City on fire
By Lynn Eden

By ignoring the fire damage that would result from a nuclear attack and taking into account blast damage alone, U.S. war planners were able to demand a far larger nuclear arsenal than necessary.

AUTHOR'S WEB SITE

This article has been adapted from Lynn Eden's book Whole World on Fire: Organizations, Knowledge, and Nuclear Weapons Devastation.

ADDITIONAL INFORMATION

For more on this subject please visit the National Security Archive's "New Evidence on Nuclear Weapons Effects Shows That U.S. Nuclear War Plans Underestimated Destructiveness of Nuclear Arsenal By Ignoring Firestorms"

For more than 50 years, the U.S. government has seriously underestimated damage from nuclear attacks. The earliest schemes to predict damage from atomic bombs, devised in 1947 and 1948, focused only on blast damage and ignored damage from fire, which can be far more devastating than blast effects.

The failure to include damage from fire in nuclear war plans continues today. Because fire damage has been ignored for the past half-century, high-level U.S. decision makers have been poorly informed, if informed at all, about the extent of damage that nuclear weapons would actually cause. As a result, any U.S. decision to use nuclear weapons almost certainly would be predicated on insufficient and misleading information. If nuclear weapons were used, the physical, social, and political effects could be far more destructive than anticipated.

How can this systematic failure to assess fire damage have persisted for more than half a century? The most common response is that fire damage from nuclear weapons is inherently less predictable than blast damage. This is untrue. Nuclear fire damage is just as predictable as blast damage.

One bomb, one city

To visualize the destructiveness of a nuclear bomb, imagine a powerful strategic nuclear weapon detonated above the Pentagon, a short distance from the center of Washington, D.C. [1] Imagine it is a "near-surface" burst—about 1,500 feet above the ground—which is how a military planner might choose to wreak blast damage on a massive structure like the Pentagon. Let us say that it is an ordinary, clear day with visibility at 10 miles, and that the weapon's explosive power is 300 kilotons—the approximate yield of most modern strategic nuclear weapons. This would be far more destructive than the 15-kiloton bomb detonated at Hiroshima or the 21-kiloton bomb detonated at Nagasaki. [2]

Washington, D.C., has long been a favorite hypothetical target. [3] But a single bomb detonated over a capital city is probably not a realistic planning assumption.

When a former commander in chief of the U.S. Strategic Command read my scenario, he wanted to know why I put only one bomb on Washington. "We must have targeted Moscow with 400 weapons," he said. He explained the military logic of planning a nuclear attack on Washington: "You'd put one on the White House, one on the Capitol, several on the Pentagon, several on National Airport, one on the CIA, I can think of 50 to a hundred targets right off. . . . I would be comfortable saying that there would be several dozens of weapons aimed at D.C." Moreover, he said that even today, with fewer weapons, what makes sense would be a decapitating strike against those who command military forces. Today, he said, Washington is in no less danger than during the Cold War.

The discussion that follows greatly understates the damage that would occur in a concerted nuclear attack, and not only because I describe the effects of a single weapon. I describe what would happen to humans in the area, but I do not concentrate on injury, the tragedy of lives lost, or the unspeakable loss to the nation of its capital city. These are important. But I am concerned with how organizations estimate and underestimate nuclear weapons damage; thus, I focus largely, as do they, on the physical environment and on physical damage to structures.

With this in mind, let us look at some of the consequences of a nuclear weapon detonation, from the first fraction of a second to the utter destruction from blast and fire that would happen within several hours. This will allow us to understand the magnitude of the damage from both effects, but particularly from fire, which is neither widely understood nor accounted for in damage prediction in U.S. nuclear war plans.

Unimaginable lethality

The detonation of a 300-kiloton nuclear bomb would release an extraordinary amount of energy in an instant—about 300 trillion calories within about a millionth of a second. More than 95 percent of the energy initially released would be in the form of intense light. This light would be absorbed by the air around the weapon, superheating the air to very high temperatures and creating a ball of intense heat—a fireball.

