Environmental Consequences of Nuclear War Volume I:
Physical and Atmospheric Effects
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CHAPTER 1
Direct Effects of Nuclear Detonations

1.1 HIROSHIMA AND NAGASAKI

1.1.1 Historical Notes

The first atomic weapon used in warfare was the bomb dropped on Hiroshima, Japan at 8:15 AM (local time) on August 6, 1945. The second, and only other, weapon so used was dropped on Nagasaki, Japan at 11:02 AM on August 9, 1945. The Hiroshima bomb (Little Boy) had an energy yield of about 15 ± 3 kilotons (kt; a one kt explosion is equivalent in energy release to the detonation of about 1000 tons of TNT; one megaton, Mt, equals 1000 kT). The Nagasaki bomb (Fat Man) had an energy yield of 21 ± 2 kilotons (Ohkita, 1985). From these unique events, much of what is known about the effects of nuclear explosions on people and cities has been learned. About 120,000 people were killed outright in both cities, and the eventual fatalities, as of 1981, were about 210,000 (Ishikawa and Swain, 1981). In Hiroshima, an urbanized area of approximately 13 square kilometers was laid to waste, while in Nagasaki, an area approximately 7 square kilometers was destroyed. Figure 1.1 starkly illustrates the extent of the devastation in central Hiroshima; only the hulks of the most resilient steel-reinforced concrete buildings were left standing.

1.1.2 Physical Effects of the Bombings

Both the Hiroshima and Nagasaki nuclear explosions were airbursts—at elevations of 580 meters and 500 meters, respectively. These heights are near optimal for thermal irradiation and blast damage, but produce relatively little radioactive fallout because the fireball does not touch the ground (see below). The most immediate consequence was the intense thermal irradiation "pulse", which caused serious skin burns and primary fire ignitions at distances of up to several kilometers from the hypocenter. The blast pressure wave that immediately followed caused severe damage to structures at distances of 2 km at Hiroshima and 3 km at Nagasaki. While many of the primary fires were suppressed by the blast winds, numerous "secondary" ignitions occurred through breaches of domestic fires, electrical short

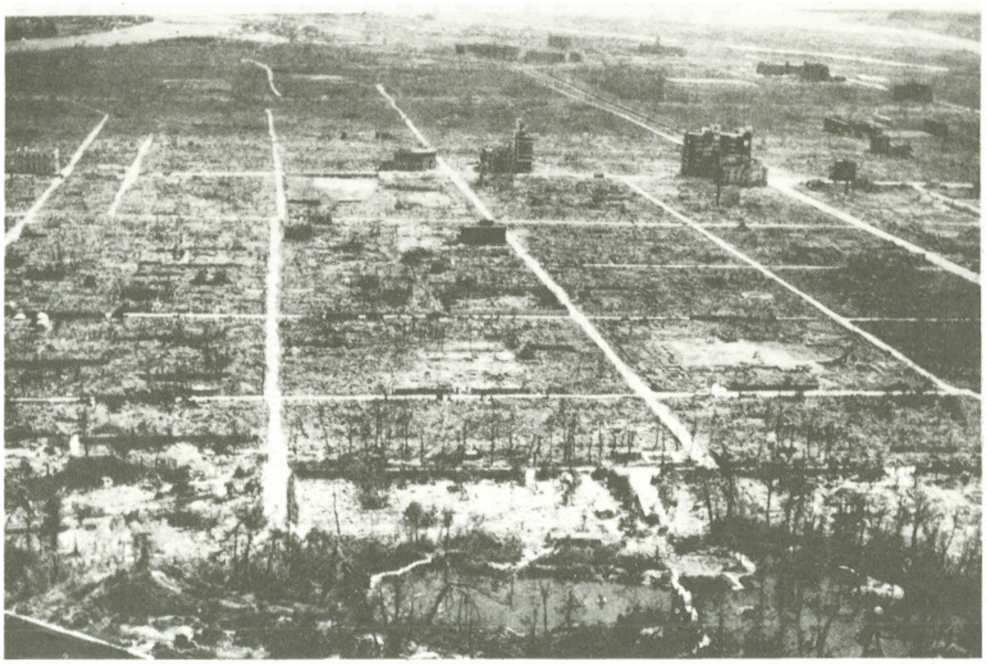

Figure 1.1 Panoramic view of Hiroshima following the atomic bomb explosion of August 6, 1945. In the few standing structures of reinforced concrete, the interiors were totally gutted and burned. Reproduced by permission of Popperfoto

circuits, and so on. As a result of the combined thermal irradiation, blast damage and loss of water pressure, firefighting was made all but hopeless, mass fires developed in the ruins of both cities, and burned out large areas within 24 hours.

