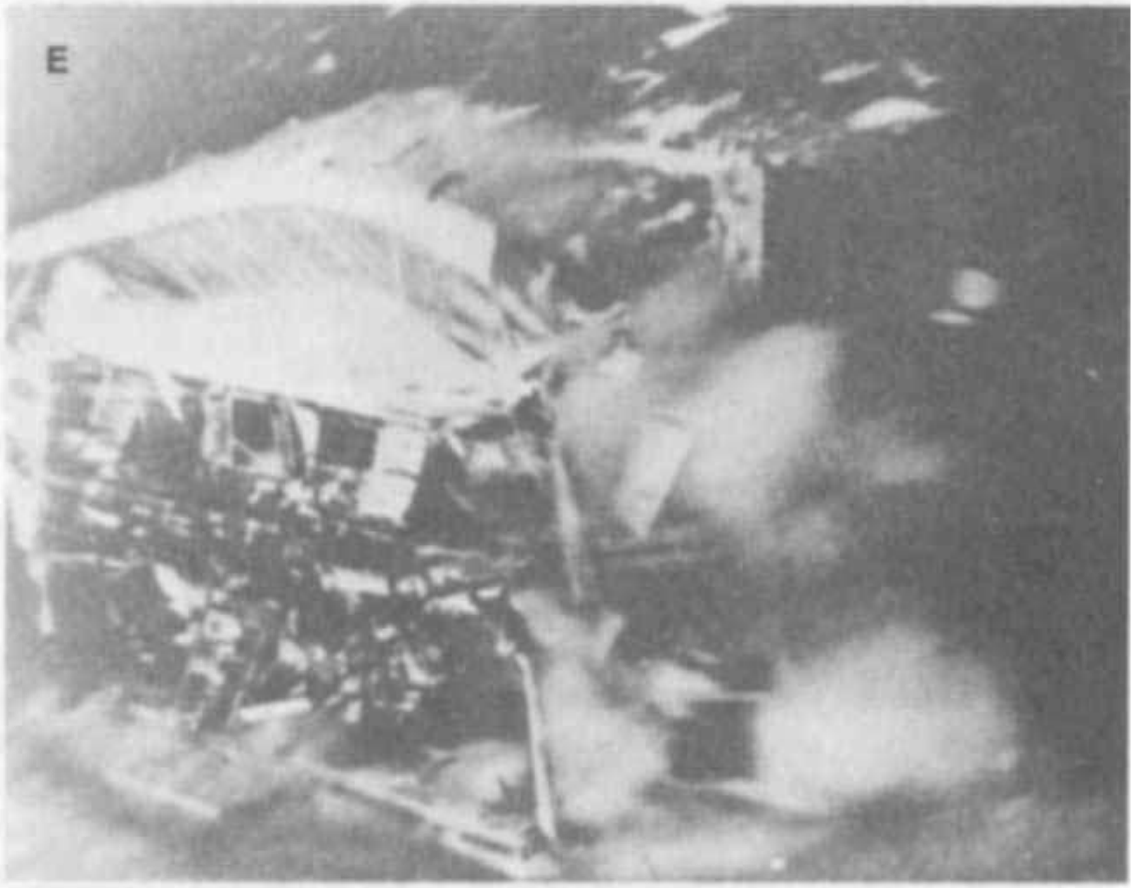
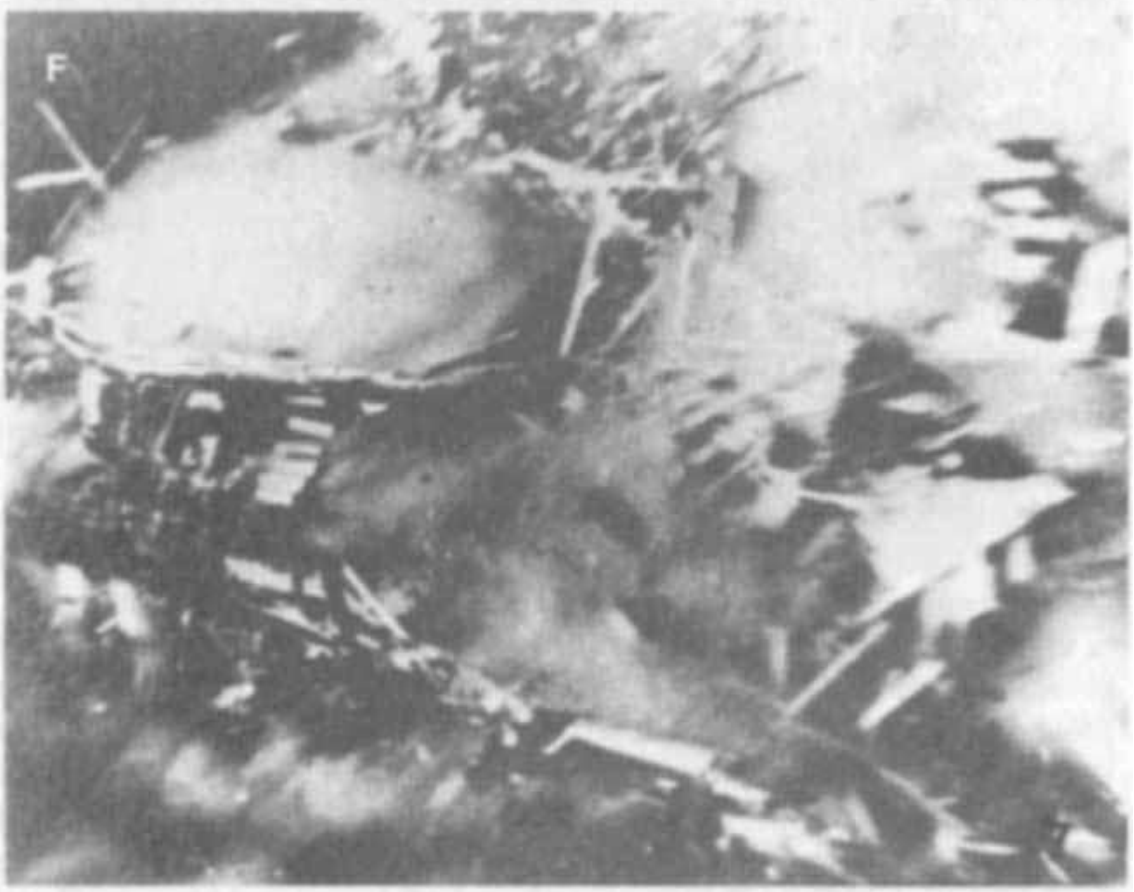



FIGURE 2 The sequence of prompt nuclear effects as observed at a range of about 4 miles (about 6.5 km). Light from the fireball begins to illuminate the structure a few tenths of seconds after the detonation (A). As the brightness of the fireball increases (B), the front of the house gives off a thick black smoke as paint is burned off by the heating action of the very intense light. After the paint is burned off, the house is bathed in light of decreasing intensity as the fireball rises and cools (C). About 16 seconds after the detonation, the shock wave arrives (D). As it propagates across the building, the front wall begins to cave in, and tiles are stripped from the roof. When the building is completely engulfed by the passing shock wave (E and F), the high pressure that now surrounds the building crushes the structure, and the high winds cause further damage to the building as it collapses. Source: Glasstone and Dolan (1977)[3] and Glasstone (1962).[6]


E


F

thus would be simultaneously knocked down and crushed as the shock wave propagates past.

Figures 3A and 3B show typical urban residential structures that have been subjected to overpressures of about 5 psi from nuclear bursts at the Nevada Test Site. Because these structures were constructed to study the effects of blast, precautions were taken to prevent them from burning. The exteriors were painted white to reflect rather than to absorb light from the fireball, windows facing the explosion were equipped with light-reflecting aluminum finish, metal Venetian blinds, and roofs were made of light gray asbestos cement shingles. Also, there were no utilities (gas lines, electric lines, stoves, etc.) that could be sources of secondary fires from blast effects.

Of course, if fires from thermal and secondary blast effects had been allowed to initiate in these structures, they would clearly burn with great efficiency.

It would take 37 seconds from the time of detonation for the shock wave to reach a distance of about 9.5 miles (about 15.3 km). At this distance, 35 to 36 seconds before its arrival, the fireball would be about 100 times brighter than the Sun at noon. This is bright enough to cause first- or second-degree skin burns on those in line of sight. It is also possible, but much less certain, that some scattered fires could be set in very highly combustible items (possibly some dry grass, leaves, or newspapers, and also interior curtains and other lightweight materials).

When the shock wave finally arrives, it will have a peak overpressure between 1 and 1.5 psi, which would knock windows (possibly with then-frames) out, along with many interior building walls and some doors (see Figures 4 through 7 and their figure captions).

By 110 seconds, the characteristic mushroom cloud will have reached about 7 miles (about 11.3 km) altitude (see Figure IE). However, from the ground within the target area, it might be difficult to observe, as great amounts of dust kicked up by the blast wave and the accompanying high winds, as well as smoke from the fires initiated by the bright thermal flash of the fireball, could obscure the vision of those inclined to look. For those in the target area who are uninjured or still alert enough to be aware of their surroundings, the drama would not yet be over, as fires would begin to simultaneously develop and intensify over a vast area.

The situation in the target area therefore would be one of extremely severe blast damage to a range of 3 to 4 miles (about 4.8 to 6.4 km) from ground zero and very slowly diminishing levels of serious damage out to ranges well beyond 10 miles (about 16 km). Streets would be blocked with debris, water pressure would drop to zero, gas lines would be opened in places, and power would be off. Essentially all windows would have been broken, buildings that were not knocked down would have suffered

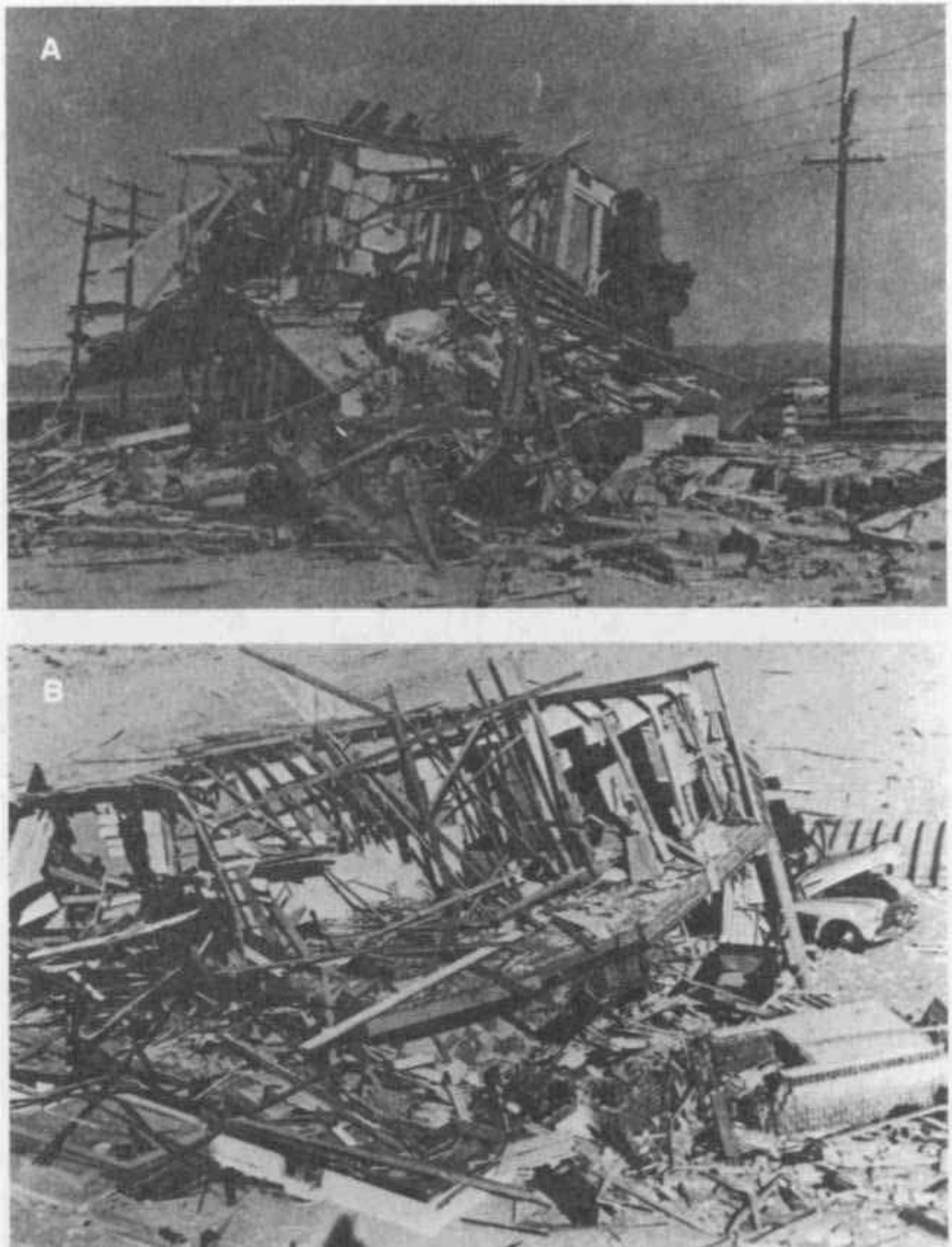



FIGURE 3 The effects of 5 psi of overpressure from a nuclear detonation are shown for two structures (A and B) that are typical of those in the United States. Since the structures were built to study the effects of blast, precautions were taken to minimize the possibility that fires would be initiated by light from the fireball or blast disruption effects. For this reason, neither of the buildings contained utilities of any kind. In addition, the roofs were made of light gray asbestos shingles, and windows facing the blast were equipped with metal Venetian blinds with an aluminum finish. Source: Glasstone (1962).[6]

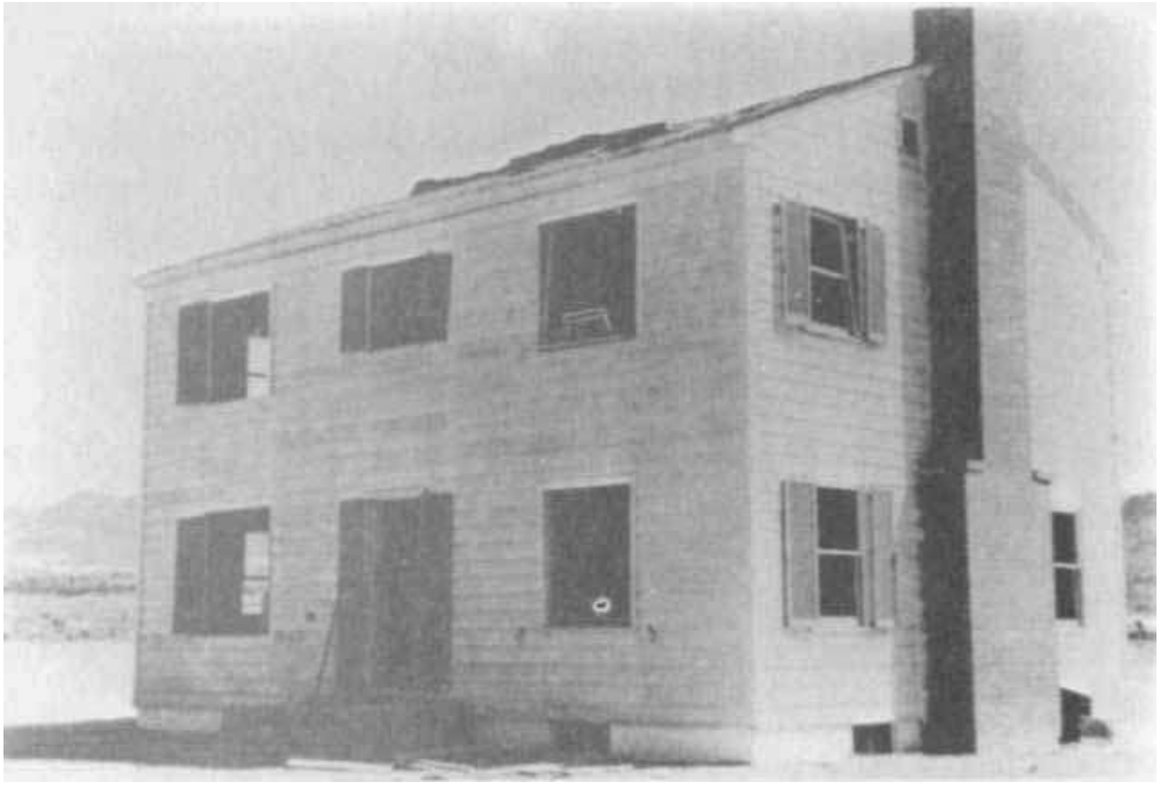


FIGURE 4 The effects of a nuclear detonation-generated blast of 1.7 psi on a wood-frame building. Figure 2A shows a similar structure before the blast and Figure 3B shows that structure after a blast of 5 psi. Although the building shown in this figure was not knocked down, the front door was broken into pieces and the kitchen and basement doors were torn off their hinges. In addition, many of the windows, including their frames, were blown into the building interior. Such a building, if ignited by blast or thermal effects associated with a detonation, might burn with great efficiency. Source: Glasstone (1962).[6]

extensive interior and wall damage (see Figures 4 through 7), and fires of varying intensity would have been initiated at many points within the target area.

Figures 8 through 10 show plots of the overpressure and thermal fluence as a function of range for airbursts of 1-, 0.5-, and 0.1-Mt yields. Each graph assumes a visibility of 12 miles (about 19.3 km), and for purposes of comparison, each graph is also accompanied by a plot of the overpressure and thermal energy that occurred at Hiroshima.

It should be noted that the ratio of thermal to blast effects changes drastically in Figures 8 through 10, as the scales of each of these two quantities are different with changes in weapon yield. The reasons for this are as follows.

Blast energy from a detonation fills the volume surrounding it. A detonation would therefore fill a volume with blast energy in direct proportion to its yield. Since the size of the sphere's radius varies as the cube root of its volume, so does the range at which a given peak overpressure occurs. Hence, the range at which a given peak overpressure occurs scales as the cube root of the yield.

Thermal energy, unlike blast energy, instead radiates out into the surroundings. Thermal energy from a detonation will therefore be distributed over a hypothetical sphere that surrounds the detonation point. If the sphere's area is larger in direct proportion to the yield of a detonation, then the amount of energy per unit area passing through its surface would be unchanged. The radius of this hypothetical sphere varies as the square root of its area. Hence, the range at which a given amount of thermal energy per unit area is deposited varies as the square root of the yield.