Because this fireball would be so hot, it would expand rapidly. Almost all of the air that originally occupied the volume within and around the fireball would be compressed into a thin shell of superheated, glowing, high-pressure gas. This shell of gas would compress the surrounding air, forming a steeply fronted, luminous shockwave of enormous extent and power—the blast wave.

By the time the fireball approached its maximum size, it would be more than a mile in diameter. It would very briefly produce temperatures at its center of more than 200 million degrees Fahrenheit (about 100 million degrees Celsius)—about four to five times the temperature at the center of the sun.

This enormous release of light and heat would create an environment of almost unimaginable lethality. Vast amounts of thermal energy would ignite extensive fires over urban and suburban areas. In addition, the blast wave and high-speed winds would crush many structures and tear them apart. The blast wave would also boost the incidence and rate of fire-spread by exposing ignitable surfaces, releasing flammable materials, and dispersing burning materials.

Within minutes of a detonation, fire would be everywhere. Numerous fires and firebrands—burning materials that set more fires—would coalesce into a mass fire. (Scientists prefer this term to "firestorm," but I will use them interchangeably here.) This fire would engulf tens of square miles and begin to heat enormous volumes of air that would rise, while cool air from the fire's periphery would be pulled in. Within tens of minutes after the detonation, the pumping action from rising hot air would generate superheated ground winds of hurricane force, further intensifying the fire. [4]

Virtually no one in an area of about 40–65 square miles would survive.

A little farther away

At Pentagon City, a shopping and office complex about seven-tenths of a mile from ground zero, light from the fireball would melt asphalt in the streets, burn paint off walls, and melt metal surfaces within a half second of the detonation. The interiors of vehicles and buildings in line of sight of the fireball would explode into flames.

Roughly one second later, the blast wave and 750-mile-per-hour winds would arrive, tossing burning cars into the air like leaves in a windstorm. At this distance, the blast wave and thermal radiation would be more powerful and destructive than at ground zero in Hiroshima.

The compressed air and winds associated with the shockwave could cause structures to cave in and might even topple large office buildings. The massive concrete and steel office buildings at Pentagon City might not be knocked down, but all nonsupporting interior walls and doors would be shattered, their fragments blown away at high speed. Window frames, glass, heavy desks, tables, filing cabinets, chairs, and other furnishings would become missiles and shrapnel. Within minutes, the insides of buildings still standing would be burning pyres of splintered walls, doors, and other combustibles.

Seconds after the blast wave passed, suction effects created in part by the rising fireball would reverse the winds, drawing them toward ground zero. Trees and other objects could be sucked toward the point of detonation.

Within a slightly longer distance from the Pentagon—about 1.3 miles—are most of Arlington National Cemetery, most of the Virginia Highlands and Addison Heights neighborhoods, and parts of Washington, D.C., including the Lincoln and Jefferson memorials.

At this distance, for a split second the fireball would shine more than 5,000 times brighter than a desert sun at noon. Thermal energy from the fireball—more than 15 times more intense than that at the edge of the mass fire that destroyed Hiroshima—would radiate onto exposed surfaces in just seconds.

All combustible materials illuminated by the fireball would spew fire and black smoke. Grass, vegetation, and leaves on trees would explode into flames; the surface of the ground would explode into superheated dust. Any flammable material inside buildings (paper, curtains, upholstery) that was directly exposed would burst into flame. The marble on the Lincoln and Jefferson memorials would crack, pop, and possibly evaporate. If the light from the fireball illuminated part of the bronze statue of Jefferson, its surface would melt.

Trees and telephone poles would recoil from the flaming gases. Birds in flight would drop from the sky in flames. The air would be filled with dust, fire, and smoke. Visitors at Arlington National Cemetery or the Lincoln or Jefferson memorials who were directly exposed to the fireball's light would be killed instantly. Others would not survive long.

It would take about four seconds after the detonation for the shockwave to arrive at the Lincoln and Jefferson memorials. They would collapse instantly. As the shockwave passed over, it would engulf all structures in high pressure and crush all but the strongest. The blast wave would generate ferocious winds of 300–400 miles per hour that would persist for about a second and a half.