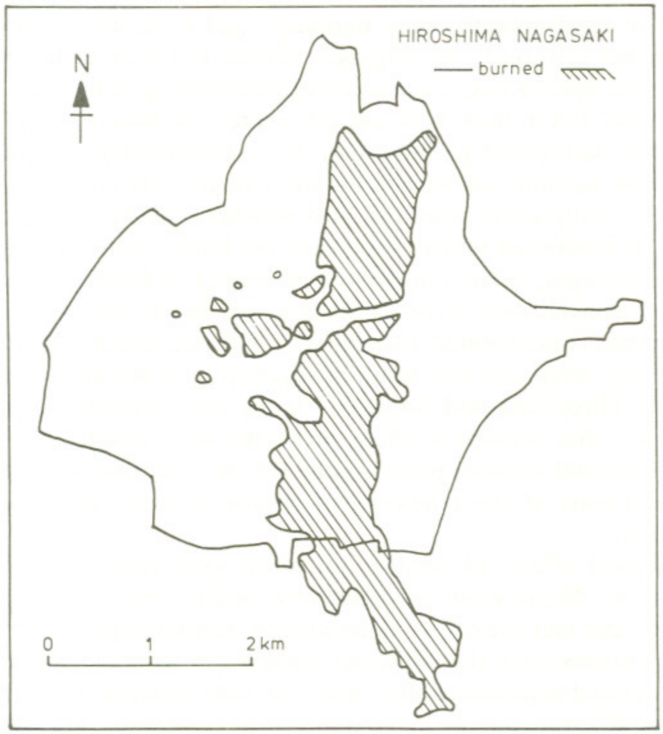

Figure 1.2. Comparison of fire-damaged areas in Hiroshima and Nagasaki (from Kiuchi, 1953, and Ishikawa and Swain, 1981). Originally published in Japanese by Iwanami Shoten, Publishers, Tokyo. Reproduced by permission of Hiroshima City and Nagasaki City

Figure 1.2 compares the burnout areas at Hiroshima and Nagasaki. These areas are often quoted as 13 km^2 and 6.7 km^2, respectively (Ishikawa and Swain, 1981). There are several important features of the fire patterns shown in Figure 1.2. At Hiroshima, with its relatively flat topography, the fire zone was roughly symmetrical about the burst point and encompassed essentially all of the area heavily damaged by the blast. Fire spread outside of this zone may have been hindered by the centrally directed winds established during the intense fire that appeared soon after the bombing. At Nagasaki, which lies at the mouth of a river valley, the fires were confined within the valley. To the east and west, hills protected the regions beyond from the most severe effects of thermal irradiation and blast. To the south, fire ignition and spread were limited by open waters. Although the fire area at Nagasaki was smaller than that at Hiroshima, the burned out area in the direction of urban development extended a greater distance from the hypocenter, which is consistent with the larger bomb yield. The fire zones reached well beyond the zones of total demolition of buildings, and even the regions of dense rubble burned vigorously. In Nagasaki, the central zone of heavy industry, with its broad open areas, was also extensively damaged by fire.

"Black rain" fell in both Japanese cities after the atomic bombings. From the recorded patterns of precipitation, it is clear that the rain was induced by convective motions established by the mass fires. In both Hiroshima and Nagasaki, typically warm humid August weather prevailed at the time of the bombings. It is believed that a "firestorm" (an intense mass fire with strongly rotating, converging winds) may have developed at Hiroshima, with attendant strong convective activity (Ishikawa and Swain, 1981). A thundering cumulonimbus cloud formed over the city. The rain which fell was, at times, black and oily, obviously as a result of scavenging of smoke and charred fire debris. The Hiroshima and Nagasaki "black rain" events provide qualitative evidence that prompt washout of smoke in city-sized fires can occur (at least in humid environments), although no quantitative measurements or estimates exist of the efficiency of smoke removal in the fire-induced precipitation.