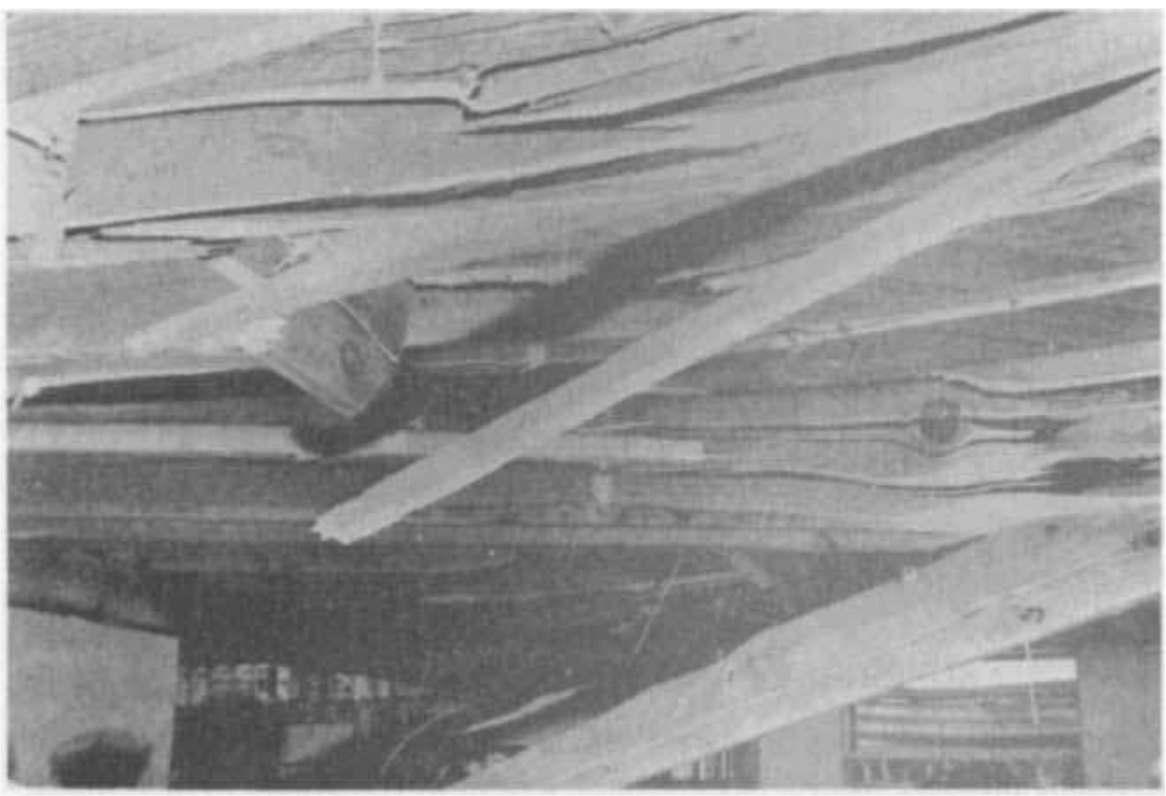


FIGURE 5 The first floor joists of a strengthened wood-frame building that has been subjected to a 4-psi blast from a nuclear detonation. If the building structure had not been strengthened, the blast would likely have caused it to collapse. At the 4-psi range, the light from the fireball of a 1-Mt detonation could be 500 to 700 times brighter than a desert sun at noon. Such intense light would ignite furnishings and curtains in the building, which could then ignite the rest of the damaged structure. Source: Glasstone (1962).[6]

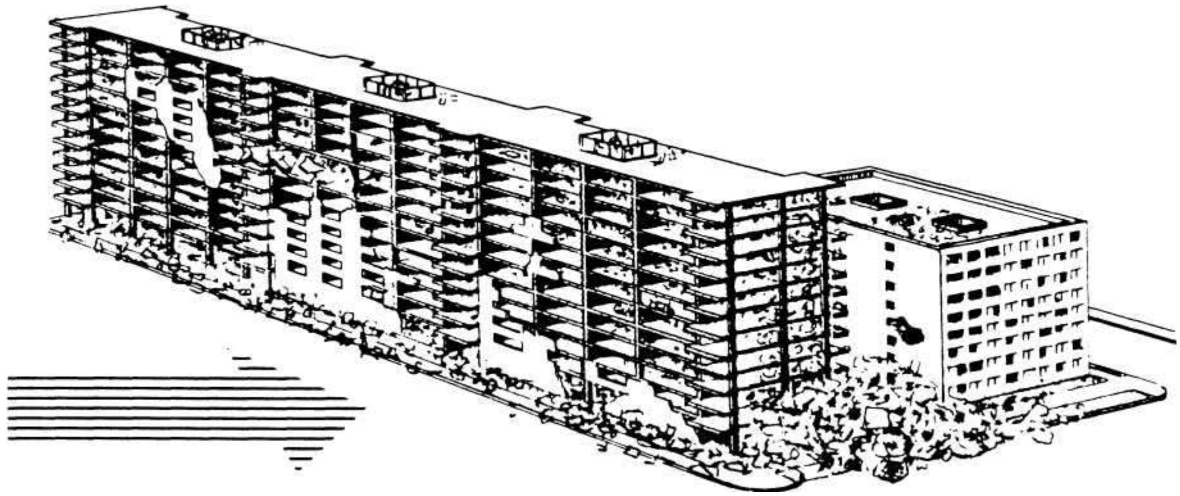


FIGURE 6 Illustration of the possible appearance of a building whose exterior walls are predicted to collapse when loaded at normal incidence with a 1.5-psi blast from a nuclear detonation. Ignitions caused by the light of the fireball or blast disruption could potentially result in the rapid development of well-aerated and extremely intense fires in such structures. Adapted from J. Wiersma and S. B. Martin, 1973. An Evaluation of the Nuclear Fire Threat to Urban Areas, Contract DAHC20-70-C-0219, Menlo Park, Calif.: Stanford Research Institute.

This square root scaling is further modified by absorption and scattering of light in the air, and so it would vary with weather and visibility.

As a result of these different scaling rules, at any range at which a given overpressure were to occur, the ratio of thermal to blast energy would vary with weapon yield. For almost all ranges of interest here, in which fires can be set by light from the fireball, unless visibility is significantly less than 12 miles (about 19.3 km), the ratio of thermal to blast effects would increase with an increase in weapon yield. Hence, weapons of higher yield are yet better incendiaries than those of lower yield.

## SUPERFIRES AND THEIR ENVIRONMENTS

Figure 11 shows the area over which simultaneous fires could be initiated by the light from a 1-Mt airburst if visibility is good (10 to 12 miles [about 16 to 19.3 km]). The radius of the circle is 12 km.,

At this range the 2 psi of peak overpressure from the blast wave would be sufficient to knock nonsupporting interior walls out of most buildings (see Figure 7). It may shatter or badly damage exterior nonsupporting walls on many buildings as well. Secondary fires from overturned stoves, broken gas lines, and electrical shorts could then be expected with low but significant frequency. In addition, the 10 calories per square centimeter (cal/cm$^2$) deposited by the fireball would ignite some light fabrics, curtains, and perhaps other easily combustible items.

At the center of Figure 11 is a silhouette of the area that burned in the firestorm following the atomic attack of August 6, 1945, on Hiroshima. A box with sides of 1 mile (about 1.6 km) length puts the scale of the possible fire region in perspective.

Under the assumptions used in the construction of Figure 11, an area of about 175 mile$^2$ (about 450 km$^2$), about 40 times larger than that at Hiroshima, would simultaneously contain fires. It is emphasized, however, that the area over which ignitions could play an important role in the development of a mass fire is highly uncertain.

If clouds or heavy fog were in the path of radiant energy from the

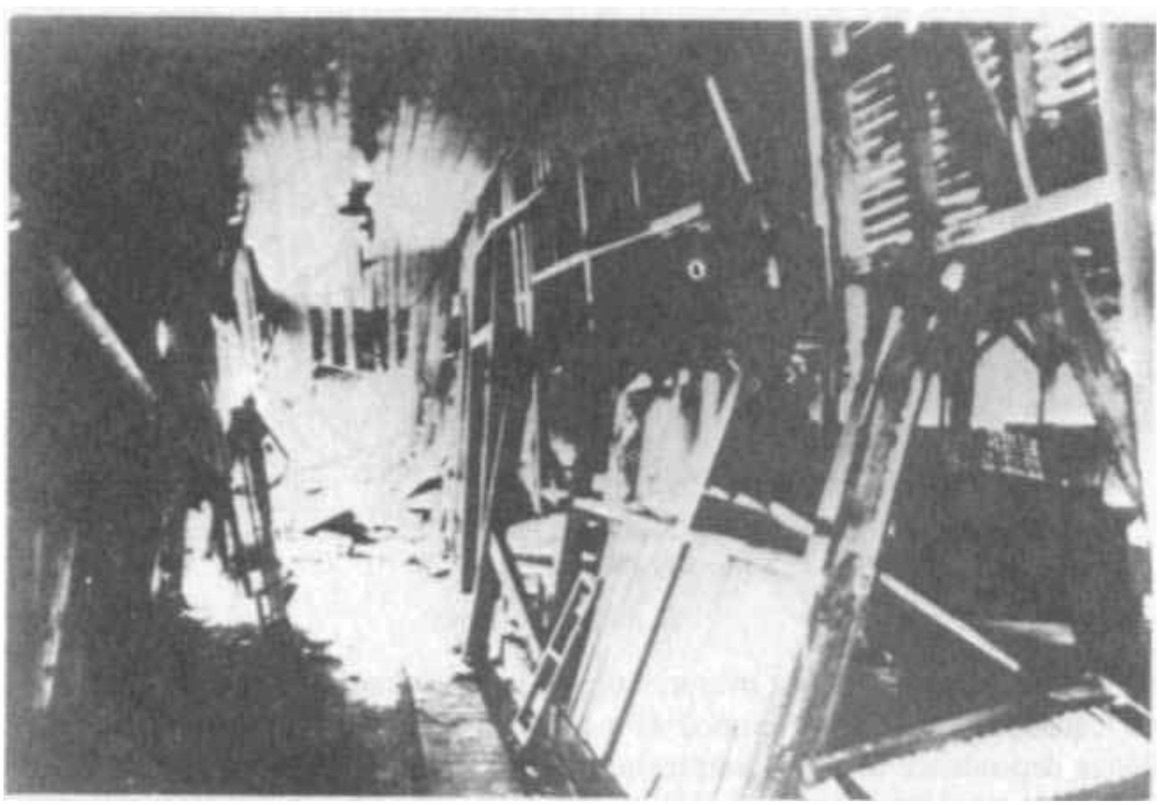


FIGURE 7 The interior of the Hiroshima District Monopoly Bureau building, about 2.3 km from the hypocenter. The building was probably subjected to a blast of about 3 psi, which did not knock it down but caused heavy interior damage. Because of the different way blast and thermal effects scale with weapon yield, the amount of thermal energy from the fireball of a 1-Mt detonation would be greater than that which occurred at the 3-psi range at Hiroshima. At the 3-psi range from a 1-Mt detonation, the amount of thermal energy delivered by the fireball would be about 3 times greater than that which occurred at Hiroshima. This would greatly increase the likelihood of fire ignitions in the building interior. Adapted from The United States Strategic Bombing Survey, Physical Damage Division, 1947.

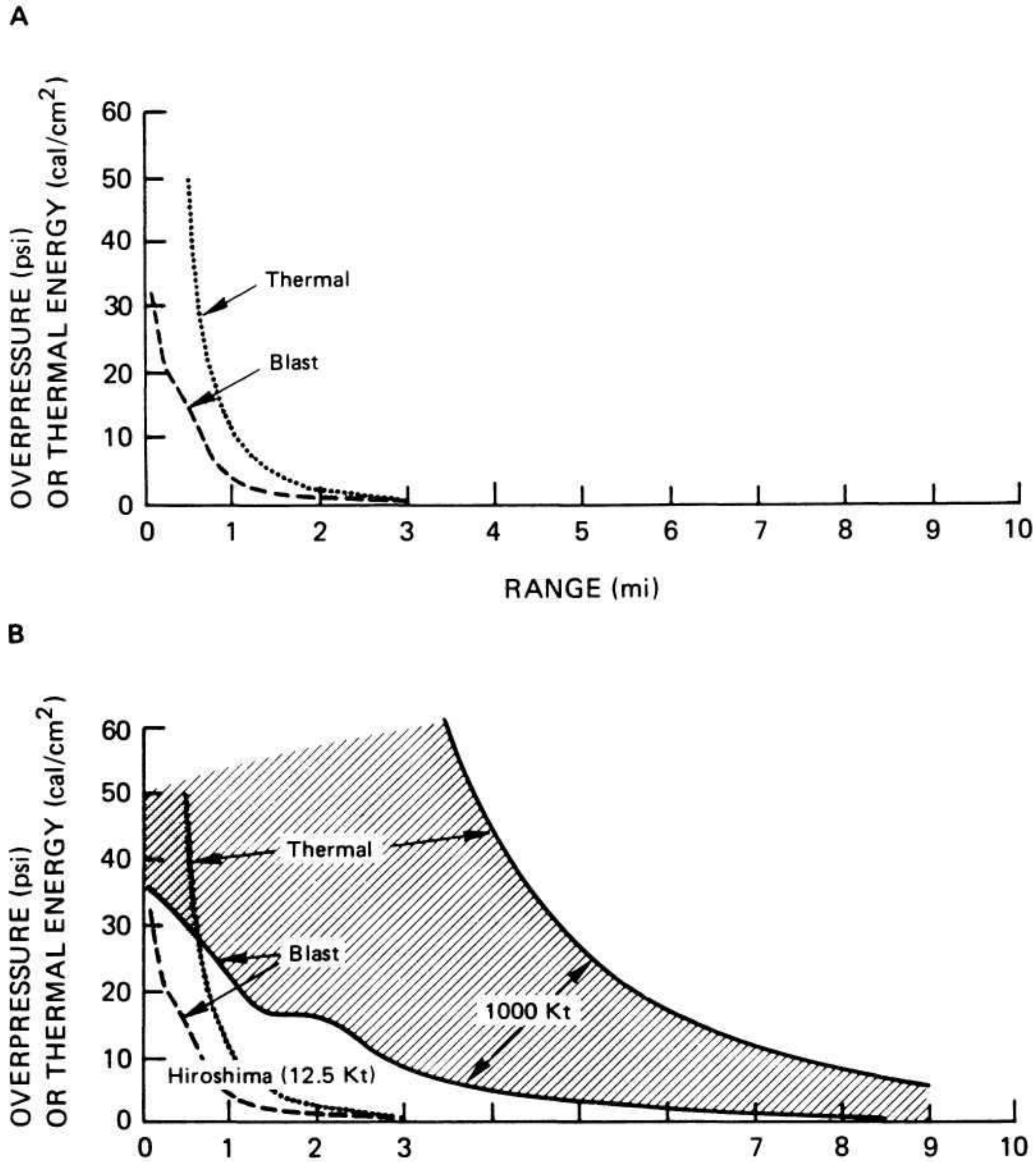



FIGURE 8 The peak blast overpressure and the total amount of thermal energy per square centimeter are plotted as a function of range from detonation. (A) Range dependence of peak overpressure and thermal energy from a 12.5-kt detonation at a height of burst of about 1,800 to 2,000 feet (about 550 to 610 m). (B) Similar curves for a 1,000-kt detonation at a height of burst of about 8,000 feet (about 2,440 m). Because the two heights of burst are chosen so that they are related by the $^{1}$A power of the ratio of the two yields [1,000 kt/12.5 kt$^{1/3}$ = 4.3], the range at which a given overpressure in B occurs is simply 4.3 times that in A. However, as can be seen from a comparison of these graphs, the thermal energy per square centimeter does not scale in the same way as the peak overpressure. For the 1,000-kt weapon (and assuming 12 miles [about 19 km] visibility), the thermal energy at a range which results in a given overpressure is much higher than that which occurs at the same peak overpressure for the smaller detonation. Thus, the use of blast scaling alone as a method of defining the environments in which casualties may occur could potentially lead to predictions that could seriously be in error.

fireball, the range of thermal ignitions shown in Figure 11 would likely be reduced (however, secondary ignitions from blast effect would likely be affected little). If the target area were instead experiencing dry summer weather, many fires could be set in grass and leaves at a greater range. In winter, if there were snow cover, this could not occur. But the snow would reflect additional fireball light into the low-relative-humidity interiors of houses, where fires would then be more likely.

Also influencing the nature and scale of mass fire dynamics is blast damage from the shock wave. The blast from the detonation would knock down some buildings and leave others standing. In standing buildings, windows would be shattered and many interior walls and doors would be

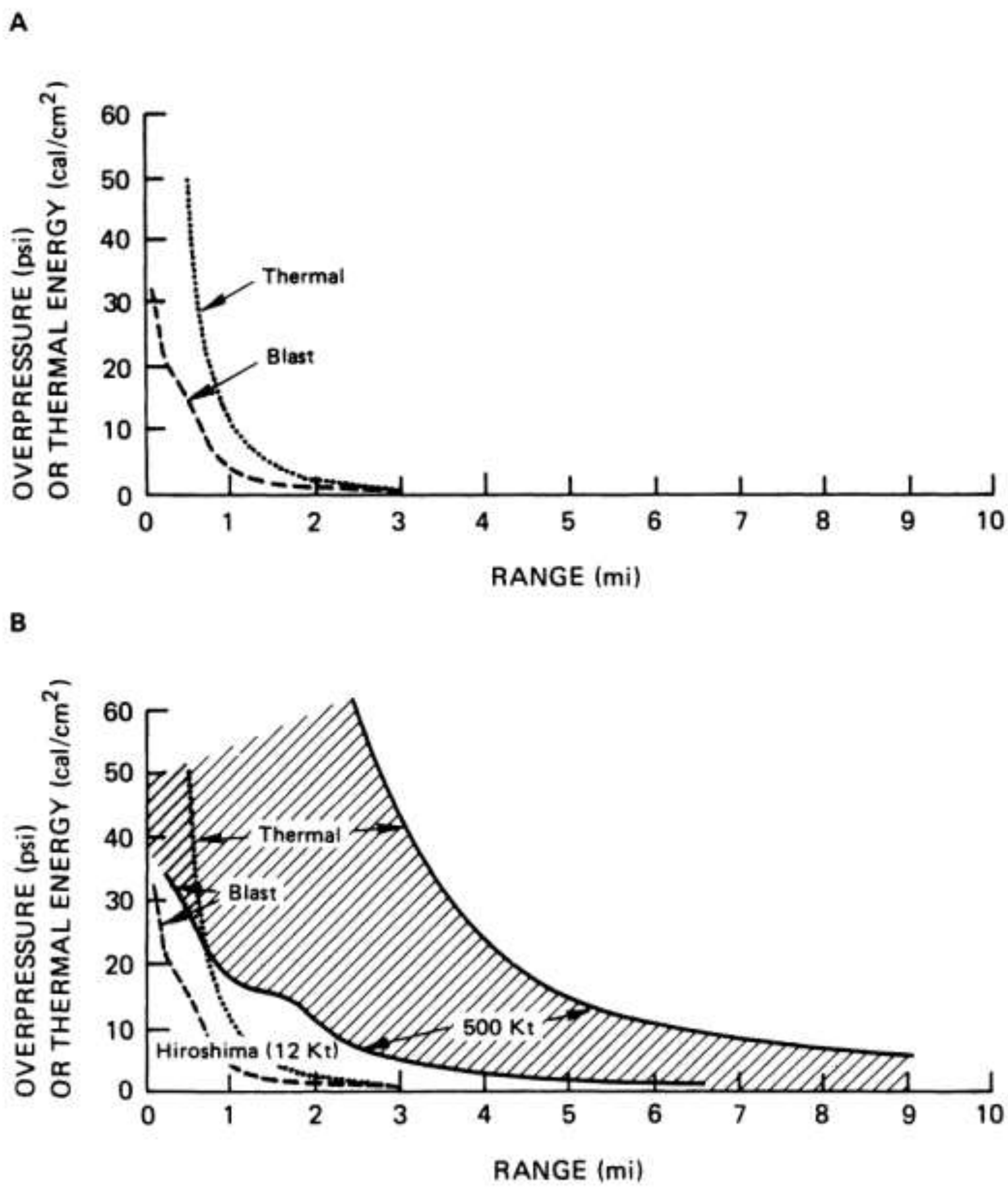



FIGURE 9 The two graphs are similar to those shown in Figure 8, except the choice of yields is 12.5 (A) and 500 (B) kt.

blown out or badly damaged, making the buildings and their interiors more combustible (see Figures 4, 5, and 7). In other standing buildings, exterior walls could also be knocked down or badly damaged (see Figure 6). These buildings could provide a well-aerated structure for fire development.

In addition, the blast wave could also initiate secondary fires, as gas mains would be broken, electrical shorts would be created, stoves would be knocked over, and the like.