The winds and the crushing overpressure would tear apart many strong structures. Wood-frame and residential brick buildings would be completely destroyed. Other structures at this range, such as the Arlington Memorial Bridge and the George Mason Memorial Bridge, might not collapse, but anyone caught in the open or even sheltered behind these structures would be killed within seconds or minutes.

The high winds would tear structural elements from buildings and cause them to disintegrate explosively into smaller pieces. Some of these pieces would then become destructive projectiles, causing further damage. The superheated, dust-laden winds would be strong enough to overturn trucks and railroad cars.

Just beyond this range, about 1.6 miles from the Pentagon, aircraft at Reagan National Airport would be exposed to a light flash from the fireball more than 3,000 times brighter than a desert sun at noon. The thermal radiation would melt and warp aluminum surfaces on aircraft. Interior sections of the aircraft illuminated by the fireball would burst into flames. The tires of the aircraft would catch fire, as would the tires and fuel hoses of service vehicles near the aircraft.

Three miles from ground zero

The Capitol, the House and Senate office buildings, and the Library of Congress are all about three miles from the Pentagon, and just beyond is Union Station. The Mall and the White House are closer. The monumental structures on Capitol Hill are among the strongest civilian buildings in the world: They are reinforced concrete, two- to 10-story buildings of earthquake-resistant design. The surrounding neighborhood mostly comprises private two -to four-story dwellings with brick, load-bearing walls, surrounded by many trees.

At the Capitol, the fireball would be as bright as a thousand suns and would deliver nearly three times the thermal energy deposited at the perimeter of the mass fire at Hiroshima. The Capitol is well constructed to resist fire and stands in an open space at a distance from other buildings, but it would probably suffer heavy fire damage. Light from the fireball shining through its windows would ignite papers, curtains, light fabrics, and some upholstery. The House and Senate office buildings would suffer greater damage—their interiors would probably burn, as would the area's adjacent residential buildings and trees.

Fire would be virtually everywhere within three miles of ground zero. Clothes worn by people in the direct line of sight of the fireball would burst into flames or melt, and uncovered skin would be scorched, charring flesh and causing third-degree burns.

It would take the blast wave 12–14 seconds after the fireball's light flash to travel three miles. At this distance, the blast wave would persist for well over two seconds and be accompanied by near-hurricane winds of 100 miles per hour. Buildings of heavy construction on Capitol Hill would suffer little or no structural damage, but all exterior windows would be shattered, and nonsupporting interior walls and doors would be severely damaged or blown down.

At a distance of 3.5 miles from the detonation, the light flash from the fireball would still be severe, delivering twice the thermal energy at the edge of the mass fire at Hiroshima. The light and heat to surfaces would approximate 600 desert suns at noon. Black smoke would effuse from wood houses as paint burned off wood surfaces and furnishings ignited.

At Union Station, not quite 3.5 miles from the Pentagon, the majestic front facade of glass would be smashed into razor-sharp projectiles. Curtains, table cloths, and other combustibles would ignite on the upper decks. Blast damage would not be nearly as severe as it would be closer to the point of detonation, but streets would be blocked with fallen debris. The scouring effects of the high winds accompanying the shockwave would loft dust into the air. Fires would be everywhere. Dust and smoke would create a dense, low-visibility, foglike environment, impeding the ability of individuals and emergency response teams to move about.

Even at this and greater distances from the detonation, fires would result from the tremendous release of thermal energy. Fires would also be started by the breakup of buildings from the blast wave and its accompanying winds.

Structural breakup would start fires by releasing flammable materials (gas, chemicals, and other hazards), by exposing and shorting electrical lines and equipment, and by exposing additional ignitable surfaces. These are "blast-disruption" fires. More ignitions would be caused by fire spread from radiant heat and from the winds accompanying the blast wave, which would carry firebrands. [5] In all probability, fires would be ignited to a distance of about 4.6 miles from the detonation—over an area of approximately 65 square miles.