Physiological effects of nuclear radiation were observed in Hiroshima and Nagasaki. Because of the relatively small sizes of the first atomic bombs, and the fact they were detonated as airbursts, prompt gamma rays and fast neutrons were the principal nuclear radiations to produce effects. Gamma rays and neutrons cannot penetrate long distances through air at sea level—several kilometers is the effective limit (Glasstone and Dolan, 1977). Accordingly, individuals who were close enough to ground zero to receive a lethal dose of prompt nuclear radiation were more likely to have been killed outright by the blast or thermal flash. Nevertheless, cases of radiation sickness appeared frequently among the survivors in Japan (Ishikawa and Swain, 1981).

Some deposition of radioactive fission debris ("fallout") occurred at Hiroshima and Nagasaki. The black rain in both cities apparently washed out a small fraction of the airborne radioactive aerosols (Molenkamp, 1980). The consequences of this radioactive fallout (in combination with the residual radioactivity induced by the weapon's fast neutrons) are not well defined. The maximum total whole-body gamma ray doses accumulated by survivors are estimated to have been about 13 rads in Hiroshima and 42 to 129 rads in Nagasaki (Shimazu, 1985). For such doses, physiological effects would not be readily identifiable (see the discussion of the effects of radiation on humans in Chapter 7).

1.1.3 Lessons of Hiroshima and Nagasaki

The atomic explosions in Japan in 1945 offer several clear lessons:

1. The destructive power of nuclear weapons is immense—a single bomb can destroy an entire city in a matter of seconds. This is particularly true since the yield of a typical strategic warhead is now at least ten times greater than the Hiroshima or Nagasaki bombs.
2. Nuclear weapons are efficient long-range incendiary devices—all of the area subject to blast damage is susceptible to burnout in conflagrations.
3. The atmosphere over a large region is affected by a nuclear explosion: smoke and dust are lofted, clouds form, precipitation may occur, and radioactive debris is dispersed through the environment.
4. The human impacts of nuclear explosions can be enormous—physical injuries from the blast, severe burns from the heat rays, exposure to radiation, psychological trauma—in addition to the long-term effects discussed elsewhere in this report.

A survey is made below of the basic processes of nuclear detonations that are relevant to an assessment of the potential global-scale physical effects of nuclear war. The biological implications are discussed at length in Volume II of this report.

1.2 THERMAL IRRADIATION

1.2.1 Fireball

Upon detonation, a nuclear fission weapon disassembles and vaporizes within one millionth of a second (Glasstone and Dolan, 1977). At that time, about 70 to 80% of the energy has been converted into "soft" X-rays with an effective radiation temperature of several tens of millions of degrees Celsius; most of the remaining energy comprises kinetic energy of the bomb debris. At sea level, the primary thermal X-radiation is absorbed by the air within several meters of the device, heating the air and forming an embryonic fireball. This enormously hot sphere continues to expand rapidly by radiative transfer to the surrounding ambient atmospheric gases. As the fireball grows and cools to about 300,000°C, the thermal irradiation becomes less penetrating, and the radiative fireball growth slows. At this point, a shock wave forms and propagates ahead of the fireball ("hydrodynamic separation"). The shock-heated air is opaque and luminous and shields the direct radiation of the fireball. However, as the shock wave continues to expand, the temperature of the shock-heated air decreases and it becomes less opaque. At about 3000°C, the thermal irradiation of the fireball again becomes visible through the shock front ("breakaway"). From a distance, the apparent radiation temperature then increases rapidly to the temperature of the fireball, which is about 7500°C (approximately the temperature of the Sun's surface), before decreasing again as the fireball continues to cool by radiation, expansion, and entrainment of ambient air.

Corresponding to the formation and growth of the fireball, two pulses of thermal irradiation are emitted. Together, these carry away about 35% of the total energy of the explosion, mainly as visible and near-infrared radiation (spectrally, the average emission is very similar to sunlight). The first pulse of light originates from the shock wave front (attenuated to some degree by ozone and nitrogen oxides generated ahead of the shock wave by prompt penetrating nuclear radiation). The timescale for the first emission is of the order of milliseconds, and it carries only about 1% of the total thermal energy. While this pulse has little incendiary effect, it can damage the retina of the eye. The second burst of light, the true "thermal pulse", commences as the shock wave becomes transparent and the incandescent fireball is revealed. The time scale for this emission is of the order of seconds, and its duration tends to increase with yield. Almost all of the thermal emission (about 35% of the total energy yield of the explosion) is liberated during this pulse.