Thus, highly uncertain sources of ignition and conditions of fire spread could influence the extent of a mass fire region, its development over time, and its intensity following an airburst over or near an urban/industrial

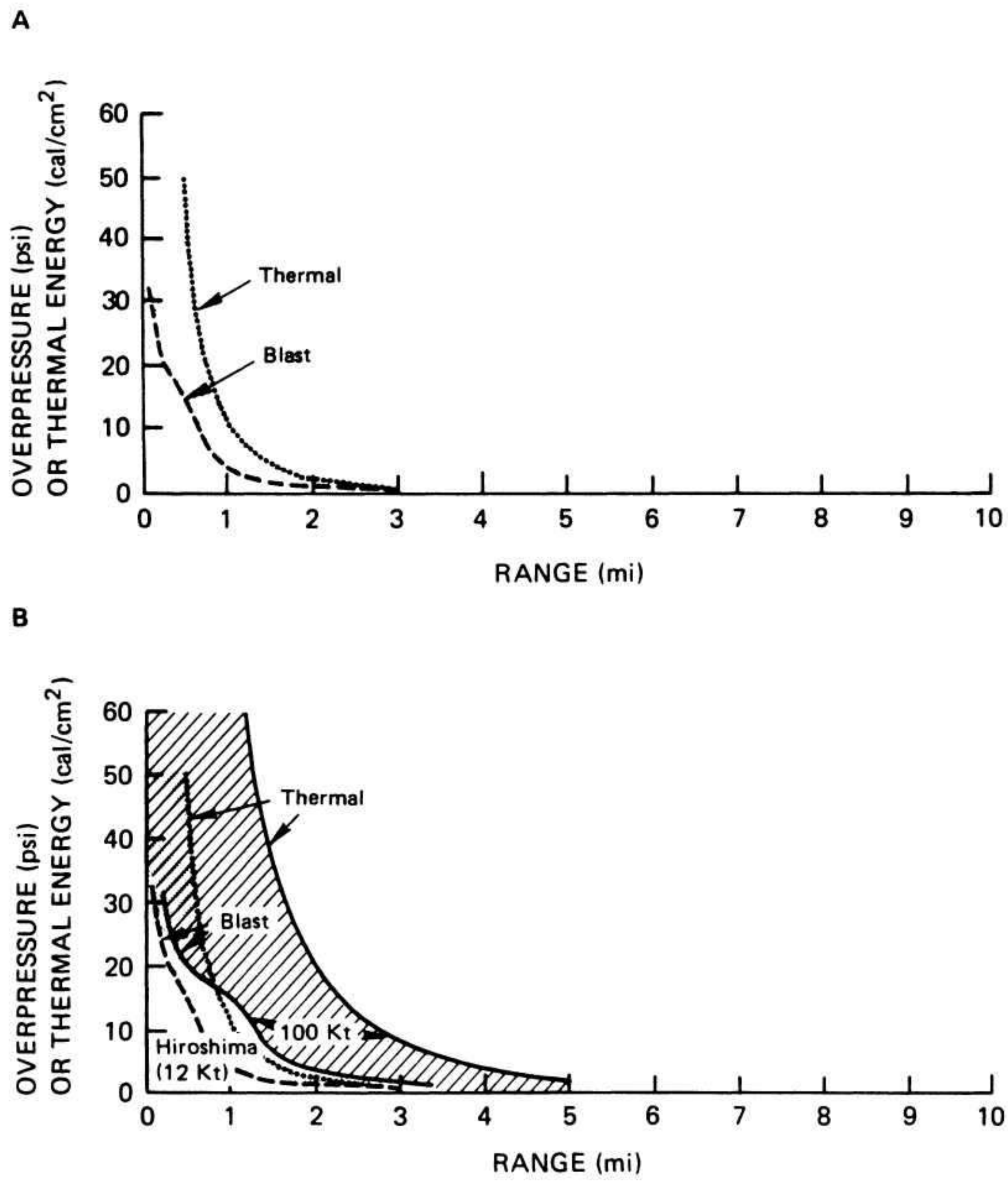



FIGURE 10 The two graphs are similar to those shown in Figures 8 and 9, except the choice of yields is 12.5 (A) and 100 (B) kt.

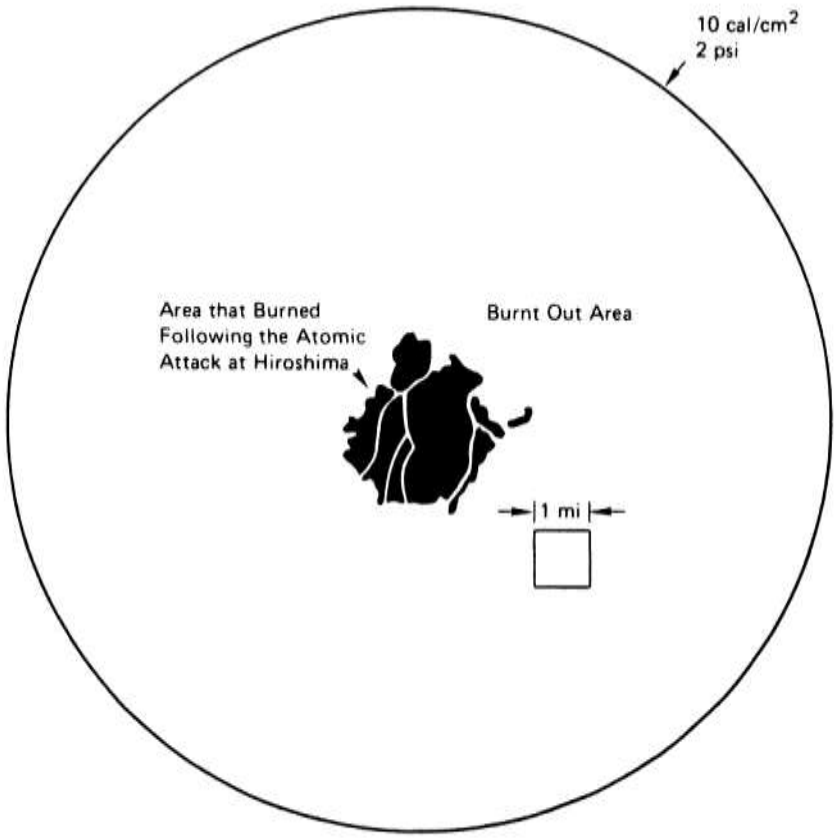



FIGURE 11 The area over which a mass fire could be initiated from the combined blast and thermal effects of a l,OOO-kt detonation at a height of burst of 8,000 feet (about 2,440 m). The outer circle is highly speculative, as 10 calories/cm$^2$ from the fireball might only initiate scattered and isolated fires in highly combustible exposed materials. However, the 2-psi blast would result in considerable interior and exterior damage to structures of the type shown in Figures 4 through 7. The disruption from blast effects could then initiate many secondary fires that could also contribute to the growth of a mass fire of unprecedented scale. By comparison, the silhouette shown in the center of the diagram is the area that burned following the atomic bombing of Hiroshima.

area.[7] Nevertheless, as individual fires burn and intensify over a vast region, the volume of heated and buoyantly rising air from the fire zone could increase to significant levels. If a sufficiently intense source of air heating were created within the fire zone, the expanding hot air from that region could begin to lift the vertical column of cooler air above it (see Figure 12A). If the rate of air heating were very high, this pumping action could be very great. Conversely, if it were very low, the pumping action could be insignificant relative to that of other forces influencing the motion of the air above.

Conceptually, as such a fire develops and as each layer of air in the column is pushed upward to a slightly higher altitude, that layer would bear a greater weight of air above it than that of the outside air at the same altitude (Figure 12A). Because air pressure at each altitude would be a result of this weight, the pressure within the air column would be initially greater than that of the surroundings, resulting in an outward horizontal expansion of the air in the column (see Figure 12B).

As this occurs, the weight of air above the ground within the column would decrease, while it would increase above the ground outside the column. In response, the air pressure at ground level within the column would also decrease, and the air pressure external to the column would increase. Air would then begin to flow into the fire zone from the surrounding regions at ground level.

At upper altitudes, the buoyantly rising heated air from the fire zone would still create outward driving pressure differentials, and a gigantic circulating air flow would develop with winds moving outward at high altitudes and inward at low altitudes.

On the ground, the resulting fire winds would begin to fan the individual fires, causing them to burn more intensely, radiating greater heat, and generating firebrands. This action then would cause the fires to spread and intensify yet more rapidly, increasing the rate of air heating within the fire zone and generating still more intense fire winds, further fanning fires of still greater intensity. Thus, a fire of gigantic scale and ferocity could develop, resulting in very high average air temperatures and winds near the ground.

Figure 13 shows the circulating air motion predicted by two exploratory numerical simulations of extremely intense firestorms.[8] Such numerical simulations contain many assumptions that can result in artifacts; and hence, their predictions should be taken as illustrative, and detailed results should be viewed with appropriate caution.

The calculations assume heat inputs per unit area comparable to those of the Dresden firestorm (about 250 kilowatts per meter squared), but over a circle of much larger radius (10 km). Of interest is the circulating vortices which occur at about a 10-km altitude in Figure 13A and at a 5-km altitude in Figure 13B.

In Figure 14 the two different assumptions about the rate of change of temperature with altitude used in these calculations are shown. The simulated result in Figure 13A assumed a dry adiabatic lapse rate* of -9.8 °K/km, while the simulated result shown in Figure 13B assumes a standard U.S. atmosphere, with a tropospheric lapse of -6.5 °K/km (see Figure 14).

The additional buoyancy generated by the colder atmosphere simulation in Figure 13A relative to that in 13B is likely the cause in the upward

*The lapse rate is the rate at which the atmospheric temperature changes with altitude.

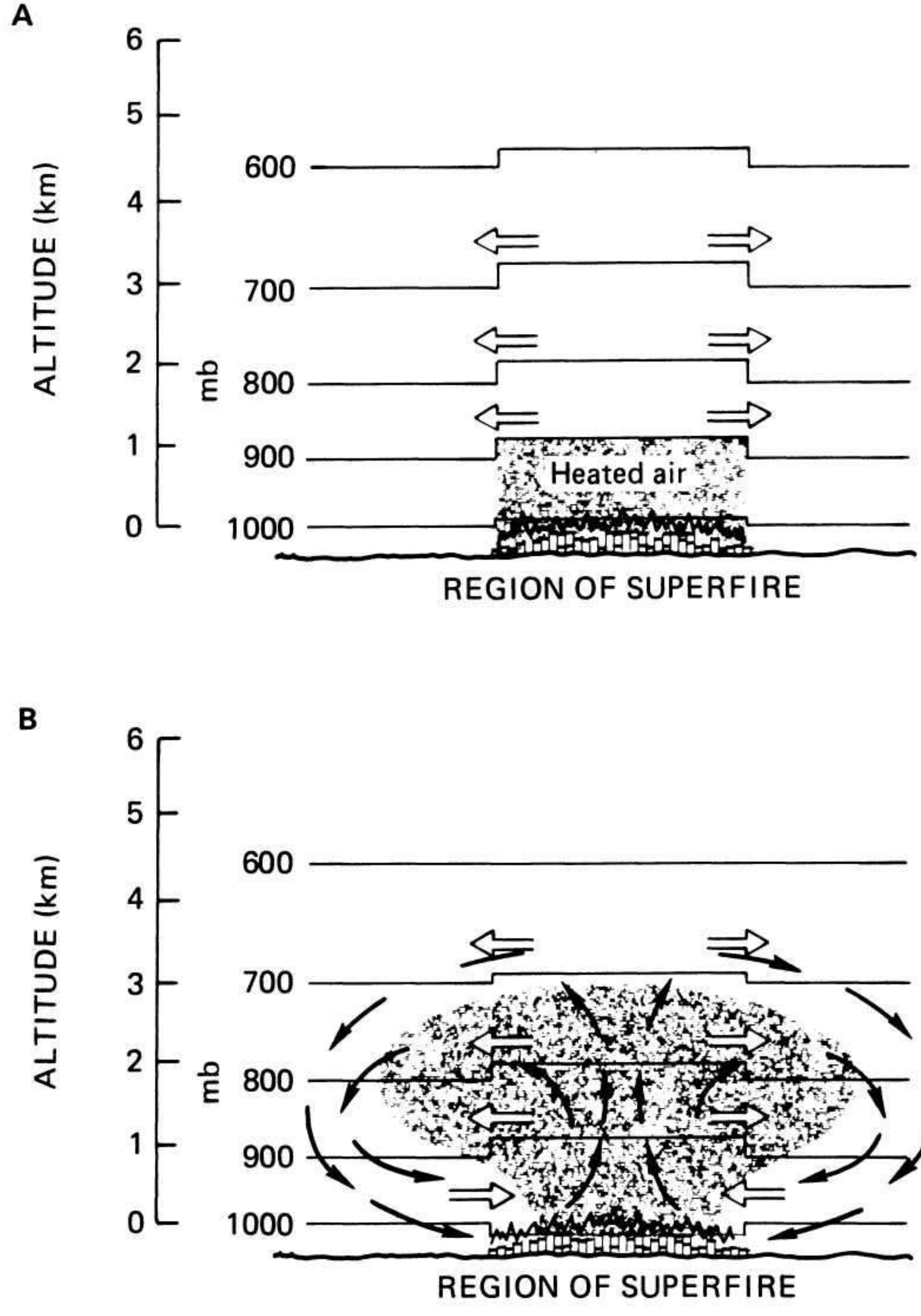



FIGURE 12 The drawings show how a mass fire that burns simultaneously over a large area can generate high ground winds. In A, buoyantly rising air from a fire zone pushes air at higher altitudes upward and outward. Eventually this action can result in the establishment of a macroscopic flow field of enormous power and extent (B). If the heat output per unit area from combustion is reduced, but the area over which the heat output is produced is increased, such a large circulating pattern might still occur. Thus, predictions of ground winds and air temperatures from mass fires must consider both the scale of the fire and the heat input per unit area in the region where such fires burn.

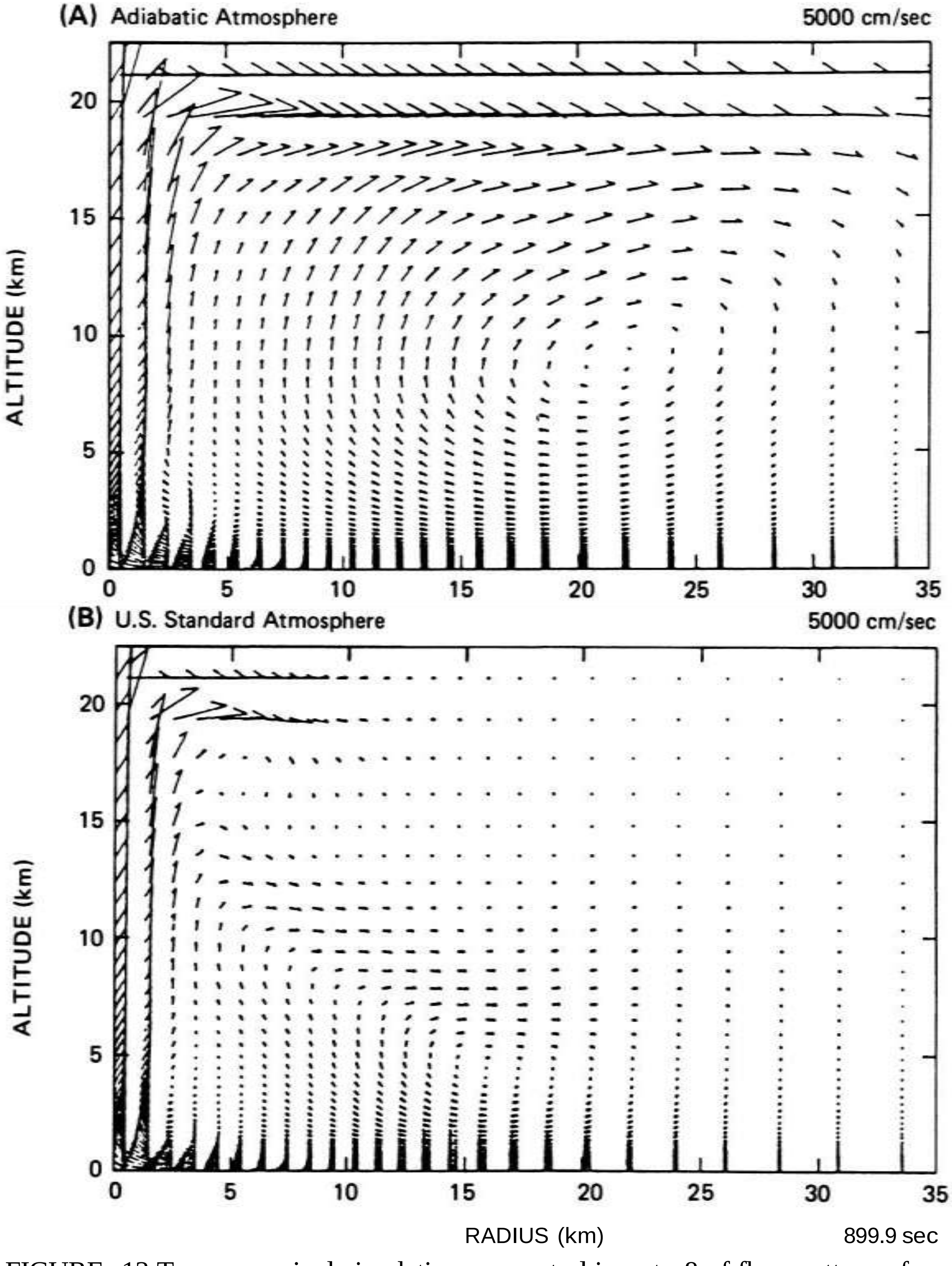



FIGURE 13 Two numerical simulations reported in note 8 of flow patterns from a very intense mass fire that results in 250 $kw/m^2$ of heat input over a circle of radius 10 km are shown. The two simulations assume different vertical temperature profiles (shown in Figure 14). Although the large-scale atmospheric motions for the two different vertical temperature profiles differ, the predicted ground winds near and within the fire region are almost identical. It is therefore possible that subtle details of weather may not be an important factor in the creation of severe ground conditions in and around a sufficiently intense mass fire. Source: Hassig and Rosenblatt (1983).[8]

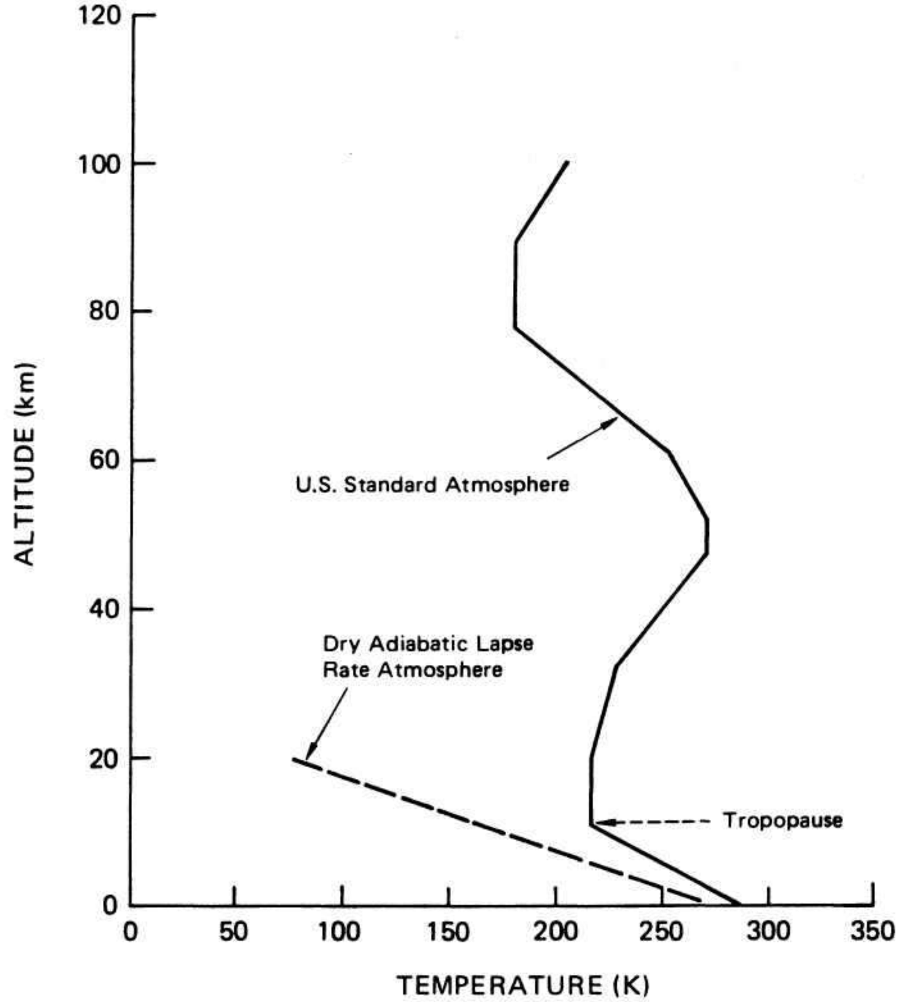



FIGURE 14 Vertical temperature profiles assumed in the numerical simulations shown in Figure 13. Source: Hassig and Rosenblatt (1983).[8]

shift of the circulating vortices. However, in spite of the very different physical assumptions about conditions in the upper atmosphere, the winds at lower altitudes are essentially unchanged, indicating that the postulated energy input at ground level dominates the dynamics in both circumstances.