A hurricane of fire

Within tens of minutes after the cataclysmic events associated with the detonation, a mass of buoyantly rising, fire-heated air would signal the start of a second and distinctly different event—a mass fire of gigantic scale and ferocity. The firestorm would quickly increase in intensity, generating ground winds of hurricane force with average air temperatures well above the boiling point of water. This would produce a lethal environment over a vast area.

The Pentagon is located near the relatively wide Potomac River, but fires would start simultaneously in large areas on both sides. The direction of fire winds in regions near the river would be modified by the water, but the overall wind pattern from these two huge and nearly contiguous fire zones would be similar to that of a single mass fire and will be treated as one.

The first indicator of a mass fire would be strangely shifting ground winds of growing intensity near ground zero. (Such winds are entirely different from and unrelated to the earlier blast-wave winds that exert "drag pressure" on structures.) These fire-winds are a physical consequence of the rise of heated air over large areas of ground surface, much like a gigantic bonfire.

The inrushing winds would drive the flames from combusting buildings horizontally toward the ground, filling city streets with hot flames and firebrands, breaking in doors and windows, and causing the fire to jump hundreds of feet to swallow anything that was not yet violently combusting. These extraordinary winds would transform the targeted area into a huge hurricane of fire.

Within tens of minutes, everything within approximately 3.5 to 4.6 miles of the Pentagon would be engulfed in a mass fire. The fire would extinguish all life and destroy almost everything else.

Firestorm physics

This description of the physics of mass fire is based on the work of a few scientists who have examined in detail the damaging effects of nuclear weapons, including nuclear engineer Theodore A. Postol and physicist Harold Brode. Postol is one of the country's leading non-government-funded technical experts on nuclear weapons, missiles, and arms control. Brode's five-decade career has been devoted to the study of nuclear weapons effects.

That mass fires have occurred, and that something like the firestorm described here *could* occur, is not in dispute. What is not widely accepted is that nuclear weapons detonated in urban or suburban areas would be virtually certain to set mass fires, and that the resulting damage is as predictable as blast damage. The much more widely held view is that the probability and range of mass fire depends on many unpredictable environmental variables, including rain, snow, humidity, temperature, time of year, visibility, and wind conditions.

But the work of Postol, Brode, and Brode's collaborators shows that mass fire creates its own environment. Except in extreme cases, environmental factors do not affect the likelihood of mass fire. Weather can affect the fire's range, but this can be reasonably well predicted. For nuclear weapons of approximately 100 kilotons or more, the range of destruction from mass fire will generally be substantially greater than from blast. The extraordinarily high air temperatures and wind speeds characteristic of a mass fire are the inevitable physical consequence of many simultaneous ignitions occurring over a vast area. The vacuum created by buoyantly rising air follows from the basic physics of combustion and fluid flow (hydro- or fluid dynamics). As the area of the fire increases, so does the volume of rising air over the fire zone, causing even more air to be sucked in from the periphery of the fire at increasingly higher speeds.

Only a few mass fires have occurred in human history: those created by British and U.S. conventional incendiary weapons and by U.S. atomic bombs in World War II. These include fires that destroyed Hamburg, Dresden, Kassel, Darmstadt, and Stuttgart in Germany, and Tokyo, Hiroshima, and Nagasaki in Japan. History's first mass fire began on the night of July 27, 1943, in Hamburg—created by allied incendiary raids. Within 20 minutes, two-thirds of the buildings within an area of 4.5 square miles were on fire. It took fewer than six hours for the fire to completely burn an area of more than five square miles. Damage analysts called it the "Dead City." Wind speeds were of hurricane force; air temperatures were 400–500 degrees Fahrenheit. Between 60,000 and 100,000 people were killed in the attack. [6]

A mass fire from a modern nuclear bomb could be expected to destroy a considerably larger urban or suburban area, in a similarly short time.