For burst heights between the surface and roughly 30 km, the basic explosion phenomenology remains essentially unaltered. In this regime, the overall energy partition of a nuclear fission explosion is: thermal irradiation, 35%; blast and shock, 50%; initial or prompt nuclear radiation, 5%; residual nuclear radiation, 10%. In quoting the energy yield of a nuclear explosion, the energy of the residual nuclear radiation, i.e., that released by nuclear decay beyond the first minute, is generally omitted. For a fission weapon this is approximately 10% of the total energy yield, and for a fission/fusion weapon, approximately 5%. Typical thermonuclear devices are driven by roughly 50% fission and 50% fusion energy; most of the fission yield results from the disintegration of a heavy shield of ^{238}U used as an X-ray and neutron reflector for the fusion stage. Except for radioactive fallout, the distinction between fission and fission/fusion weapons is unimportant in the present analysis (see Chapter 7).

1.2.2 Thermal Effects

The intense thermal irradiation from a nuclear fireball, emitted at visible wavelengths, can readily ignite a fire, much as does sunlight focused by a lens. Hence, the first effect of a nuclear explosion is to ignite "primary" fires over a large area (where kindling fuels are exposed). The radiant energy from a nuclear detonation impinging on an object can be expressed as a fluence in calories per square centimeter; that is, the energy per unit area perpendicular to the surface of the object, integrated over wavelength and time for the duration of the thermal pulse. A 1-Mt airburst, which is equivalent in energy release to detonation of about a million tons of TNT, can ignite newspaper and leaves at 6 cal/cm^2, fabrics at 15 cal/cm^2, and roofing and wood at 30 cal/cm^2 (Glasstone and Dolan, 1977). The fluence required to ignite a material depends weakly on the explosion yield for yields ≤ 1 Mt. Generally, the lower the yield, the less fluence that is needed for ignition. This occurs because larger yield explosions have longer thermal pulses, which are somewhat less efficient at heating and igniting bulk materials at modest levels of fluence. The size, shape, color, and orientation of an object also affects its flammability by the thermal flash.

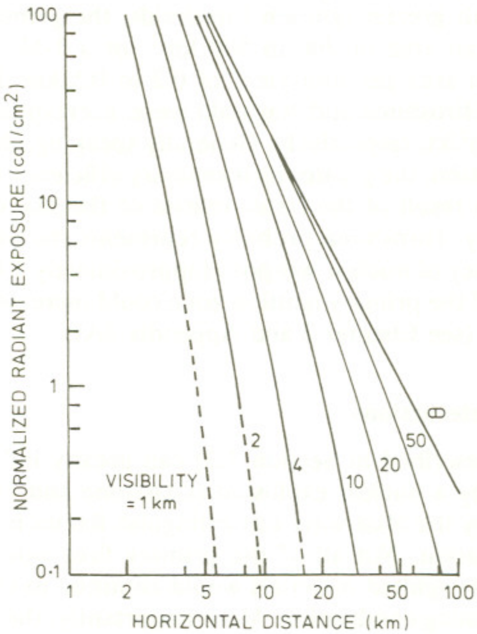

Figure 1.3. Maximum radiant exposures versus ground range for a 1 Mt airburst (detonated between about one and several kilometers altitude) as a function of the ground level visibility. The radiant exposures scale roughly with the yield in megatons for yields between 0.1 and 1 Mt (from Kerr et al., 1971)

Figure 1.3 provides an estimate of the thermal fluences associated with a 1-Mt low-altitude airburst as a function of distance from ground zero for several different atmospheric visibilities. A surface burst produces thermal fluences that are roughly 50% of those of an airburst for yields between 0.1 and 10 Mt (Glasstone and Dolan, 1977). Within several kilometers of a 1-Mt explosion, the thermal fluence can exceed 100 cal/cm^2. The actual energy flux on a surface may be much lower, however, because of (a) the shading of surfaces by topography, structures, and vegetation; and (b) the attenuation of the fireball radiation by steam, smoke, and dust raised from vegetation and soil by the thermal irradiation and blast. Fireball radiation can also be scattered and focused by clouds, dust and steam, accentuating thermal effects over a large area around the burst point and possibly causing isolated ignitions well beyond the perimeter of the nominal zone of thermal effects.