Also noteworthy is that the average winds predicted near ground level would be over 100 miles per hour (about 161 km per hour) at many ranges, and the circulating vortices in both calculations would be of the order of 15 km from the center of the fire region. This suggests that fires separated by 20 to 30 km could distort each other's flow field, resulting in pressure differentials that could cause these fires to merge.

However, as noted above, these calculations are numerical simulations, and of necessity they require the application of boundary conditions as well as numerical simplifications of very complex hydrodynamic processes. The above observations must therefore be viewed as being only of the most qualitative nature.

A conceptual demonstration of fire interactions on a much smaller scale is shown in photographs of a fire experiment with candles (see Figure 15). The flow fields from the separate fires clearly interact, as the fires and their plumes begin to merge, resulting in a mass fire of enormously greater scale.

It is therefore possible, at least conceptually, that intense regions of fire initiated from multiple attacks with low-yield nuclear weapons could also generate mass fires of enormous scale and intensity, possibly indistinguishable from those initiated by larger-yield weapons.

Small, Larson, and Brode have constructed a hydrothermodynamic theory that permits exploratory scaling studies of possible near surface environments in regions of mass fire.[9–17] The average ground temperatures predicted in some of their calculations are shown in Figure 16.

In these calculations, it is assumed that a mass fire would burn out to a range of 12 km. Heating rates that are appropriate for fuel loadings found in lightly built-up cities of the type found in the western United States are assumed as input for the results presented in Figure 16A (average heat input rates of about 25 to 30 $kw/m^2$), and rates more appropriate to heavily built-up eastern industrial cities are used as input in Figure 16B (average heat input rates of about 75 to 80 $kw/m^2$). Other assumptions of a blast-modified versus unmodified city assume that centers of the fire regions would be so heavily damaged by blast that much of the combustible material would be buried in rubble and, hence, would not be sufficiently exposed to burn.

A most striking prediction of these calculations is that the average ground level air temperatures would be above the boiling point of water throughout the fire zones, even if the city were lightly built-up. The calculation for the lightly built-up city also predicts average winds of 35 to 40 miles/h (about 56.3 to 64.4 km/h), which is comparable to those that are known to have occurred at Hamburg. Predictions for a heavily built-up city estimate that there would be average wind speeds near 60 miles/h (about 96.5 km/h). Channeling of such average winds down streets or over terrain features for either case could well result in hurricane-force winds at the street level.

## ESTIMATES OF NOXIOUS GAS CONCENTRATIONS WITHIN THE MASS FIRE REGION

The physical environments discussed in the previous sections are average environments. Actual physical conditions could differ substantially from location to location within a fire zone. However, areas that experience winds less than the average may experience temperatures higher than the

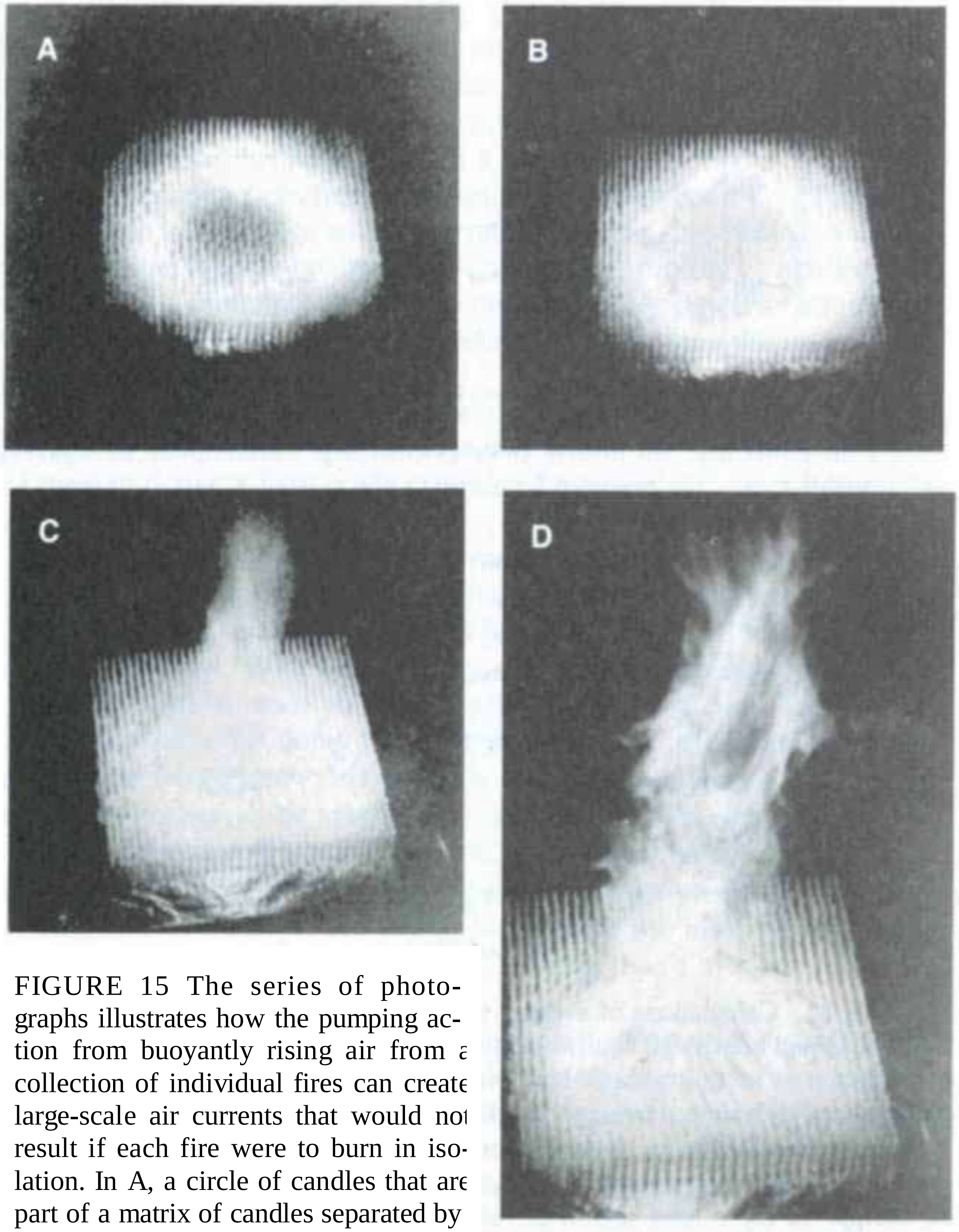



FIGURE 15 The series of photographs illustrates how the pumping action from buoyantly rising air from a collection of individual fires can create large-scale air currents that would not result if each fire were to burn in isolation. In A, a circle of candles that are part of a matrix of candles separated by 0.5 inch (1.27 cm) are lit. Buoyantly rising air from individual fires immediately results in large-scale air currents that bend the flames toward the center of the burning circle. In B through D, the inward air motion becomes increasingly well established, resulting in fire spread to the entire area surrounded by the original circle of flames. Reprinted from A "Fire Book" on Fire Safety in the Atomic Age. © 1952 National Fire Protection Association, Quincy, Mass. Reprinted with permission.

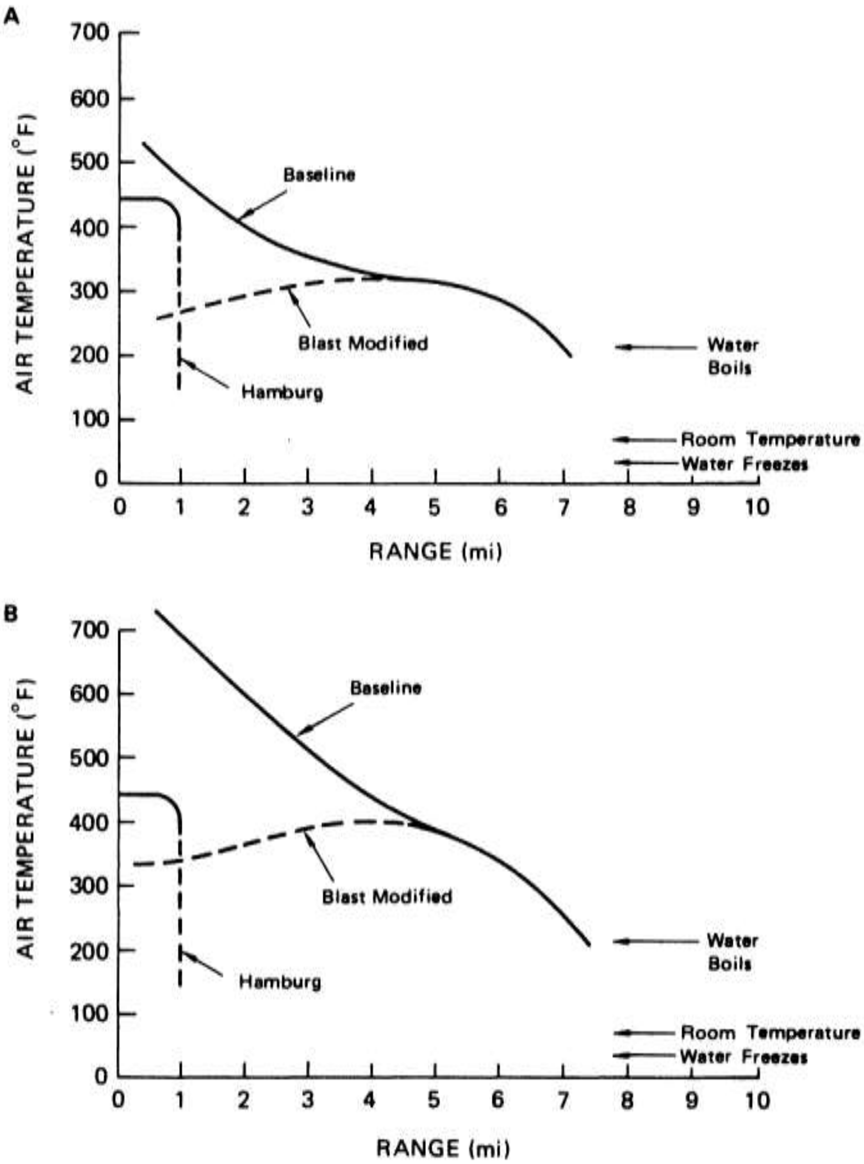



FIGURE 16 Calculations of average air temperatures for modeled mass fires in lightly (A) and heavily (B) built-up cities. The lightly built-up city is assumed to consist of a 3- to 12-km outer belt where 15 percent of the area is covered by buildings of 1.5 stories average height. The average fuel loading per story is assumed to be 16 lbs/ft$^2$. It is further assumed that 90 percent of the fuel is consumed within 3 hours and each pound of fuel consumed releases 8,000 BTUs of energy. In the central region of radius 3 km, the average fuel loadings are higher. The heavily built-up city shows similar results for a city that consists of a 6- to 12-km outer belt with 25 percent of the area covered by buildings of 2.5 stories average height. The fuel loading per story is also 16 lbs/ft$^2$, and the region within 6 km of the city center is still more built up. The solid curve shows average air temperatures (in degrees Fahrenheit) for the cities if all materials are assumed to burn according to these rules. The dashed curves are predictions of the model if it is assumed that the centers of the cities mostly do not burn, due to rubble from blast burying most that is combustible. Adapted from Larson and Small (1982).[16]

average, as heat generated by local fires might not be carried off as efficiently. In addition, other toxic effects of a mass fire may play an important role in determining whether or not those within the fire zone could survive. It is therefore of interest to examine and identify some of the other possible threats to those in a fire zone.

Because heating rates from combustion in the fire zone would result in high ground winds, there would be considerable mixing of large volumes of air with combustion products. A detailed calculation of combustion gas concentrations therefore requires a computationally powerful simulation or hydrothermodynamic modeling techniques of the kind discussed in the previous section.

However, because these techniques already provide estimates of the average air temperature and heating rates within the fire zone, they can be used to derive a very crude estimate of average gas concentrations as well.

In addition to estimates of the average air temperature and heat input for both the lightly and heavily built-up cities, estimates of the average output of energy and noxious gases per unit weight of burned material are also required. With these inputs, a very rough estimate of gas concentrations can be made for the postulated regions of mass fire.

The procedure for doing this is as follows. First, the average air temperature and heat input data from the hydrothermodynamic calculations are used to estimate the mass of air that would be heated per unit weight of material burned. The mass of material that must be burned to produce this energy and the amount of gas that would be given off in the process of combustion are then calculated. The ratio of the mass of combustion products to that of the heated air then gives a rough measure of the gas concentration.

Quantitative estimates of carbon monoxide and carbon dioxide generation in open fires vary by about an order of magnitude, ranging from about 600 pounds of carbon monoxide per ton (about 273 kg per metric ton) to about 50 pounds per ton (about 23 kg per metric ton).[18,19] Values for the ratio of carbon dioxide to carbon monoxide produced in different combustion experiments also vary considerably (from 10 to 50).[20–22] Using these extremely varied data on combustion product outputs and the heating rate/average air temperature relationships calculated by Small, Brode, and Larson,[9,17] the range of average carbon monoxide and carbon dioxide concentrations can be estimated for the area within the region of combustion.

Neglecting radiative losses, the amount of energy required to raise the temperature of a mass of air in the combustion zone by T degrees is governed by the heat capacity of air:

| Energy required to raise a mass of air by T° F | = | Mass of air | x | Heat capacity per unit mass | x | Change in air temperature | (1) |
|---|---|---|---|---|---|---|---|

or E = M x $C_M$ x T, where E is the amount of energy in British thermal units (BTUs) required to raise a mass of M pounds of air by T° F; M is the mass of air to be heated in pounds; $C_M$ is the heat capacity of air, which is equal to 0.24 BTU/pound/°F; and T is the change in air temperature from its ambient value.

This energy equation (equation 1) can, of course, also be used to estimate the mass of air (per unit time) that is heated within the combustion region of the superfire:

$$M = \frac{E}{C_M T} \tag{2}$$

For the lightly built-up city environment, the average temperature would be raised from around room temperature to slightly more than 200°F (about 93°C) (hence, T = 130 - 150°F) by a postulated heating rate of 6.55 kcal/m$^2$/s = 26 BTU/m$^2$/s. This results in the heating of a mass of air per unit time of about M = 26 BTU/s/m$^2$/[(0.24 BTU/lb/°F)(150°F)] = 0.72 lbs/s/m$^2$.

Because about 8,000 BTU of energy is released per pound of burning material, and between 50 and 1,000 pounds of carbon monoxide is released per ton of material burned (about 23 and 455 kg per metric ton), the rate at which carbon monoxide (CO) might be produced is between

$$\text{Mass of CO produced/m}^2\text{/s} = \frac{(26\ \text{BTU/m}^2\text{/s})(50\ \text{lb CO/ton})}{(8{,}000\ \text{BTU/lb})(2{,}000\ \text{lbs/ton})} = 8.1 \times 10^{-5}\ \text{lb/m}^2\text{/s}$$

and

$$\text{Mass of CO produced/m}^2\text{/s} = \frac{(26\ \text{BTU/m}^2\text{/s})(1{,}000\ \text{lb CO/ton})}{(8{,}000\ \text{BTU/lb})(2{,}000\ \text{lbs/ton})} = 1.6 \times 10^{-3}\ \text{lb/m}^2\text{/s}$$

The fraction of carbon monoxide that could be present may therefore be between 8.1 x $10^{-5}$/0.72 = 0.0001, or 0.01 percent, and 1.6 x $10^{-3}$/ 0.72 = 0.0022, or 0.22 percent.

Because the estimates given here are so rough, the range of carbon dioxide to carbon monoxide ratios quoted earlier is applied to estimate the carbon dioxide concentrations. This suggests that at the lower end of the carbon monoxide production, the amount of carbon dioxide in the air could be of order 0.1 to 0.5 percent. At the higher end the average concentration could be as high as several percent.

The reader may wish to note, when reviewing the contents of the next section on combined toxic effects of fire gases, that a carbon dioxide to carbon monoxide ratio of about 30 results in both thresholds for human collapse being reached simultaneously.

In addition, it is known that a variety of relatively typical building materials (Douglas fir and red oak woods) can produce hydrogen cyanide and sulfur dioxide when they burn. Ratios of hydrogen cyanide to carbon monoxide production of about 0.0025 to 0.005 have been observed experimentally.[23] Similar ratios have also been observed for sulfur dioxide. These ratios suggest that if these materials are common, average hydrogen cyanide and sulfur dioxide levels could be in concentrations of parts per million to tens of parts per million.

The estimates given above are very crude, and they therefore should be considered with appropriate caution.

The efficiency of combustion, for example, would vary strongly with circumstances at each location within the fire zone. When materials are exposed to high air temperatures and winds, they burn differently than when they are confined to closed spaces or under rubble.

On the other hand, the calculations given above underestimate the mass of material that is burned per mass of heated air, as the radiative energy is not included in the energy balance equation (equation 1).

## COMBINED TOXIC EFFECTS OF FIRE GASES AND ELEVATED TEMPERATURES

The combined toxic effects of heat, combustion gases, aerosols (smoke from fires and dust heated and carried by hot winds), and physiological stresses created by fear, hysteria, and strenuous attempts to escape can result in a serious threat to the lives of unsheltered individuals within a region of mass fires. Even sheltered individuals may be threatened by a similar array of toxic effects, as shelters must be carefully designed to protect occupants from the effects of infiltration of poisonous gases and from heating by fire and hot rubble.[24,26]

During World War II in Germany, for example, the infiltration of carbon monoxide into shelters was the apparent immediate cause of death of many in the shelters. It was further judged to be the cause of death in 70 to 80 percent of reported fatalities from large-scale incendiary raids. However, such statistics have great potential to be misleading.[12]

**TABLE 1 Physiological Effects from Exposure to Elevated Temperatures (Hyperthermia)**

| Exposure Level | Physiological Effects |
|---|---|
| 100°F (38°C) | Danger of heat prostration and heat stroke. |
| 110°F (43°C) | Body heat balance cannot be long maintained. |
| 120°F (49°C) | Three to five hours tolerance time. |
| 130°F (54°C) | Danger of heat prostration and stroke within tens of minutes. |

For instance, after the extremely successful allied incendiary air attack of July 26 and 27, 1943, on Hamburg, the heating of rubble from the fire made it impossible to enter the main area of the firestorm for 2 days following the raid. In fact, the heat content of the debris was so great that nearly a month after the raids (up to August 25), hosing of hot rubble and smoldering fires had to be carried out at different locations every day.[27] Thus, even if sheltered individuals had escaped death from the carbon monoxide that infiltrated the shelters, they may have instead met death in the extreme temperatures of shelters buried under fire-heated smoldering debris.

Some of the physiological effects of exposure to various levels of excessive heat, oxygen starvation, carbon monoxide, and carbon dioxide are summarized in Tables 1 through 5 and Figures 17 through 20. The Figures are derived from those published previously,[22,24,28] and Tables are derived from data published previously.[22,28,34] It is unlikely that these toxic agents would be encountered singly in the environment of a mass fire.

**TABLE 2 Physiological Effects from Exposure to Carbon Dioxide**

| Exposure Level | Physiological Effects |
|---|---|
| 2% $CO_2$ | Breathing becomes deeper. |
| 4% $CO_2$ | Considerable discomfort with quickened and deeper breathing. |
| 7% $CO_2$ | Extremely labored breathing, accompanied by headache, dizziness, and sweating; may also be accompanied by nausea. |
| 8% $CO_2$ | Dizziness, stupor, and unconsciousness within about 4 hours. |
| 9% $CO_2$ | Labored respiration and extreme shortness of breath accompanied by congestion; loss of blood pressure and death within about 4 hours. |
| 10% $CO_2$ | Unconsciousness occurs within about 10 minutes. |

TABLE 3 Physiological Effects from Exposure to Carbon Monoxide

| Exposure Level | Physiological Effects |
|---|---|
| 0.01% CO | No appreciable effects if exposure limited to several hours. |
| 0.02% CO | Headache after 2 to 3 hours, followed by collapse within 4 to 5 hours. |
| 0.03% CO | Headache within about 1.5 hours, followed by collapse within about 3 hours. |
| 0.04% CO | Headache within 1 hour, followed by collapse within 2 hours and death within about 3 to 4 hours. |

TABLE 4 Physiological Effects from Exposure to Oxygen Starvation (Anoxia)

| Exposure Level | Physiological Effects |
|---|---|
| 17% $O_2$ | Respiration volume increases, muscular coordination diminishes, attention and clear thinking require greater discipline. |
| 14% $O_2$ | Dizziness, shortness of breath, headache, numbness, quickened pulse, efforts fatigue quickly |
| 11% $O_2$ | Nausea and vomiting, exertion impossible, paralysis of motion |
| 8% $O_2$ | Symptoms become serious and stupor sets in, unconsciousness occurs |

The most immediate threat to individuals caught within a zone of mass fire is excessive heating of the body (hyperthermia) due to extended exposure to high-temperature air and to radiant energy from combusting materials (Tables 1 and 5 and Figure 20).