The unique features of the mass fire fundamentally distinguish it from the more slowly propagating line fire. Famous line fires include the great urban fires that destroyed London (1666), Chicago (1871), and San Francisco (1906); the forest fire that swept Peshtigo, Wisconsin (1871); the suburban fire that burned the Oakland, California, hills (1991); and the combined forest and suburban fires that recently devastated southern California (2003). [7] These fires were terrifying and destructive, but they were not mass fires. They burned and spread for days and were not ignited simultaneously over very large areas. They generated high temperatures and winds, but not on the scale or with the intensity of mass fires.

The dynamics of mass fire are grounded in Newtonian laws of conservation of mass, momentum, and energy; classical hydrodynamic equations can be applied to mass fire. A nuclear detonation ignites material that releases energy into a fluid—the atmosphere. The region of atmosphere being heated can be approximated as a thin disc-shaped volume near the earth's surface. By solving the hydrodynamic equations, it is possible to calculate the flow of rising air from the heated fire zone and the lateral inflow of cool air near the ground from just outside the periphery of the fire zone. These equations model the behavior of mass fire.

Fire environments created by mass fires are fundamentally more violent and destructive than smaller-scale fires, and they are far less affected by external weather conditions. They are not substantially altered by seasonal and daily weather conditions.

There are, of course, uncertainties in the damage ranges associated with the initiation and spread of mass fires, and variations in environmental conditions could contribute to these uncertainties. For example, the location of the perimeter of mass fire following a nuclear attack cannot be predicted precisely. How the topography or the weather might affect the range of mass fire is also uncertain. But uncertainty over the extent of damage associated with mass fire can be estimated and modeled, and this uncertainty is not greater than that associated with blast damage.

Moreover, for higher-yield weapons (more than 100 kilotons), under almost all conditions fire damage will be far more destructive than blast damage. In addition, "fire may cause more complete and permanent damage. A structure only moderately damaged by blast may be gutted and rendered useless by fire. Similarly, building contents may survive the blast but be destroyed by the fires." [8]

What effect could the weather have on the probability and range of mass fire? Reductions in visibility because of rain, fog, haze, or smoke could absorb or scatter thermal radiation from the detonation and reduce or attenuate the amount that would reach exposed structures, equipment, and people. But even with a reduction in visibility from 10 miles to five (from the visibility of a relatively clear day to a misty rainy day), enough thermal energy would be delivered to set a mass fire out to three miles from ground zero. Even with visibility reduced to two miles, the flash would set a mass fire out to 2.2 miles from ground zero. (Visibility in the Washington, D.C., area is 10 miles or greater about 64 percent of the time. Visibility is five miles or greater 90 percent of the time, and visibility is two miles or greater 98.5 percent of the time.) [9]

The flash from the fireball from a 300-kiloton detonation would set a mass fire under virtually all weather conditions.

If the ground were snow-covered, vegetation covered by snow would not be ignited at first, but light and heat from the fireball would be reflected by the snow, roughly doubling the amount of light entering building windows. Further, during periods of cold weather when snow cover would be a factor, the warm interiors of buildings have very low relative humidities, greatly increasing the likelihood of ignitions. The mass fire set at Dresden in February 1945 by non-nuclear incendiary weapons occurred in "winter with snow on the ground. It was cold and wet and cloudy outside, but there was fuel inside where it was warm and dry." Similarly, in the first incendiary attack on Tokyo, in February 1945, the city "was covered by snow . . . but about one square mile was burned out." [10]

If a nuclear weapon were detonated below cloud cover, reflections off the clouds would increase the light shining into buildings by a factor of about two. When there is both snow and cloud cover, light reflected could intensify the fire-initiating fireball flash roughly by a factor of four.

Only if detonations occurred at altitudes above cloud cover or in periods of very intense rain or heavy ground fog would the size of the fire zone be as small as the zone of severe blast damage.

Severe weather conditions in Washington, D.C., are rare and can be taken into account by military war planners. More generally, the likelihood of severe weather is known for many locations and time of year. In addition, real-time or near real-time weather data have been available on a global basis for decades. The U.S. military maintains its own weather satellites to forecast cloud cover, predict low-altitude weather systems, and collect wind data.