The thermal pulse of a 1-Mt fireball can ignite primary fires over an area of 1000 square kilometers when the atmosphere is exceptionally clear and dry flammable materials (with ignition thresholds of approximately 5–10 cal/cm^2) are present (Figure 1.3). For more typical visibilities, and for substances with greater ignition thresholds, the primary ignition zone may extend over an area of 200 to 500 km^2 for a 1-Mt airburst (equivalent to an ignition area per unit yield of 0.2 to 0.5 km^2/kt) (NRC, 1985). The fire areas at Hiroshima and Nagasaki were, correspondingly, about 0.9 km^2/kt and 0.3 km^2/kt, respectively. Generally speaking, the lower the yield of a nuclear explosion, the greater its incendiary efficiency (ignition area per kiloton). This is a result of the faster release of thermal energy and lesser impact of visibility. Hiroshima probably represents the maximum primary incendiary efficiency of nuclear weapons (approximately 1 km^2/kt), although fire spread beyond the primary ignition zone could increase the effective fire area considerably (see Chapter 3 and Appendix 3A).

1.2.3 Blast/Fire Interactions

Blast effects (described in Section 1.3) can greatly influence the course of fires initiated by a nuclear explosion (Glasstone and Dolan, 1977). The winds generated by the blast wave can extinguish flames in materials ignited by thermal irradiation. Not all of the primary fires would be blown out, however, and many ignited materials would continue to smolder and eventually rekindle flaming combustion. More importantly, the blast wave causes secondary fires, creates conditions favorable to fire spread, and hinders effective firefighting, but can also bury burnable material under non-combustible rubble. In Hiroshima and Nagasaki, secondary ignitions were apparently as important as primary ignitions in the mass fires which developed (Ishikawa and Swain, 1981). Secondary fires result from electrical short circuits, broken gas lines, breaches of open flames, and similar effects. Typically, about one secondary fire is expected for every 10,000 square meters of building floor space (Kang et al., 1985, see also Appendix 3A). In general, blast damage would facilitate fire spread and hinder efforts to suppress the fire. Fires can propagate more effectively through buildings with broken windows, doors, and firewalls, across natural firebreaks breached by flammable debris, and along flows of spilled liquid and gaseous fuels and petrochemicals. With the additional burden of large numbers of injured personnel, widespread fire ignitions, blocked streets, and loss of water pressure, meaningful firefighting efforts could not be mounted. This was precisely the situation that arose in Hiroshima and Nagasaki (Ishikawa and Swain, 1981).

In urban/industrial regions close to the explosion hypocenter, even buildings of heavy construction could be reduced to rubble. Nonflammable debris, such as concrete and steel, would cover some of the flammable materials. However, zones of thick rubble (formed in tracts that are very densely built-up) would probably account for less than 10% of the total area of destruction and fire (NRC, 1985), although they could contain a disproportionately high areal density of combustible material. However, even within this central zone, many materials would be instantly ignited by the intense thermal irradiation in "flashover" fires (an effect observed during the Encore nuclear test—27 kt, Nevada Test Site, May 8, 1953—in which an entire room was ignited simultaneously, that is, "flashed over", within seconds of irradiation). These "instantaneous" fires would continue to spread and smolder in the rubble. Because of the Encore effect and the other known incendiary effects of nuclear weapons, it is expected that all urbanized areas, from modern city centers to spacious suburban zones, from commercial tracts to industrial parks would be subject to burning by nuclear explosions (NRC, 1985).