When the body carries a burden of excess heat and the air temperature is elevated, it is difficult for the body to radiate, convect, or evaporate away this excess energy to the environment. The body reacts to this circumstance by increasing its respiration and heart rate, which then results

TABLE 5 Estimated Levels of Toxic Agents Causing Death in 4 Hours

| Variable | Estimated Lethal Levels |
|---|---|
| Temperature | 130°F (54°C; hyperthermia) |
| Oxygen | 8.00% (anoxia) |
| Carbon monoxide | 0.04% |
| Carbon dioxide | 20.00% |

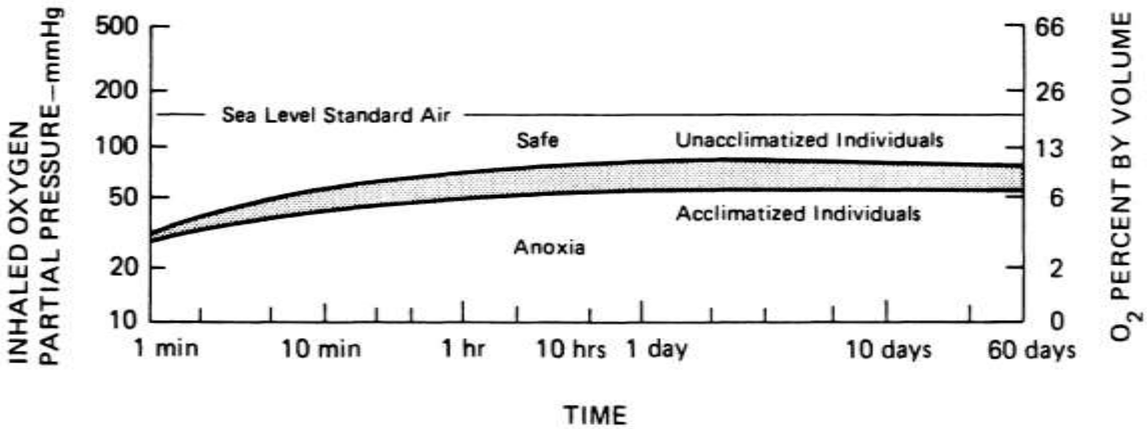



FIGURE 17 Human tolerance to variations in oxygen levels as a function of time. The lower band represents the minimum oxygen partial pressure that can be tolerated in the air entering the lungs. The reaction to changes in oxygen levels depends both on the magnitude of the change and the time over which the change occurs. When oxygen levels drop gradually from the normal sea level value, the usual symptoms are sleepiness, headache, fatigue, altered respiration, psychologic impairment, inability to perform even simple tasks, and eventual loss of consciousness. When oxygen levels instead drop suddenly, the intermediate symptoms are bypassed, and humans rapidly lose consciousness and go into spasms or convulsions. Adapted from Wilton et al. (1976)[22] and Bucheim (1958).[45]

in increased sweat production followed by the transport of excess body heat to the environment by evaporation. If the metabolic rate is increased from strenuous activity or excitement, a significant additional burden of body heat is added to that which already must be conducted to the environment. In addition, evaporative cooling in humid air is much less efficient than that in dry air, and there is a constant biological need for the replacement of essential body water throughout this process.

Thus, even if only the effects of elevated air temperature are considered, a combination of apparently nonthreatening contingencies can still result in a serious, near certain threat to life from heat prostration or stroke.

Keeping this in mind, note that exposure to air temperatures much above 130 to 140°F (54.4 to 60°C) for several hours will result in death from excessive body heating, even if the individual were calmly resting.

If, as expected, the regulator of the breathing function, carbon dioxide, is also present in the fire, it will cause the body to react by further increasing the respiration rate (Tables 2 and 5 and Figure 18).

In isolated circumstances, when carbon dioxide concentrations rise above about 2 percent, breathing becomes deeper. At a 5 percent carbon dioxide concentration, extremely labored breathing is induced, and this is possibly also accompanied by nausea. The human carbon dioxide tolerance level is usually considered to be between 7 and 9 percent, with unconsciousness generally occurring within 10 minutes when the concentration level is about 10 percent.

Carbon dioxide is found in fire environments because it is formed in the process of combustion. It may also be accompanied by small but biologically significant concentrations of carbon monoxide, which is also formed in the process of combustion.

Carbon monoxide, which is a chemical asphyxiant, is an extremely dangerous combustion product of fires (Tables 3 and 5 and Figure 19), and it bonds to the hemoglobin in red blood cells with an affinity of between 200 and 300 times that of oxygen. Because of this high affinity, very small concentrations of this material can cause a considerable decrease in the oxygen-carrying capability of the blood, as well as in the blood's ability to eliminate its presence by subsequent exposure to oxygen.

When the body respiration rate is increased by exposure to both carbon

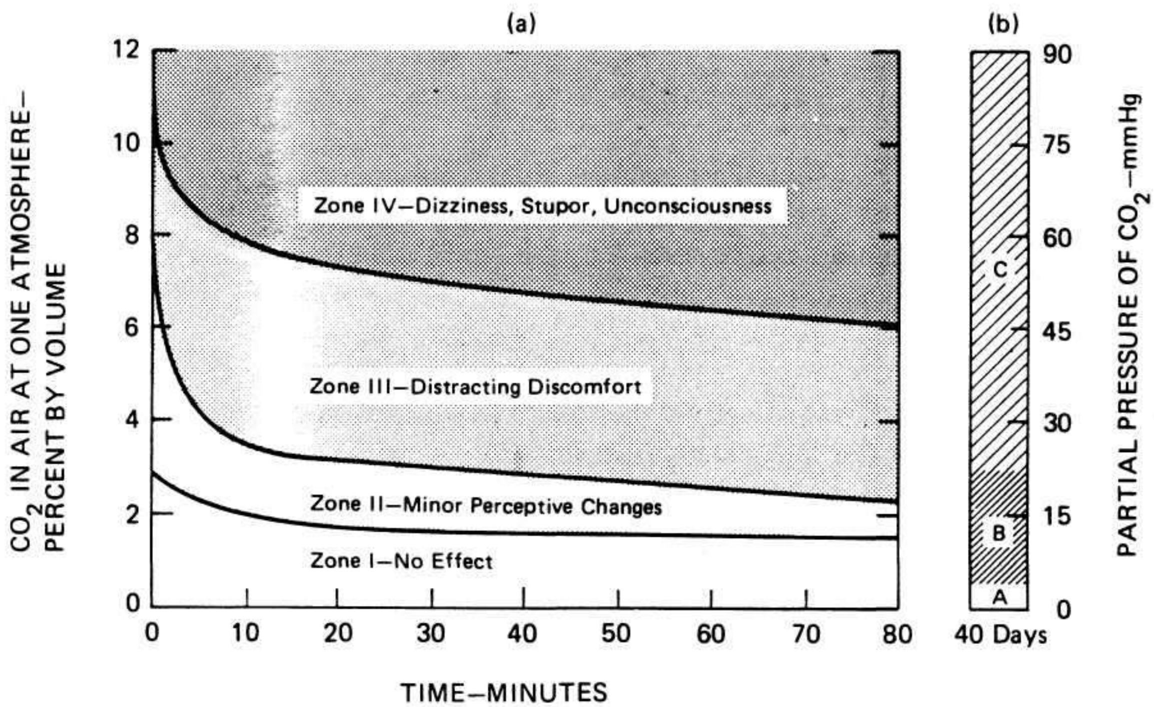



FIGURE 18 Human tolerance to variations in carbon dioxide levels as a function of time. As with exposure to changes in the level of oxygen, if changes are gradual, tolerances and symptoms are different than when changes are sudden. In Zone I, no psychophysiological effects occur in most subjects. In Zone II, a perceptible doubling in the depth of breathing will occur and small threshold hearing losses occur. In Zone III, mental depression, headache, dizziness, nausea, air hunger, and decreases in visual discrimination occur. In Zone IV, deterioration results in inability to take steps for self-preservation. Dizziness and stupor is then followed by unconsciousness. Adapted from Wilton et al. (1976)[22] and Bucheim (1958).[45]

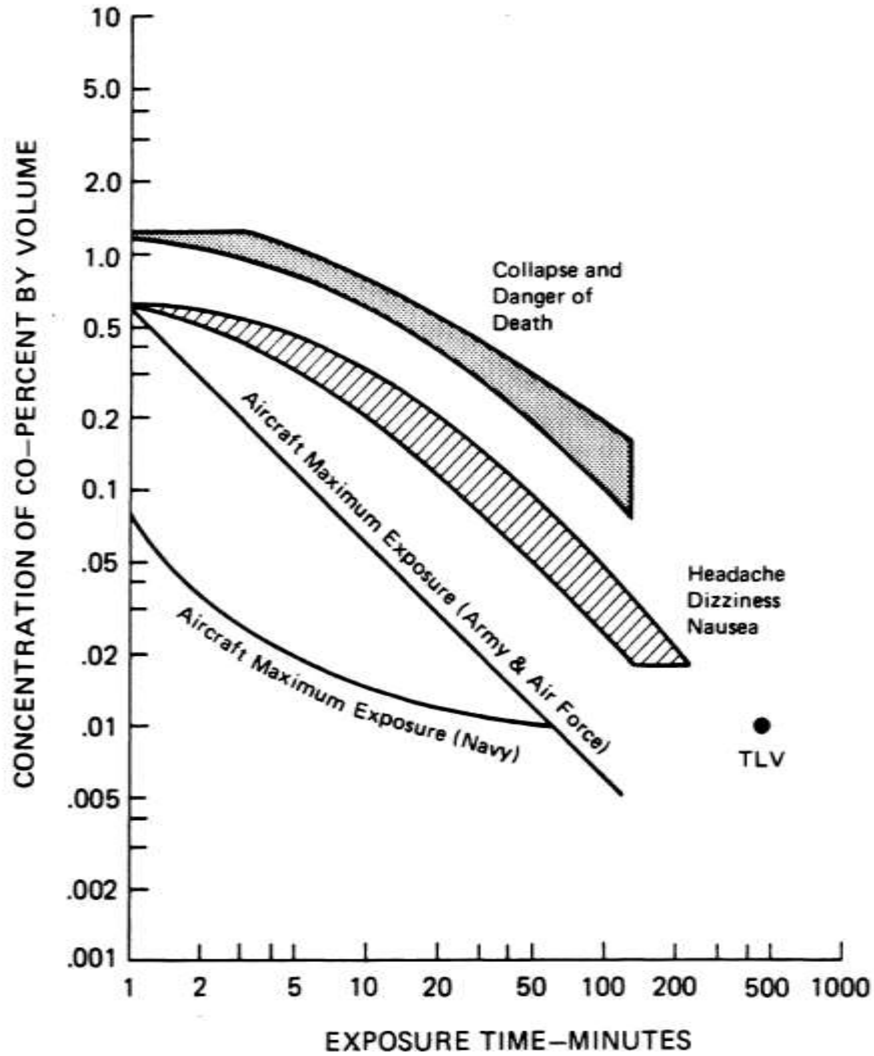



FIGURE 19 The effects of carbon monoxide as a function of concentration and exposure time. Milder effects are shown in the lower band of concentrations and exposure times, while dangerous or lethal times and concentrations are delineated by the upper band. The solid lines are exposure limits set by the military services. The point marked TLV at 0.01 percent (100 ppm) and 480 minutes is the Threshold Level Value, which is the allowed 8-hours-a-day exposure in industry. Adapted from Wilton et al. (1976).[22]

dioxide and elevated temperatures and its excess heat burden is further stressed by an elevated metabolic state from excitement or strenuous activity, enhanced take up of carbon monoxide by the body occurs.

Furthermore, if there is carbon dioxide and other gases in the air, these gases will displace oxygen, adding still another insult of oxygen starvation to the body burden (Tables 4 and 5 and Figure 17).

Other less well understood noxious threats include soot and smoke, which can cause inflammation and blockage within the respiratory system and which can transport poisonous materials into the respiratory tracts; sulfur dioxide and nitrogen dioxide, each of which can induce physiolog-

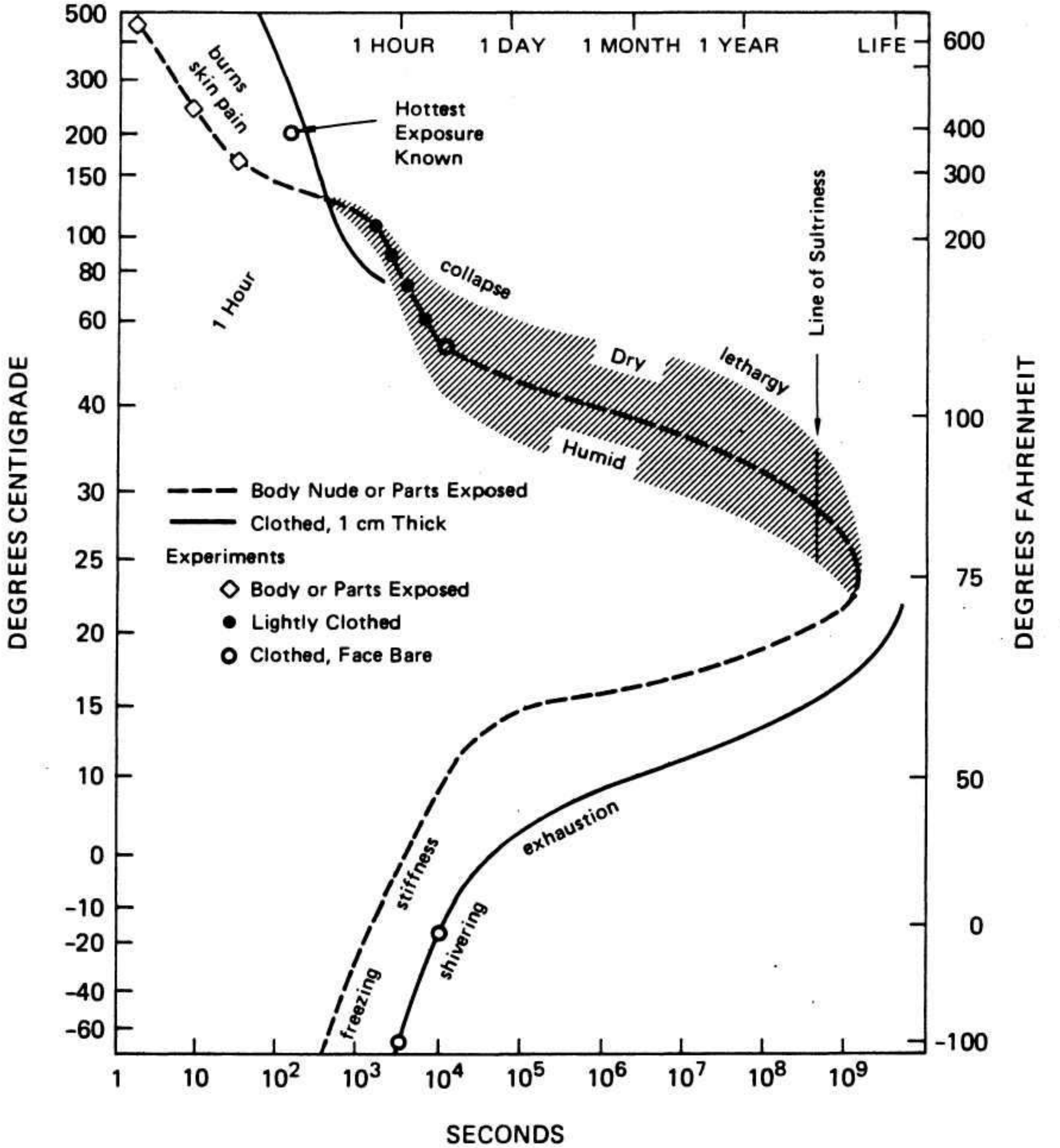



FIGURE 20 The safe exposure time for humans in high-temperature environments is highly dependent on relative humidity and water consumption. It is also dependent on the level of activity, acclimatization, and body weight. For example, at 100°F (38°C) and low humidity, lethargy may not occur. In high humidity it might instead occur within an hour of exposure. However, for a human to function in the 100°F temperatures for an extended period, required water consumption would roughly increase by about a factor of 4 over that which would be required at an air temperature of about 70°F. At 120°F (49°C) a 6 to 8 times higher water consumption might be needed to sustain an individual. Adapted from Wilton et al. (1976)[22] and Bucheim (1958).[45]

ical effects in humans at concentrations as low as 1 to 5 parts per million; hydrogen cyanide, which is also a threat at trace concentrations; and many other materials that can be generated by the combustion of both synthetic and natural materials found in urban and commercial areas.

The combined effects of exposure to elevated temperatures and different concentrations of carbon monoxide, carbon dioxide, and oxygen are shown in Table 6. These data were derived from those published previously[34] by extrapolation from experiments performed on adult albino Swiss mice, and therefore, they should only be regarded as indicative of trends.

The experimental studies reported previously[34] indicate the possibility of strong synergisms among the identified toxic agents produced in fires. In particular, some combustion products of synthetic materials like polyvinyl chloride (PVC) plastic pipe could be 50 times more toxic when exposures occur in combination with other combustion agents. However, at this time much additional work is required before useful insights along these lines will be available.

TABLE 6 Estimated Combined Levels of Toxic Agents Causing Death in 4 Hours

| Toxic Agents | Estimated Lethal Levels |
|---|---|
| Combination of Two | |
| Carbon monoxide + temperature | 0.02% CO + 120°F (49°C) |
| Carbon dioxide + temperature | 14% $CO_2$ + 120°F (49°C) |
| Oxygen + carbon monoxide | 17% $O_2$ + 0.02% CO |
| | 14% $O_2$ + 0.01% CO |
| Oxygen + carbon dioxide | 14% $O_2$ + 14% $CO_2$ |
| Carbon monoxide + carbon dioxide | 0.02% CO + 14% $CO_2$ |
| Combination of Three | |
| Oxygen + carbon monoxide + carbon dioxide | 14% $O_2$ + 0.01% CO + 5% $CO_2$ |
| | 17% $O_2$ + 0.01% CO + 14% $CO_2$ |
| Oxygen + carbon dioxide + temperature | 11% $O_2$ + 5% $CO_2$ + 120°F (49°C) |
| | 14% $O_2$ + 7% $CO_2$ + 120°F (49°C) |
| | 17% $O_2$ + 10% $CO_2$ + 120°F (49°C) |
| Carbon monoxide + carbon dioxide + temperature | 0.01% CO + 5% $CO_2$ + 120°F (49°C) |
| | 0.01% CO + 10% $CO_2$ + 110°F (43°C) |
| | 0.02% CO + 7% $CO_2$ + 110°F (43°C) |
| Oxygen + carbon monoxide + temperature | 17% $O_2$ + 0.01% CO + 110°F (43°C) |

## MASS FIRE EXPERIENCES OF WORLD WAR II*

Although it is known that firestorms occurred at Hamburg, Kassel, Darmstadt, and Dresden in Germany and at Hiroshima and other cities in Japan, there are little quantitative data from these experiences, and much information is in fact contradictory.

The firestorm resulting from the second of three highly successful saturation incendiary raids at Hamburg is the most well documented to date.[1,35,37] The German Fire Protection Police reports indicate that between 50,000 and 60,000 people in the fire zone were killed. At the peak of the fire's intensity, 5 to 6 $mile^2$ (about 12.9 to 15.4 $km^2$) were simultaneously in flames, and estimates suggest that its power output reached 1 million or 2 million megawatts (MW).