Because of the many ways fires can start and spread, it is reasonable to assume that a mass fire with a radius of at least 3.5 miles would occur in all but the most extreme weather conditions. The fire would generate its own extremely intense winds; air temperatures would be so high that wet surfaces would quickly dry, and the relative humidity within the fire zone would be very low. Such a fire would be only weakly influenced by external weather conditions.

Blast and fire damage

In the late 1970s, Brode and a team of scientists at Pacific-Sierra Research began to investigate the possibility of incorporating the effects of fire into damage prediction for nuclear targeting under contract for the Defense Nuclear Agency. By the late 1980s, Brode and his colleagues thought they had developed an analytical basis for predicting fire and blast damage from nuclear weapons. But in early 1992, federal funding for the nuclear fire and blast damage studies begun by Brode was canceled. (The issue was later revisited and, as far as I know, remains under consideration.) If the U.S. government were to take both fire and blast into account, its predictions regarding nuclear weapons damage would have to change.

We can see how great the changes would be by comparing the differences in damage predicted by the above hypothetical scenario, which takes into account both blast and fire damage, with the results of the method used by the U.S. government, which predicts only blast damage. For many targets, although not all, the differences are great.

The government's way of predicting damage to structures, installations, and equipment uses the *Physical Vulnerability Handbook—Nuclear Weapons*, published by the Defense Intelligence Agency. It exists in a number of editions, from 1954 to 1992. [11] The *Handbook* characterizes structures in terms of their physical vulnerability to blast effects using "vulnerability numbers" (VNs) at specified damage levels. [12] Physical vulnerability sounds like the opposite of the widely used term "target hardness," but for all practical purposes it is the same: A target is strong, or hard, up to the point at which it is vulnerable, or fails. Physical vulnerability is stated in terms of level of damage that the structure would be expected to sustain at a given overpressure—severe, moderate, or light damage. Severe structural damage is defined as "that degree of structural damage to a building which precludes further use of the building for the purpose intended without essentially complete reconstruction or replacement. A building sustaining severe structural damage requires extensive repair before it can be used for any purpose." Moderate damage is "that degree of structural damage to principal load-bearing members . . . of a building which precludes effective use of the building for the purpose intended until major repairs are made." [13] The *Handbook* does not describe light structural damage for buildings, presumably because such damage would not be severe enough to bother with in targeting calculations.

Despite the sophisticated understanding of blast waves and structural response embedded in the government's vulnerability number system, for many types of targets the total damage that would occur in a nuclear attack is vastly understated because only blast damage is taken into account.

Take, for example, a target of interest to military planners—an aircraft carrier. The *Handbook* gives aircraft carriers a VN of 11P0 for moderate damage. (In this code, 11 is a rating of target hardness that translates to blast pressure; P indicates a type of target that responds mainly to overpressure, not drag pressure; 0 means the target is not sensitive to the duration of blast pressure.) At this rating, according to the government's method of calculating damage the aircraft carrier would sustain "about half loss in ability to deliver weapons effectively, because of damage to equipment or topside structure, or because of personnel casualties." The carrier's target-acquisition and communication equipment, however, are predicted to be operative. [14]

This code corresponds to blast-wave pressure that in a 300-kiloton nuclear weapon attack on the Pentagon would occur about 1.6 miles from ground zero. For purposes of illustration, such a target could be located in the Potomac River near Reagan National Airport. On an aircraft carrier at this range, the thermal flash would be more than 4,000 times brighter than a desert sun at noon, and the winds would be over 250 miles per hour. The light flash would ignite clothing, rubber, and exposed petroleum products; seven seconds later, the blast wave and winds would overturn and break up the carrier's fuel-laden planes. Under these conditions, the carrier could become a floating inferno. It is highly unlikely that sailors on it would be able to deliver half of its weapons effectively.