Forests, agricultural lands, and wildlands are also susceptible to complex nuclear fire effects. Thermal irradiation not only ignites dry fuels, but also dessicates moist fuels and live vegetation (Kerr et al., 1971), making them more susceptible to fire. The blast wave extinguishes some fires, but also spreads firebrands. Blast-induced winds can knock down foliage and branches (blowdown) not usually involved in wildfires; on relatively flat terrain, a 1-Mt airburst causes such damage over an area of roughly 500 km^2 in foliated deciduous forests, and over about 350 km^2 in leafless deciduous stands and unimproved coniferous forests (Glasstone and Dolan, 1977). The simultaneous ignition of fuels over a vast area by thermal flash, the dessicating effect of the thermal pulse on vegetation, and the augmentation of ground fuel by blowdown imply that nuclear-initiated wildland fires could be more easily ignited, consume more fuel, and burn more intensely than natural wildfires (NRC, 1985). At the present time, only historical information gathered on natural and prescribed wildland fires is available to estimate the extent and effects of the wildland fires that would be ignited in a nuclear conflict. A very large seasonal variation in the susceptibility of wildlands to fire is expected, with fewer fires likely in the winter. Historically, seasonal variations in fire occurrence in urban areas have been much less significant (Chandler et al., 1963).

A number of additional technical issues related to nuclear-initiated fires and smoke production are discussed in Chapter 3.

1.3 DYNAMIC PHENOMENA OF NUCLEAR EXPLOSIONS

1.3.1 Shock Wave in Air

As explained in Section 1.2.1, the air shock wave of a nuclear explosion begins to move away from the fireball at the time of hydrodynamic separation. Thereafter, it acts as a simple pressure wave in air. For low altitude explosions, the shock wave is also reflected from the surface; the incident and reflected waves may then combine to form a "Mach stem", in which the shock pressures are roughly twice the incident values. For bursts below about 30 kilometers, approximately 50% of the total energy of a nuclear explosion is carried away by the shock waves.

One measure of the destructive power of a nuclear explosion is the peak overpressure it creates at various distances from the hypocenter. The peak overpressure in the shock wave is the maximum increase of static air pressure over ambient atmospheric pressure. The overpressure is usually measured in pounds per square inch in the American literature (psi; 1 psi = 6.9 kPa; the mean atmospheric pressure at sea level is 14.7 psi). Figure 1.4

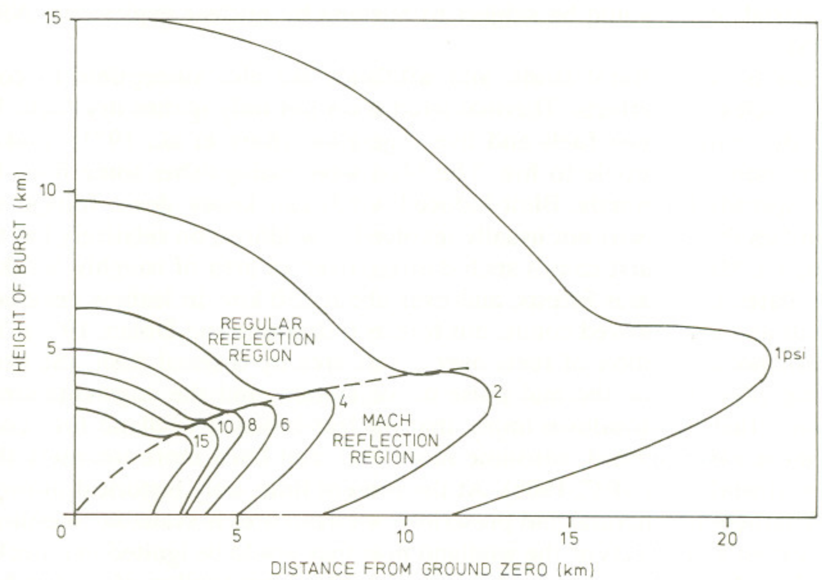

Figure 1.4. Peak blast overpressure at the ground in pounds per square inch (psi; 1 psi = 6.9 kPa) for a 1 Mt detonation as a function of the distance from ground zero and the height-of-burst. For other explosive yields, the distance and height-of-burst scale as $Y^{1/3}$ where Y is the yield in megatons. For example, in the case of a 1 kt explosion, all lengths would be multiplied by 0.1 (from Glasstone and Dolan, 1977)

illustrates the peak overpressure produced by a 1 Mt detonation as a function of distance from ground zero and height-of-burst (HOB). For a given overpressure, there is generally an optimum HOB to maximize the range for that overpressure. However, very close to the explosion, nearly identical peak overpressures can be achieved for bursts at the surface to a moderate height above the surface.