By comparison, a mass fire initiated by a 1-Mt airburst over a typical urban area in the United States could involve areas considerably larger than 100 $mile^2$ (about 259 $km^2$) and have peak intensities of perhaps 15 to 50 million MW. Because of this considerable difference in scale and the instantaneous way fire and high levels of blast damage would be delivered by airbursts with weapons of megaton or fractional megaton yield, comparisons with these much smaller fire experiences of World War II could be misleading. This possibility is at least suggested by the casualty data obtained from studies of the atomic attack on Hiroshima. In that attack, the report of the U.S. Strategic Bombing survey noted that the near simultaneous initiation of fires, collapse of buildings, blockage of streets, and loss of water and power over an area of about 4.4 $mile^2$ (about 11.3 $km^2$) made escape from the aftermath of the attack considerably less likely, resulting in the very high casualty rates.

In support of this view, about the same number of people were killed in the incendiary saturation raid of March 9 and 10, 1945, against Tokyo (84,000 people were killed in the Tokyo raid, and between 70,000 and 80,000 are believed to have been killed at Hiroshima).

Although a much larger, more heavily populated area of nearly 16 $mile^2$ (about 41 $km^2$) of Tokyo was subject to an intense fire, which was sometimes accompanied by winds that were described as hurricane force, many were able to escape, presumably because street access was relatively

*This section draws heavily on the extraordinary accounts of allied fire protection engineers in World War II, who not only felt a duty to plan the incendiary attacks against Germany and Japan in war but also felt a duty to report their consequences in peace. I have also benefited greatly from numerous conversations with Horatio Bond, who has shared much of his knowledge and time with grace and generosity.

unimpaired and the fire developed and propagated over a much longer time period.

It should also be noted that more recent analyses of the most successful incendiary attacks of World War II indicate a high correlation of success with raid intensity.[38] When raids delivered large amounts of ordnance in short intervals of time, casualties were extremely high, as was the total damage. In this sense, a nuclear weapon could be considered the nearly ideal example of an incendiary weapon.

In the period between July 24 and July 30, 1943, there were three large raids against Hamburg.[39] The first of these raids occurred on July 24 and 25 and destroyed about 1.5 $mile^2$ (about 4 $km^2$) of the west section of the city; the next raid occurred on July 27 and 28 and resulted in the famous firestorm that destroyed 5 to 6 $mile^2$ (about 13 to 15.4 $km^2$) of the city's southeast section; and the last raid occurred on July 29 and 30, involving about 2 $mile^2$ (about 5 $km^2$) of the city's south section, while many units were still involved in fighting the great firestorm started 2 days earlier.

Each of these great raids involved about 700 planes, delivering about 1,300 tons (about 1,181 metric tons) of high-explosive bombs, 500 tons (about 455 metric tons) of oil incendiaries, and 600 tons (about 545 metric tons) of 4-pound (about 1.8-kg) magnesium incendiaries.

The incendiaries were designed to penetrate roof and floors into the interior of buildings, where tests had shown that fires were most efficiently set. High explosives were used to block access roads with rubble and craters and to break waterlines that might be utilized by firefighters. In addition, contrary to the advice of experts, military analysts believed that high explosives would also open buildings so they would burn more rapidly and with greater efficiency.[40]

Delivery of high-explosive bomb loads was spaced out over the entire period of the raid, so that firefighters would be kept in shelters, creating time for fires set by incendiaries to intensify. In addition, small high-explosive air mines with delayed fusing were dropped along with incendiaries to deter attempts to put out newly initiated fires.

In the second and most successful of the great raids at Hamburg, the raid of July 27 and 28, 1943, within about 20 minutes, two of three buildings within a 4.5-$mile^2$ (11.6-$km^2$) area were on fire, and a major fire was in progress.[35] As the individual fires grew and increased in intensity, sparks and radiated heat reached combustible interiors of nearby uninvolved buildings through shattered and undamaged windows. The fires thereby increased in volume and intensified for a period of about 3 hours and then raged at full force for another 3 hours.

During the period of intensification, a tremendous hurricane of fire developed; this was accompanied by irregular intervals of squall. As air was drawn toward the fire from all directions, the pumping action from different sections of the fire may have resulted in the unusual shifts of winds noted by firefighters in their reports. The rapidly shifting winds and fire spread foiled attempts to establish firebreaks. At the edge of the fire, the winds were sufficiently intense to uproot trees 3 feet (about 1 m) in diameter and to prevent firemen from coming within hose range.

In the air above the intensifying storm of fire, pilots encountered turbulent flying conditions, presumably due to the buoyantly rising heated air that was causing the intense ground winds below.[12] The intensity of these turbulent updrafts from fires could even have posed a threat to those in the bombers above.

In incendiary raids over Japan, for example, B-29 pilots reported that rising columns of hot air from mass fires below could bounce the planes from 15,000 to 17,000 feet(about 4,572 to 5,182 m) in a matter of seconds. Such violent air disturbances were sometimes encountered 3 or 4 miles (about 4.8 or 6.4 km) laterally from the center of a mass fire. Because these air disturbances were quite violent and it was believed that several B-29s had been lost due to encounters with them, missions were planned so that planes could drop their bombs and turn away before reaching areas of danger downwind.

The extremely intense ground winds at Hamburg, in combination with the fire, soon caused buildings to collapse into streets, further preventing the movement of firefighting units and the escape of people (Figure 21B shows a fire truck buried in the debris of a Hamburg street, and Figure 21C shows debris piled at the edges of formerly blocked streets). In some cases, units were trapped by debris' and could not withdraw, resulting in the loss of both equipment and the lives of firemen. With many simultaneous large fires burning unchecked and with winds tending to go toward the center of the firestorm region, many streets became filled with flames, acting as gigantic channels for the high-velocity fire winds. Because of the terrific heat and showers of embers, existing open spaces, even parks, could not be used as sanctuaries by firefighters. In some cases, even strong men had to crawl on their hands and knees, hugging street curbs, to move against the wind.

Even though warning had been adequate and people had entered shelters by the time the raid began, thousands still died in the streets.

As the raid and fires intensified, heat and smoke became intense within shelters, and panic broke out in many places. Those who remained calm still had to choose between the increasingly unviable circumstance of the shelter and the intensifying hurricane of fire in the streets.

For most people there was no question of getting away. The areas hit were so great that once the fire intensified, the long travel time to the perimeter made it physically impossible for them to escape.

From areas where fire-filled regions could be observed, hundreds of

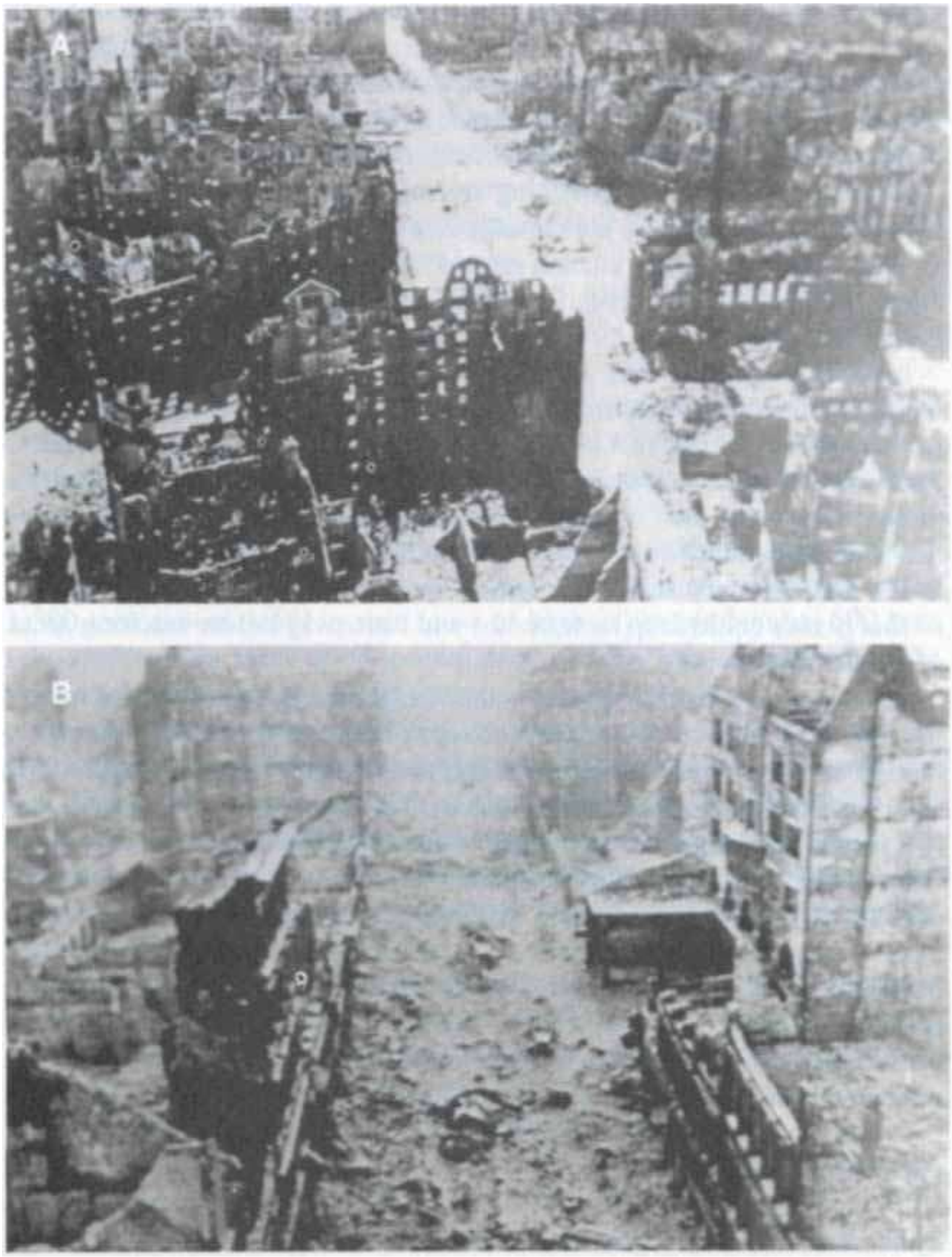
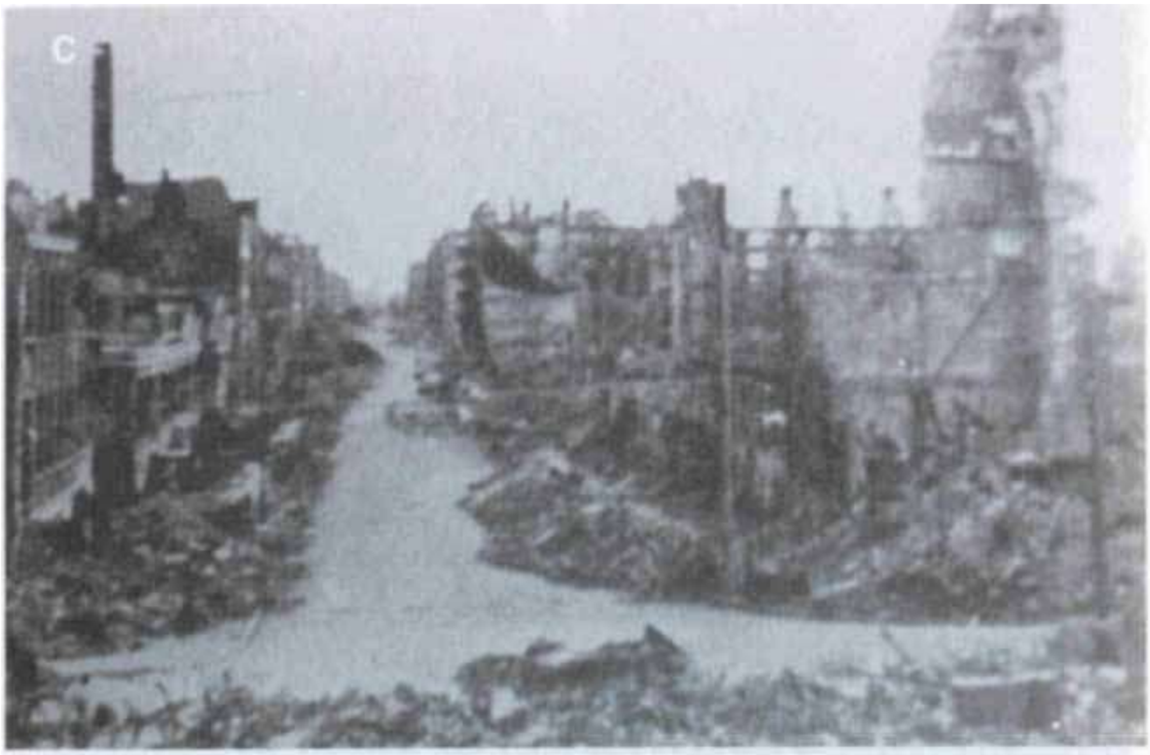
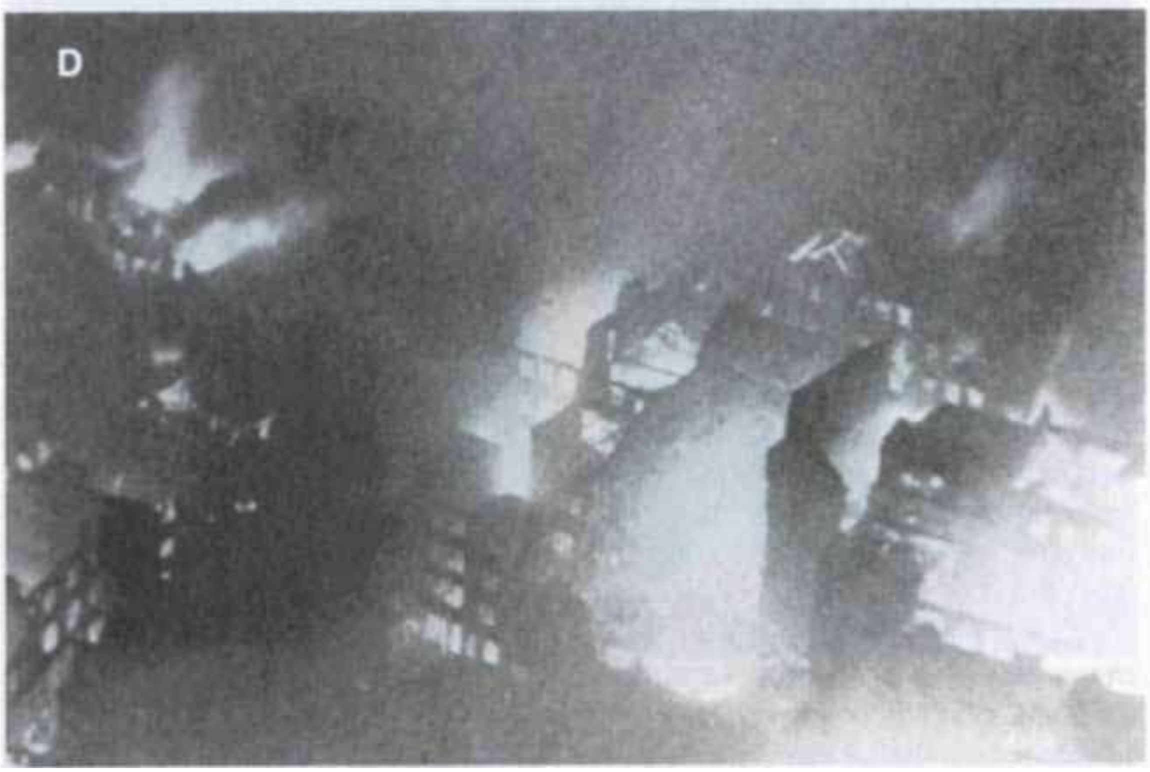



FIGURE 21 A, B, and C show various street scenes after the great incendiary raids at Hamburg in late July of 1943. A shows a district near the city center after streets have been partially cleared of debris. This section was not in the firestorm. B shows the condition of streets in a firestorm area after the attack. This street acted like a channel, creating very high winds which carried flames, firebrands, and debris. The buried vehicles in the middle of the picture are fire-trucks that were trapped by falling debris. Since the lives of their crews were threatened by the heat and high winds, the vehicles had to be abandoned. C shows a street level view of the firestorm-devastated area after debris was cleared from




the streets. During the firestorm, and for 2 days afterward, such streets were impassable even with tracked vehicles, as they were covered with high-temperature rubble from collapsed buildings. D is a picture of a burning section of London taken from the dome of St. Paul's on 29 December 1940. The relatively ineffective German incendiary raids early in World War II alerted allied military decision makers to the potential effectiveness of incendiaries for destruction. Reprinted from Fire and the Air War.© 1946 National Fire Protection Association, Quincy, Mass. Reprinted with permission.



FIGURE 22 A through E show some of the ways hundreds of thousands died in mass fires resulting from large-scale incendiary raids during World War II. A through C are photos of the dead found in shelters. The sequence of events varied, but it appears that those in shelters most often succumbed to carbon monoxide that filtered into shelters from partially combusting debris around shelters. A and C show corpses that were desiccated from the effects of extreme heating of shelters from surrounding rubble of collapsed buildings. In some cases shelter heating may have been the cause of death, but it is believed most victims in shelters were killed by carbon monoxide poisoning. However, even if carbon monoxide poisoning could have been avoided, the heating of many shelters from overburdens of fire-heated rubble would have almost certainly killed the occupants at a later time. D shows a victim who attempted to flee the fire zone rather than stay in a

shelter. Since the street winds and temperatures were so high, hyperthermia, possibly in combination with combustion product poisoning, killed many thousands in the streets of Hamburg. E shows corpses in a truck. These victims were probably overcome by heat and carbon monoxide as they attempted to escape a fire zone. Reprinted from Fire and the Air War.© 1946 National Fire Protection Association, Quincy, Mass. Reprinted with permission.

people were seen leaving shelters. After traveling short distances in the open, they would slowly collapse, as if exhausted. In some cases they did not immediately become motionless, but they tried to get up. In other cases their clothes burst into flames as they were engulfed in tornado-like fire whirls that propagated unpredictably down streets. Many killed in this manner were found to be naked (see Figure 22D).

Those who stayed in their shelters faced a different fate. As buildings collapsed under the heat of fire and the force of winds, many shelters became overburdened with debris (Figures 22A, B, and C). In many cases, death came easily (Figure 22A), as people slipped calmly into unconsciousness in carbon monoxide-infiltrated shelters. In other cases, there were signs of panic and attempts to escape.

Many shelters that had been closed off by rubble also suffered very high heating rates from an overburden of hot rubble and burning debris (Figure 22B). In these shelters, shrunken bodies were often found lying in a thick greasy black mass, which appeared to be melted body fat. In many shelters in which shrunken bodies were found, there were also bodies that had been reduced to bits of ashes.

Since many of the shrunken bodies burned to ash within a few weeks of exposure to air, it may be that oxidation exposure or temperatures differed markedly even within the same shelter.

In all cities that were subjected to successful Allied incendiary attacks and surveyed by German medical teams, carbon monoxide poisoning was regarded as the primary cause of death or injury, sometimes reaching to as much as 80 percent of all incendiary raid casualties. Air blast was found to be a relatively infrequent cause of death, generally affecting only those within a radius of about 30 meters of the explosions.

I was unable to find any unambiguous data on survival rates within the region of mass fire at Hamburg. It is interesting to note that a figure of 15,000 to 18,000 lives is often quoted as the number of people saved from the Hamburg fire storm. However, a review of Hamburg Fire Department records[37] reveals no data regarding survival in the fire zone, although documents do indicate that 18,000 people were rescued during the period from July 25 to August 4.

There is a reference to the fact that hundreds of thousands of people possibly escaped the fire, presumably in its early phases, and there are additional personal reports[35] of people who survived in bomb craters, in which the water table was sufficiently high that body parts could be covered with water-soaked clothing, and in public bunkers, which apparently were thick-walled, freestanding structures that were removed from the areas covered with the debris of collapsed buildings. However, the location of these bunkers in the fire zone and the numbers of people saved by them were not reported.

At this time, the complete absence of any tabulated data for a circumstance that is relatively well documented remains conspicuous.

## MODEL FOR ESTIMATING FATALITIES FROM SUPERFIRES

As should be evident from the three previous sections, the environment resulting from a mass fire over vast blast-disrupted regions of a nuclear target area could plausibly kill all or most people who could not escape the region of fire.