Damage to aircraft on the carrier and a little farther away at Reagan National Airport is also underestimated. According to the *Handbook*, light fighter and bomber aircraft located about 1.8 miles from a detonation and oriented "nose-on" toward it would sustain only "light damage," which it describes as "structural failure of small control surfaces, bomb bay doors, wheel doors, fuselage skin damage, and damage due to flying debris. Requires one to four hours repair but may permit limited flight." At this distance, the blast wave would cause the complete collapse and disintegration of typical two-story wood-frame and brick buildings. The winds accompanying the blast would be a little less than 220 miles per hour. Given that aircraft routinely fly into winds of several hundred miles per hour, we can see how the *Handbook* might arrive at such a prediction of damage.

But when the thermal effects are considered, "light damage" is understated. At a range of 1.8 miles, the light flash from the bomb would be thousands of times brighter than a noonday sun. The surfaces of the aircraft would warp and melt and tires and other components would burst into flames, rendering the aircraft inoperable.

These targets would be deep within the perimeter of mass fire. Farther away from the detonation, the built-up areas of Capitol Hill would be engulfed in a mass fire that would extinguish all life and destroy nearly all buildings and residences, large or small. Only the Capitol and some similarly monumental buildings on the Mall might be spared from complete destruction.

According to the calculations used in the *Handbook*, for a 300-kiloton detonation, severe damage could be expected against such massive buildings only if they were one mile from the detonation, and moderate damage only if they were within 1.2 miles.

What level of damage would the *Handbook* predict for the buildings on Capitol Hill, approximately three miles from the Pentagon? At this range, blast pressure and wind forces would not meet the government's criteria for achieving severe or moderate damage. But fire would cause damage that would be severe indeed.

Even if visibility were below two miles, an area of 12–15 square miles would be destroyed. This is two to three times the area destroyed in the incendiary attack on Hamburg in 1943. If visibility were five miles or greater, an area of approximately 25–45 square miles would burn. On a clear day, when visibility is 10 miles or greater, 40–65 square miles would burn.

Average air temperatures in the burning areas after the attack would be well above the boiling point of water; winds generated by the fire would be hurricane force; and the fire would burn everywhere at this intensity for three to six hours. Even after the fire burned out, street pavement would be so hot that even tracked vehicles could not pass over it for days, and buried, unburned material from collapsed buildings could burst into flames if exposed to air even weeks after the fire.

Those who sought shelter in basements of strongly constructed buildings could be poisoned by carbon monoxide seeping in, or killed by the ovenlike conditions. Those who tried to escape through the streets would be incinerated by the hurricane-force winds laden with firebrands and flames. Even those able to find shelter in the lower-level sub-basements of massive buildings would likely die of eventual heat prostration, poisoning from fire-generated gases, or lack of water. The firestorm would eliminate all life in the fire zone.

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1. I have written this in close consultation with Theodore A. Postol; Alex Montgomery also provided technical guidance. Sources include: Samuel Glasstone and Philip J. Dolan, eds., *The Effects of Nuclear Weapons*, 3d ed. (Washington, D.C.: U.S. Government Printing Office [GPO], 1977); Theodore A. Postol, "Possible Fatalities from Superfires following Nuclear Attacks in or near Urban Areas," in Fredric Solomon and Robert Q. Marston, eds., *The Medical Implications of Nuclear War* (Washington, D.C.: National Academy Press, 1986), pp. 15–72; Theodore A. Postol, "Targeting," in Ashton B. Carter, John D. Steinbruner, and Charles A. Zraket, eds., *Managing Nuclear Operations* (Washington, D.C.: Brookings Institution, 1987), pp. 373–406; Lachlan Forrow et al., "Accidental Nuclear War—A Post–Cold War Assessment," *New England Journal of Medicine*, vol. 338, no. 18 (1998): 1326–1331; R. D. Small and H. L. Brode, *Physics of Large Urban Fires*, PSR Report 1010, final report for Federal Emergency Management Agency, Washington, D.C. (Santa Monica, Calif.: Pacific-Sierra Research Corp., March 1980); H. L. Brode, G. P. Fisher, P. F. X. Konokpa, A. Laupa, and G. E. McClellan, *Fire Damage to Urban/Industrial Targets*, vol. 1, Executive Summary, and voluminous unclassified material from vol. 2, *Technical Report*, PSR Report 1936, prepared for Headquarters Defense Nuclear Agency, Washington D.C. (Los Angeles: Pacific-Sierra Research Corp., 1989).