Even in the case of lightly built-up cities, average air temperatures could be well over 200°F (93°C) over nearly all of an involved region. At these temperatures, even resting individuals would be subject to serious threat of death from excess body heating within tens of minutes. Those with elevated metabolic rates due to hysteria, stress, panic, or strenuous activity would be threatened in still shorter times. The heated environment, elevated metabolic states, and the presence of carbon dioxide would induce increased respiration activity which would, in turn, increase body uptake of carbon monoxide, sulfur dioxide, nitrogen dioxide, toxic smoke, and other materials. Superheated, hurricane-force winds would do further damage to uncollapsed structures. Firebreaks of many hundreds of feet would have no inhibiting effect on the spread of mass fire.

In outlying concrete-reinforced structures that may be seriously damaged but not initially knocked down by the blast, basements would offer apparent refuge. However, winds generated by the pumping action of rising heated air over large areas would be most severe in these outlying regions near the edge of the superfire.

Burning debris and overburdens of rubble could trap sheltered individuals. Carbon monoxide and other toxic gases could, with very high probability, infiltrate such shelters, and serious delayed thermal heating could occur either from burning overburden or hot rubble from collapsed sections of buildings. In addition, high-temperature winds in combination with fire could bring down sections of many structures and spread hot and burning debris around shelter entrances and ventilation accesses.

Given this situation and the enormous range of uncertainties associated with the possible scale of such fires, even a qualitative estimate of the potential consequences of superfires on fatality and casualty estimates is necessarily uncertain. Nevertheless, as will be evident from the discussion in the two sections that follow, even qualitative, speculative estimates strongly indicate that superfires would be a threat of major importance.

Consider the baseline fire radius hypothesized at the beginning of the section Superfires and Their Environments and consider the possibility that within the baseline fire radius of 7.455 miles (12 km) the superfire

Figures 23A, 23B, and 23C show such a set of rules for an assumed 1-Mt airburst detonated at about a 2.2-km altitude (this is the same scaled height of burst used at Hiroshima). Because the height of burst is such that the likelihood of fallout in the target area would be relatively low, the weapons effects that pose major threats of death or injury would be blast, heat from the fireball, and fires that follow in the aftermath of the detonation.

Each of the three graphs in Figure 23 shows several curves for the probability of fatality, casualty (fatality plus nonfatal injury), or nonfatal injury as a function of range from the detonation. The solid curves are those used by the U.S. Congress Office of Technology Assessment (OTA) in its 1979 study The Effects of Nuclear War[41] to estimate deaths and injuries from airbursts on urban and other targets. Since OTA's assumptions about casualties and injuries are similar to those used by the Department of Defense (DOD),[42,43] they also give results similar to those of the standard DOD methodology.

The broken curves plotted in Figures 23A and 23B are derived from fatality and casualty data from Hiroshima (as noted above, casualties are the sum of fatalities and nonfatal injuries). The Hiroshima data are scaled by assuming that the probability of injury or death at each range from the 1-Mt detonation is only a function of the peak blast wave overpressure.

For example, the peak overpressure at 0.95 miles (1.5 km) from ground zero at Hiroshima was about 5 psi, and the probability of being killed was about 0.3. For the 1-Mt airburst, this same overpressure would occur at about 4 miles (6.5 km). Therefore, it is assumed that the probability of being killed would also be about 0.3.

In order to understand the potential implications of these rules for death and injury estimates, it is necessary to choose a set of targets. Obviously, if the targets are chosen in sparsely populated areas, casualties will be lower than for a choice of targets in heavily populated areas.

For purposes of analysis, a reference case of 100 1-Mt warheads on the 100 largest city centers in the United States is of interest.

This reference case results in no overlap of areas that are subject to the effects of multiple weapons, as could be the case in many imaginable nuclear attacks; and it applies the casualty rules to circumstances similar to those from which the data were derived. It is therefore a baseline measure of the potential influence of casualty rules on predictions of deaths and injuries from nuclear attacks, which can then be used as a reference against alternative possibilities of interest to analysts.

Thus, it is emphasized that the above choice of targets is chosen for its analytic interest; it is not a scenario, and I attach no significance to this target set beyond that of a baseline reference.

calculations performed by Small, Brode, and Larson would apply.[715] Then, speculate further that all individuals are killed.

Both the assumed fraction of those killed and the radius within which superfires might rage are, of course, highly uncertain numbers.

As noted many times above, the fraction of those killed within the superfire depends on numerous as yet unresolved physical uncertainties and scenario-dependent details. The radius within which a superfire might occur would depend on the type of combustible material at different ranges, its distribution, atmospheric visibility at the time of attack, whether the ground is desert or covered with dry combustible vegetation or noncombustible but highly reflecting snow, whether or not cloud heights are such that fireball light is reflected back toward the Earth or away from it, and a host of other uncertain contingencies.

For example, if there is either snow cover on the ground or clouds at heights that reflect thermal radiation back to the Earth, the range at which a major mass fire might occur (assuming that all other assumptions remain unchanged) might instead be 9 to 10.5 miles (15 to 17 km). This would increase (or decrease in the opposite circumstance) the area of superfire by Wi to 2 times.

Thus, if a population were uniformly distributed over the target area, the number of predicted fatalities, assuming a 12-km lethal radius in which all would die and a 17-km radius in which only half would die, results in the same prediction of fatalities. In light of the very great range of uncertainties and the severe environmental conditions within the region of fire, it is therefore reasonable to scope out the possibilities by assuming a cookie cutter* fatality condition.

## FATALITY POTENTIAL OF SUPERFIRES

### The Influence of Casualty Rules on Predictions of Deaths and Injuries from Nuclear Attacks

In order to estimate the number of fatalities and injuries resulting from a nuclear attack, it is necessary to know where weapons would fall in relationship to population, as well as the probability that individuals would suffer death or injury from each of many possible weapons effects. For a presumed set of detonations, such calculations therefore require both population distribution data and rules for estimating the probabilities of death or injury from each attack.

*By cookie cutter it is meant that all individuals caught within the fire zone are assumed to be killed by fire effects, while all individuals outside the fire zone are assumed to survive fire effects.

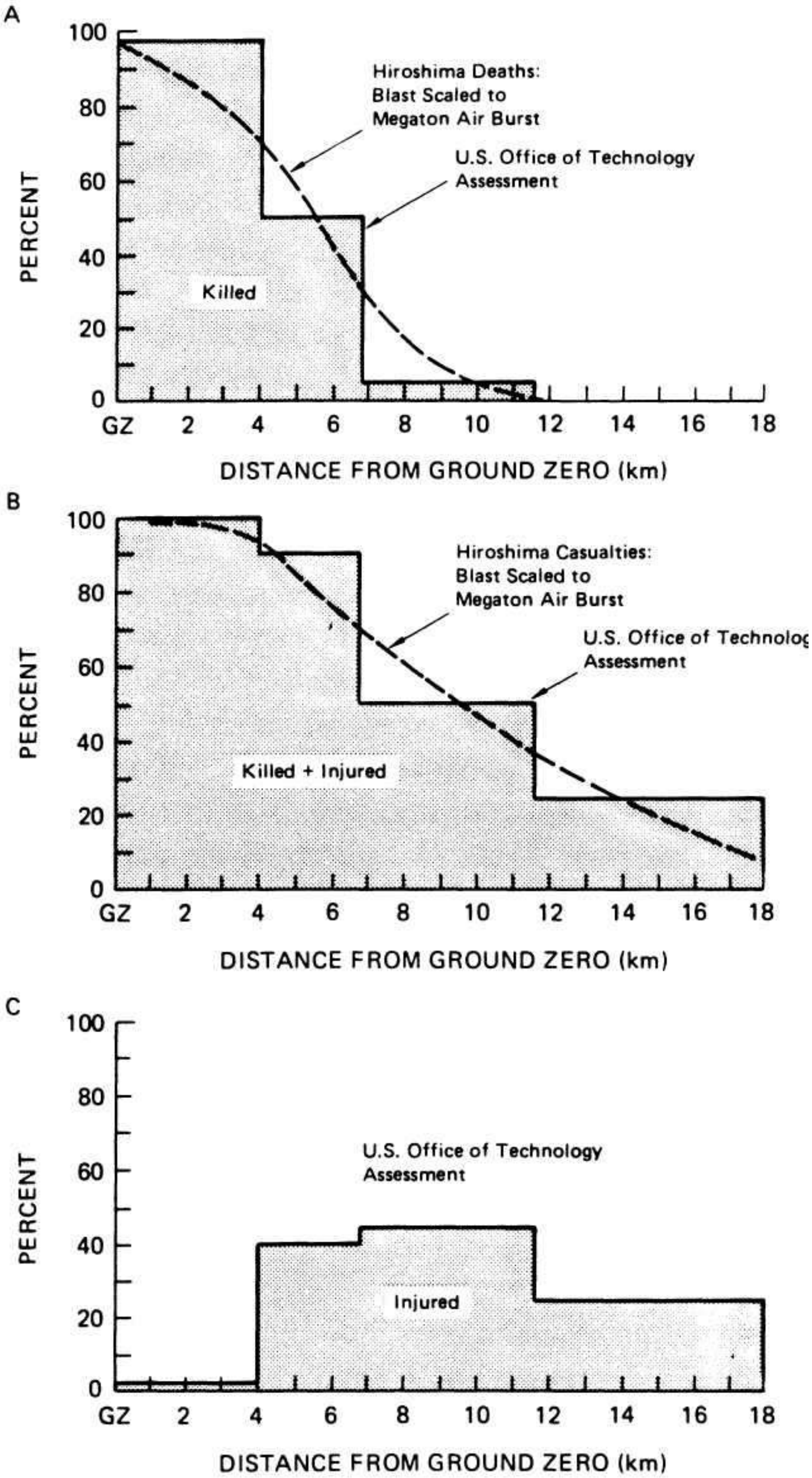



FIGURE 23 The three graphs show an application of rules used by the OTA to estimate fatalities and injuries from a 1-Mt airburst over an urban area. The solid curve in A shows the assumed probability of death as a function of range from ground zero. The broken curve shows fatality data from Hiroshima scaled by assuming that the probability of death is purely a function of the peak overpressure at each range from the detonation. In B similar curves are shown for total casualties, which is defined to be the sum of those killed and those injured. In C the OTA rules for those injured (but not killed) are shown as a function of range from ground zero.

The calculations that I performed for the presumed 100-city attack, using first the OTA/DOD rules and then a blast scaling of Hiroshima data, gave identical predictions within a few percent. It is therefore clear that the government rules for estimating fatalities and injuries are virtually indistinguishable from blast scaling of data from Hiroshima.

Figure 24 shows the range dependence of the government's probability of injury assumptions for a 1-Mt airburst. At selected ranges below the horizontal axis, the overpressure and thermal energy deposited from the fireball of a 1-Mt airburst is shown (12-mile [19.3-km] visibility). Above the axis is the thermal fluence which occurred at a similar overpressure

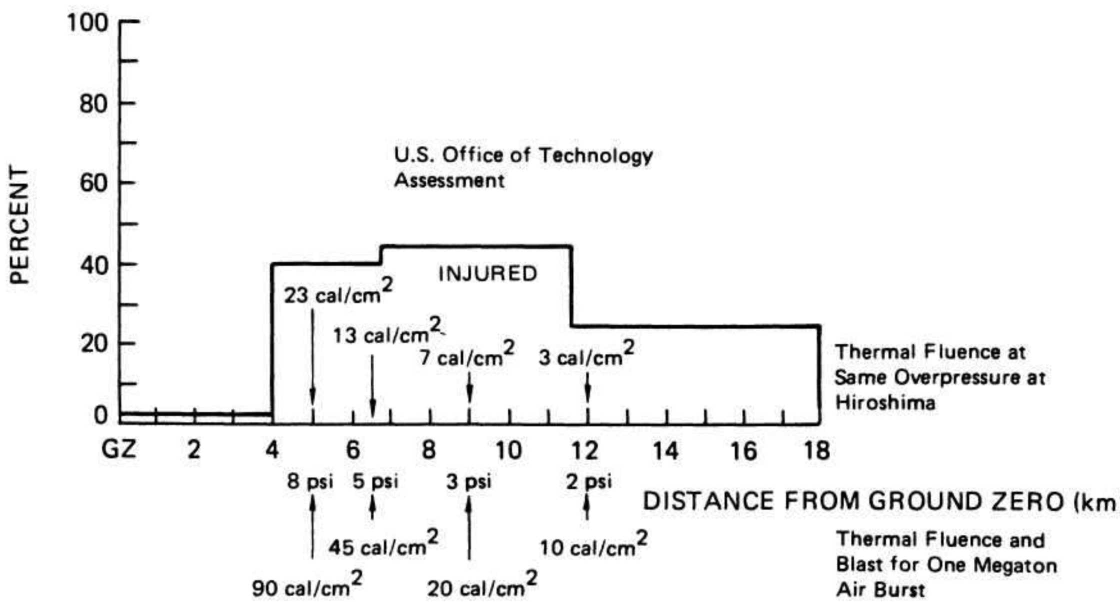



FIGURE 24 Some aspects of the physical environment that could influence the probability of death at different ranges from a ground zero are compared for 1-Mt and 12.5-kt detonations. The solid curve shows the probability of blast injury as a function of range from ground zero derived by applying the OTA rules to the case of a 1-Mt airburst. (These rules are also discussed in the legend to Figure 23 and the text.) The 3-psi range at Hiroshima occurred at about 1.5 miles (about 2.3 to 2.4 km) from ground zero. As indicated on the upper side of the range axis, the amount of thermal radiation delivered along with the blast was about 7 $cal/cm^2$. Individuals subjected to these effects at Hiroshima would not have been in the region of mass fire that occurred after the attack. At the 3-psi range for a 1-Mt airburst, about 20 $cal/cm^2$ could be delivered along with the blast. Many fires would be set at this range, and many additional fires might even be set at much greater range (perhaps at the 12-km range or greater). Individuals injured by the 3-psi blast at the 9-km range might therefore have to walk 3 or more km through a zone heavily damaged by blast and with fires of increasing intensity. By comparison, an injured individual who survived blast and radiation effects at ground zero in Hiroshima would have had to walk less than 2 km to escape the fire zone. It is therefore clear that using blast alone as the criterion for estimating fatalities could well result in a serious underestimate of the probability of death.

at Hiroshima. Thus, at Hiroshima, about 12 to 13 calories per square centimeter was deposited at the range at which 5 psi occurred. In contrast, at the 5-psi range for the 1-Mt airburst, about 45 $cal/cm^2$ occurs.

Because this environment is created at about 6.5 km from the detonation point and, as shown earlier, it is plausible that a mass fire could rage to a range of 12 km, it appears unlikely that a simple scaling rule of the kind used in the OTA/DOD methodology adequately accounts for the circumstance of those at the 6.5-km range.

Figure 25 shows estimates of fatalities and casualties for the 100-city reference case. Blast scaling predicts that there would be 14 million to 15 million fatalities and 22 million to 23 million injured.

An alternative postulate, discussed in the previous section, is that superfires of uncertain scale would occur, killing all within a range of 6 to 8 miles (9.5 to 13 km) from each ground zero. For the area outside the range of the superfire, then, it can be postulated that the blast injury rules derived from Hiroshima data apply.

Under these assumptions, the number of outright fatalities increases by a factor of between 2.5 and 4, resulting in a prediction of from 36 million to 56 million fatalities, while the number of injured decreases dramatically to between 3 million and 11 million. This is in accord with German experiences during World War II, in which medical surveys determined that incendiary raids always resulted in a much higher ratio of killed to injured.

The reason for this dramatic change in distribution of fatalities and injuries can be quickly grasped from Figure 23C. The result of the new assumption is that many who would be counted as injured in the blast methodology instead are counted as dead; it also counts uninjured individuals within the fire zone among the dead as well. The only nonfatal injured are therefore those who are injured by the effects of the blast but are outside the perimeter of the superfire.

Even though the scale, ferocity, and effects of these superfires are as yet highly uncertain, it is not difficult to test the sensibility of this hypothetical casualty estimate.

Because the area covered by such fires is proportional to the square of the fire radius, if the average fire radius were to increase or decrease by 10 to 15 percent, the result would be an increase or decrease in the affected area of about 20 to 30 percent. The population density is, to a first approximation, relatively constant for such small changes in fire radius.[44] This means that a 10 or 15 percent increase or decrease in fire radius results in about a 20 to 30 percent increase or decrease in predicted fatalities.

Thus, the minimum postulated superfire radius used in the calculations

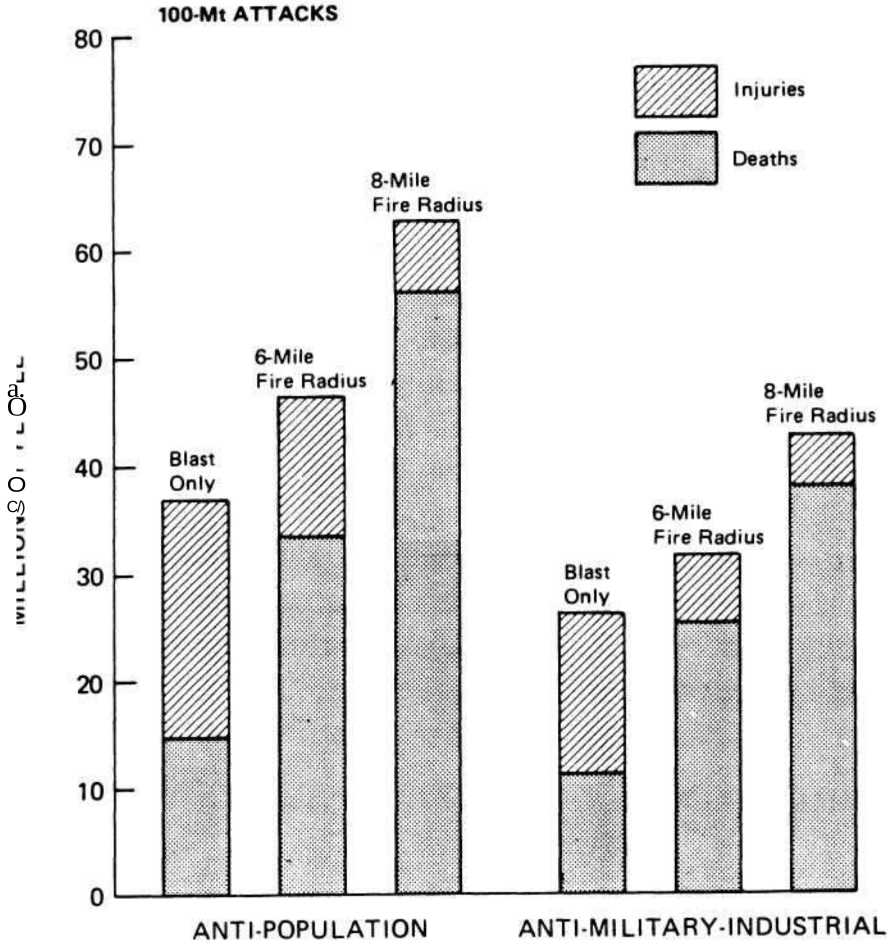



FIGURE 25 The potential effects of differing assumptions about the causes of fatalities and injuries. A reference attack that assumes that a single 1-Mt detonation occurs over the population center of each of the 100 largest metropolitan areas is used to determine the potential significance of differing fatality and injury rules. When only blast scaling from Hiroshima'is used to estimate fatalities and injuries, about 14 million fatalities and 23 million injured are projected. If it is assumed that mass fires kill everyone within 6 miles (about 9.7 km) of the ground zeros and injuries beyond that range occur because of blast at the same rate as that which occurred at Hiroshima, 33 million would be killed and 12 to 13 million would be injured. If the fire zone extends to 8 miles (about 12.9 km) instead, 56 million would be killed and 6 to 7 million would be injured. Similar results are also shown for a reference attack that does not seek to kill population but only attempts to destroy 100 of the most important industrial facilities that would provide military products that could directly support a war effort.

summarized in Figures 25 and 26 (6 miles or 9.5 km) would have to be reduced by a factor of somewhat less than the square root of two before predictions of fatalities could be similar to those of blast scaling methodologies. High survival rates at a range of about 4 miles (6.5 km) would therefore be required. At this range, however, the thermal fluence from the fireball would be about 45 cal/cm$^2$, which is enough to set almost any interior household material in line of sight of the fireball on fire immediately (Figure 2B shows the emission of smoke from the front of a wood frame house from 25 cal/cm$^2$).

If, instead, it is assumed that all those who are not injured by blast could miraculously escape the hostile effects of near-hurricane-force winds and air temperatures above that at which water boils, and only those who are injured according to the blast scaling rules shown in Figure 23C die in superfires of radius 6 to 8 miles (9.5 to 13 km), then the number of deaths would increase by a factor of around two, to 27 million to 33 million.

It is therefore difficult to see how casualty rules that do not include the hostile effects of mass fires over such vast areas can result in projections more plausible than even those that follow from the preliminary speculations contained in this study.

## COMPARISON OF OTHER TARGET SETS WITH THE REFERENCE CASE

Daugherty, Levi, and von Hippel[44] have made a very complete and uniquely systematic study of possible fatalities and injuries from nuclear attacks against the United States. They have not only systematically examined a wide range of possibilities by varying the assumptions about the biological consequences of given nuclear environments (for example, variations in the 50 percent lethal dose [$LD_{50}$] for radiation exposure) and the behavior of individuals within these environments (how fallout protection factors, and hence casualties, differ if sheltered people make short excursions from their shelters), but they have also examined the potential consequences of plausible variations in the nuclear environment itself (how injury and fatality estimates vary if populations are subject to fires as well as to blast).

Furthermore, they have systematically examined the implications of their assumptions for different potential target classes on both an individual and multiply aggregated basis. By doing this, they have created a menu of possibilities from which analysts or decision makers may choose to contemplate, or to reject as implausible, any of a wide range of potential nuclear attacks.

This kind of analysis is, so far, absent from studies and results of studies published by government agencies.

Two interesting reference cases studied by Daugherty et al.[44] are noteworthy:

1. An attack of 100 single 1-Mt airbursts on 100 U.S. urban centers.
2. An attack of 101 nuclear airbursts on 101 key military-industrial targets.

As noted by Daugherty et al., because the first reference case has no areas of overlap from the effects of multiple weapons detonations, the 100-city reference case provides a baseline of analytic interest for comparison with other cases in their menu of possibilities.

In addition, if the reference case is calculated using blast scaling casualty rules derived from data following an attack on a city center (Hiroshima), an unambiguous estimate of the potential significance of fire effects is established.

The second reference case is of interest relative to the first since it provides just such a comparative case from their menu.

This attack is of interest not only because of its central role in many policy statements and deliberations but also because it does not target population per se. Instead it uses essentially the same number of warheads (101 versus 100) to attack a small number of very-high-value military-industrial end product facilities, and therefore represents what some might argue is a minimal attack that could quickly interrupt U.S. conventional war production capabilities.

As shown in Figure 26, if I assume that the 100 detonations are airbursts of 1-Mt yield and that the hypothesized superfire casualty rules of the previous section apply, 25 million to 37 million deaths and 2 million to 7 million injured would result. Thus, if fires kill substantial numbers of people in target areas, the attack that does not target population per se might result in the death of between 1.5 and 2.5 times more people than the blast scaling would predict for the antipopulation attack of a similar size.

It is also of interest to examine the potential effects of choice of weapon yield. If the rules for guessing the radius of superfire are scaled by assuming that the fire radius occurs at the 10-cal/cm$^2$ range (12-mile [19.3-km] visibility), then Figure 27 shows the predicted results for the anti-industrial attack, assuming that the attack is instead executed with 101 weapons of either 500- or 100-kiloton (kt) yield.

In this case, the 500-kt attack would kill 23 million people, 1.5 times that predicted by blast scaling for the antipopulation reference attack, and the 100-kt attack would kill about 8 million people, about two-thirds that predicted by the application of blast scaling to the antipopulation reference attack.

However, it is noteworthy that the fire radius derived for the 100-kt weapon is about 4.5 km, and the already speculative cookie cutter fire

100-Mt ATTACKS

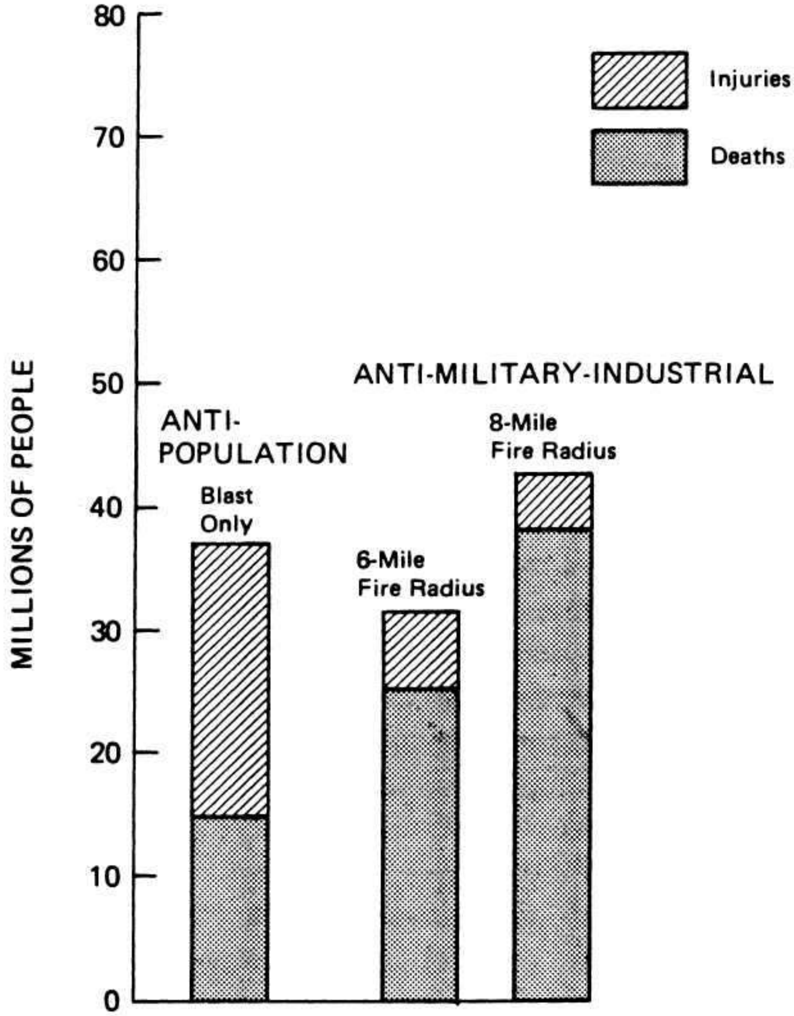



FIGURE 26 Some of the results shown in Figure 25 are rearranged to illustrate that when the proposed alternative method of assessing casualties is applied to attacks aimed at industrial facilities rather than population centers, the result could be greater casualties than in the antipopulation attack. Since such attacks have sometimes been proposed as relatively limited, and hence more sensible and more plausible than antipopulation attacks, this comparison serves to underscore the potentially misleading character of such arguments.

model is still more speculative, as it is more likely that many of those who would not have been severely injured would have some chance to attempt to escape the fire region.

## CONCLUSION

During World War II the extraordinary power of science was turned to building a weapon that could create energy densities and temperatures comparable to those that normally exist in the interiors of stars. Today,

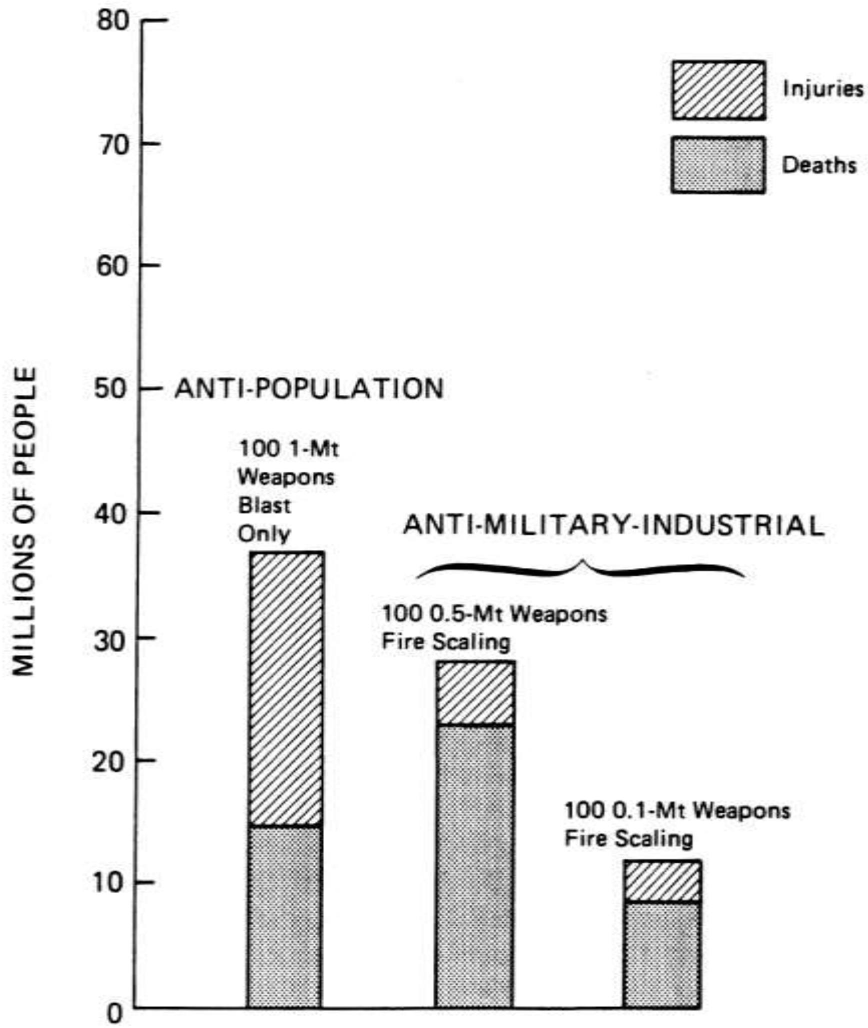



FIGURE 27 The effects of applying the fire casualty rules discussed in the legend to Figure 25 and the text to attacks that utilize weapons of lower yield. The predicted casualties when 100 0.5-Mt weapons are substituted for 1-Mt weapons are only slightly diminished. When 0.1-Mt weapons (100 kt) are substituted, casualties drop significantly. It should be noted, however, that for these much lower yield detonations, blast scaling from Hiroshima data may be no less uncertain than alternative rules discussed in this paper.

the results of those and subsequent efforts have given us weapons with effects that are of vast and nonintuitive scales.

One of these effects is superfires; they would accompany nuclear detonations in or near urban areas and might result in two to four times as many fatalities as that predicted by standard government blast scaling rules.

The effects of such fires, while recognized by many during and at the end of World War II, has remained an issue of discussion and research only among a small group of dedicated researchers. As such, an understanding of their effects and the possible scale of unpredictable consequences that could accompany the use of nuclear weapons in many applications remains poorly understood, or absent, from the cognition of planners and decision makers. Without this understanding, the probability of misjudgment and miscalculation could be considerable.

## NOTES

[1]Bond, H., ed. 1946. Fire and the Air War. National Fire Protection Association.

[2]The U.S. Strategic Bombing Survey. 1946. Washington, D.C.: U.S. Government Printing Office.

[3]Glasstone, S., and P. J. Dolan, eds. 1977. The Effects of Nuclear Weapons. Report no. 0-213-794. Washington, D.C.: U.S. Government Printing Office.

[4]Federal Emergency Management Agency. 1982. Attack Environment Manual. CPG-2-1A2. Washington, D.C.: Federal Emergency Management Agency.

[5]Defense Civil Preparedness Agency. 1973. DCPA Attack Manual. CPG-2-1A1. Washington, D.C.: Department of Defense.

[6]Glasstone, S., ed. 1962. The Effects of Nuclear Weapons. Washington, D.C.: U.S. Government Printing Office.

[7]Brode, H. L., and R. D. Small. 1983. Fire Damage and Strategic Targeting. PSR Note 567. Los Angeles, Calif.: Pacific-Sierra Research Corp.

[8]Hassig, P. J., and M. Rosenblatt. 1983. Firestorm Formation and Environment Characteristics After a Large-Yield Nuclear Burst. Proceedings of the 17th Asilomar Conference on Fire and Blast Effects of Nuclear Weapons. CONF-8305107, May 30-June 3.

[9]Brode, H. L., D. A. Larson, and R. D. Small. 1983. Hydrocode Studies of Flows Generated by Large Area Fires. Proceedings of the 17th Asilomar Conference on Fire and Blast Effects of Nuclear Weapons. CONF-8305107. May 30-June 3.

[10]Larson, D. A., and R. D. Small. 1983. The Large Urban Fire Environment: Trends and Model City Predictions. Proceedings of the 17th Asilomar Conference on Fire and Blast Effects of Nuclear Weapons. CONF-8305107. May 30-June 3.

[11] Small, R. D., and D. A. Larson. 1983. Analysis of the Large Urban Fire Environment. Proceedings of the 17th Asilomar Conference on Fire and Blast Effects of Nuclear Weapons. CONF-8305107. May 30-June 3.

[12]Small, R. D., D. A. Larson, and H. L. Brode. 1983. Fluid dynamics of large area fires. In Fire Dynamics and Heat Transfer. J. G. Quintiere, R. L. Alpert, and R. A. Altenkirch, eds. New York: The American Society of Mechanical Engineers.

[13]Brode, H. L., and R. D. Small. 1983. Fire Damage and Strategic Targeting. PSR Note 567. Los Angeles, Calif.: Pacific-Sierra Research Corp.

[14]Small R. D., and H. L. Brode. 1980. Physics of Large Urban Fires. PSR Report 1010. Los Angeles, Calif.: Pacific-Sierra Research Corp.

[15]Larson, D. A., and R. D. Small. 1982. Analysis of the Large Urban Fire Environment: Part I. Theory. PSR Report 1210. Los Angeles, Calif.: Pacific-Sierra Research Corp.

[16]Larson, D. A., and R. D. Small. 1982. Analysis of the Large Urban Fire Environment: Part II. Parametric Analysis and Model City Simulations. PSR Report 1210. Los Angeles, Calif.: Pacific-Sierra Research Corp.

[17]Brode, H. L. 1980. Large-Scale Urban Fires. PSR Note 348. Los Angeles, Calif.: Pacific-Sierra Research Corp.

[18]Feldstein, M., S. Duckworth, H. C. Wohlers, and B. Linsky. 1963. The contribution of the open burning of land clearing debris to air pollution. J. Air Pollut. Control Assoc. 13:(11).

[19]Darley, E. F., F. R. Burleson, E. H. Mateer, J. T. Middleton, and V. P. Osterli. 1966. Contribution of burning of agricultural wastes to photochemical air pollution. J. Air Pollut. Control Assoc. 11:(12).

[20]Gerstle, R. W., and D. A. Kemnitz. 1967. Atmospheric emissions from open burning. J. Air Pollut. Control Assoc.

[21]Wiersma, S. J. 1975. Characteristics of fires in structural debris. Silver Spring, Md.: Naval Surface Weapons Center.

[22]Wilton, C, K. Kaplan, B. Gabrielsen, and J. Zaccor. 1976. Blast/Fire Interaction, Blast Translation, and Toxic Agents. Final Report, URS 7030-6. Redwood City, Calif.: URS Research Co. See also note 45.

[23]Pryor, A. J., D. E. Johnson, and N. N. Jackson. 1969. Hazards of Smoke and Toxic Gases Produced in Urban Fires. San Antonio, Tex.: Southwest Research Institute.

[24]Takata, A. N.,andT. E. Waterman. 1972. Fire Laboratory Tests—Phase II, Interaction of Fire and Simulated Blast Debris, IITRI-J6217(2). Chicago, 111.: IIT Research Institute.

[25]Longinow, A., T. E. Waterman, and A. N. Takata. 1982. Assessment of Combined Effects of Blast and Fire on Personnel Survivability. Chicago, 111.: IIT Research Institute.

[26]Lee, W., H. C. Leong, C. Jee, and M. Gayle Hershberger. 1966. Design of Tests for the Effects of Mass Fires on Shelter Occupants. Final Report. Palo Alto, Calif.: Isotopes, Inc.

[27]Police President of Hamburg. 1971. Short Version of Report on Experiences of the Hamburg Fire Department During the Air Attacks from July 24 to August 3, 1943. Reprinted as Appendix 1 in Fire Fighting Operations in Hamburg, Germany During World War II, by C. F. Miller, Final Report, URS 7030-6. Redwood City, Calif.: URS Research Company.

[28]Christian, W. J., and R. C. Wands, eds. 1972. An Appraisal of Fire Extinguishing Agents. Proceedings of a Symposium at the National Academy of Sciences, April 11-12. Washington, D.C.: National Academy of Sciences.

[29]Goodale, T. 1971. An Attempt to Explore the Effect of High Blast Overpressures on the Persistence of Smouldering Combustion in Debris. Summary Report, URS 7030-6. Redwood City, Calif.: URS Research Company.

[30]Braker, W., and A. L. Mossman. 1971. Matheson Gas Data Book, 5th ed. East Rutherford, N.J.

[31]Jacobs, M. B. 1949. The Analytic Chemistry of Industrial Poisons, Hazards, and Solvents, 2nd ed. New York: Interscience Publishers, Inc.

[32]Jacobs, M. B. 1967. Chemical Analysis XXII, The Analytic Toxicology of Industrial Inorganic Poisons. New York: Interscience Publishers, Inc.

[33]Henderson and Haggard. 1943. Noxious Gases and the Principles of Respiration Influencing Their Action, 2nd ed. Oxford, England: Clarendon Press.

[34]Pryor, A. J., D. E. Johnson, and N. N. Jackson. 1969. Hazards of Smoke and Toxic Gases Produced in Urban Fires. San Antonio, Tex.: Southwest Research Institute.

[35]Kehrl, Police President of Hamburg. 1946. Secret Report by the Police President of Hamburg on the Heavy Raids on Hamburg in July/August 1943, I.O.(t)45 (translated and published by the United Kingdom Home Office, Civil Defense Department, Intelligence Branch, Document Number 43097, January 1946).

[36]Report of the Technical Services Division of the Hamburg Fire Protection Police During the Major Catastrophe and Summary of Reports on Actions During the Air Attacks on Hamburg from July 24 to August 3, 1943. 1971. Reprinted as Appendix 2 in Fire Fighting Operations in Hamburg, Germany During World War II, by C. F. Miller, Final Report, URS 7030-6. Redwood City, Calif.: URS Research Company.

[37]Miller, C. F. 1971. Fire Fighting Operations in Hamburg, Germany During World War II. Final Report, URS 7030-6. Redwood City, Calif.: URS Research Co.

[38]Taylor, D. H. 1978. Methodology for Estimating High Intensity Attacks. SAI-77-803-LJ. La Jolla, Calif.: Science Applications Inc.

[39]In fact, a fourth raid occurred on August 3, 1943; however, it took place during a severe thunderstorm. Police reports indicate that the substantial numbers of available fire fighting forces were not overwhelmed, as was the case in the three previous raids.

It should be kept in mind, however, that the most successful attacks are known to have been those of highest intensity, since they started so many potentially controllable fires so quickly, that by the time some fires were put out, others had grown beyond control. The weather's major contribution could well have been interference with the placement of bombs, rather than expuitgement of fires.

In Japan, reports indicate that successful incendiary attacks were made even during periods of light rain and often within hours of heavier rain. For example, 37 percent of the Nishinomiya-Mikage area was destroyed in a single raid despite the fact that heavy rain had fallen for the previous 48 hours.

On the other hand, German cities were much more fire resistant than Japanese (and incidentally American) cities, as building construction was cellular, relying on internal and external masonry walls to protect against fire propagation. Hence, in the absence of more complete data on these events, the effects of weather must be considered to be quite ambiguous.

[401]Horatio Bond, private communication. National Fire Protection Association.

[41]U.S. Congress, Office of Technology Assessment. 1979. The Effects of Nuclear War. Washington, D.C.: U.S. Government Printing Office.

[42]Peter Sharfman, private communication, project director of The Effects of Nuclear War, U.S. Congress Office of Technology Assessment.

[43]British Medical Association. 1983. The Medical Effects of Nuclear War. The Report of the British Medical Association's Board of Science Education. London: John Wiley and Sons.

[44]Daugherty, W., B. Levi, and F. von Hippel. Casualties Due to the Blast, Heat and Radioactive Fallout from Various Hypothetical Nuclear Attacks on the United States. This volume.

[45]Bucheim, R. W., and the staff of the Rand Corporation. 1958. Space Handbook: Astronautics and Its Applications. New York: Random House.