2. Glasstone and Dolan, *Effects of Nuclear Weapons*, list the yield of the bomb at Hiroshima as 12.5 kilotons; in *United States Nuclear Tests, July 1945 through September 1992*, DOE/NV-209-Rev. 15 (Las Vegas: Energy Department, Nevada Operations Office, December 2000), p. xi, the Energy Department lists the yield at Hiroshima as 15 kilotons. Both publications list the yield of the Nagasaki bomb as 21 kilotons.

3. See, for example, "Preview of the War We Do Not Want," special issue of *Collier's* (October 27, 1951).

4. Postol, "Possible Fatalities from Superfires," pp. 59–66.

5. Harold L. Brode and Richard D. Small, *Fire Damage and Strategic Targeting*, PSR Note 567, sponsored by Defense Nuclear Agency, Washington, D.C. (Los Angeles: Pacific-Sierra Research

Corp., June 1983), pp. 10–21; Brode et al., *Fire Damage to Urban/ Industrial Targets*, vol. 1.

6. On Tokyo, see U.S. Strategic Bombing Survey, Physical Damage Division, *Effects of Incendiary Bomb Attacks on Japan, a Report on Eight Cities* (n.p., April 1947), pp. 65–117. On Hamburg, see Postol, "Possible Fatalities from Superfires," pp. 52–53; and the broader treatment by Horatio Bond, "The Fire Attacks on German Cities," in Bond, ed., *Fire and the Air War* (Boston: National Fire Protection Association, 1946), pp. 76–97.

7. See Stephen J. Pyne, *Fire in America: A Cultural History of Wildland and Rural Fire* (Princeton: Princeton University Press, 1992). On the power of a single forest fire, see the American classic by Norman Maclean, *Young Men and Fire* (Chicago: University of Chicago Press, 1992).

8. Brode and Small, *Fire Damage and Strategic Targeting*, pp. 32, 22.

9. These figures are based on a decade of hourly weather observations at Reagan National Airport. See Federal Climate Complex, Asheville, N.C., U.S. Navy–U.S. Air Force, Department of Commerce, *International Station Meteorological Climate Survey*, prepared under authority of Commander, Naval Oceanography Command, Version 1.0, October 1990. I thank Benjamin Olding for finding these data.

10. Harold Brode, phone conversation with author, August 11, 1989; see also Small and Brode, *Physics of Large Urban Fires*, p. 18; and H. L. Brode and R. D. Small, "A Review of the Physics of Large Urban Fires," in Solomon and Marston, *The Medical Implications of Nuclear War*, p. 83. Robert Nathans, "Making the Fires That Beat Japan," in Bond, *Fire and the Air War*, p. 141.

11. I draw on a copy of the handbook marked "unclassified" (originally classified as confidential) from the late 1960s and early 1970s.

12. See Lynn Eden, *Whole World on Fire: Organizations, Knowledge, and Nuclear Weapons Devastation* (Ithaca: Cornell University Press, 2003), chapter 7, for discussion of how VNs were used to produce the VN coding system, which has been used in all the physical vulnerability handbooks after 1954. See also the explanation of the VN system in the detailed study of U.S. nuclear war planning by Matthew G. McKinzie, Thomas B. Cochran, Robert S. Norris, and William M. Arkin, *The U.S. Nuclear War Plan: A Time for Change* (New York: Natural Resources Defense Council, June 2001), www.nrdc.org.

13. DIA, *Physical Vulnerability Handbook–Nuclear Weapons*, AP-550-1-2-69-INT (Washington, D.C.: DIA, 1969, with change 1 [1972] and change 2 [1974]), p. I-3.

14. Ibid., p. I-20.

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