The blast wave also produces sudden outward displacements of air and large peak dynamic (wind) pressures. A physical relationship exists between the peak overpressure, peak dynamic pressure, and maximum wind speed (Glasstone and Dolan, 1977). At a peak overpressure of 100 psi, the peak dynamic pressure is 120 psi and the maximum wind velocity is 630 m/s (2270 km/h); at 10 psi, it is 2.2 psi and 130 m/s (470 km/h), respectively; and at 2 psi, it is 0.1 psi and 30 m/s (110 km/h), respectively. (By comparison, the winds in severe tropical cyclones reach velocities of 150 to 250 km/hr). It follows that, for wind sensitive structures, the importance of dynamic pressure relative to overpressure increases with proximity to the explosion.

1.3.2 Ground Shock

Nuclear airbursts create ground shock when the blast wave impacts the surface and induces ground motions. Surface and subsurface explosions efficiently couple energy directly into the ground and create strong local ground shock. The air blast accompanying surface and near surface bursts also produces significant ground shock away from the detonation site (Glasstone and Dolan, 1977). In deep underground explosions, energy is converted directly into ground shock waves; air blast has little importance.

Underground explosions may induce aftershocks and displacements along faults originating near the detonation site (Glasstone and Dolan, 1977). However, analyses of seismic records following megaton-range deep underground nuclear explosions at the Nevada Test Site and at Amchitka Island in the Aleutians show no major anomalous earthquake activity. Another possible groundshock hazard is related to hillslope instability and landslides that might be triggered by nuclear detonations (Bennett et al., 1984). The effects of earthquakes and landslides are dependent on detailed geological conditions near the explosion sites, and must be evaluated individually.

1.3.3 Blast Damage

The atomic explosions at Hiroshima and Nagasaki starkly revealed the destructive power of nuclear blast (Figure 1.1). All structures are vulnerable (Glasstone and Dolan, 1977). Residential wood-frame houses (with wood or brick exteriors) suffer substantial damage at 2 psi peak overpressure, and are crushed at 5 psi. Glass windows are shattered at 0.5 to 1.0 psi. Concrete and steel buildings are broken apart at 10–15 psi (although the interiors and facades are destroyed at much lower overpressures). Aircraft, parked or in flight, are susceptible to significant damage at 1–3 psi. Splitting of liquid storage tanks occurs at 3 to 10 psi, depending on their size and fluid level (a tank is generally less vulnerable if it is larger and fuller).

Flying debris is a major cause of damage in a nuclear explosion. People are particularly vulnerable to flying objects. For example, while the human body can withstand substantial static overpressures (greater than 10 psi is required to produce severe injuries), serious wounds due to flying glass and rubble can occur at 1–2 psi.

Blast damage also leads to secondary fire ignition, as previously noted. From the nature of the blast damage, it follows that secondary fires can occur anywhere within the perimeter of the 2 psi zone.

1.3.4 Fireball Rise and Stabilization

The fireball of a nuclear detonation is essentially a hot buoyant bubble of air, and it begins to rise immediately after detonation. In a matter of seconds, the fireball of a 1-Mt burst attains a vertical velocity exceeding 100 m/sec. The rising sphere becomes unstable, deforming into a torus that later defines the mushroom cloud cap. The initial upward rush of the fireball creates a strong suction beneath it. At ground level in the vicinity of the explosion, the surface winds reverse direction within a second from outward, due to the blast wave, to inward, due to the fireball rise and suction. This reversal is called the negative pressure phase. The air drawn up behind the fireball forms the stem of the mushroom cloud and contains debris initially raised from the surface by the thermal pulse and blast wave.

The fireball stabilizes when its temperature and pressure become equal to those of the ambient atmosphere. Hence, fireball rise is influenced by the local atmospheric temperature structure and humidity. For explosions of less than 100 kt at mid-latitudes, the nuclear cloud stabilizes almost entirely within the troposphere (the well-mixed atmospheric layer extending from the surface to the tropopause at about 10–15 km altitude at mid-latitudes). For explosions of greater than 100–200 kt, the fireball penetrates into the stratosphere (the thermally stable atmospheric region extending from the tropopause to 50 km altitude). A 1-Mt explosion cloud would be expected to come to rest just within the stratosphere at mid-latitudes. For yields greater than 100–200 kt, the cloud stabilization height scales approximately as $Y^{0.2}$, where Y is the yield in megatons (Glasstone and Dolan, 1977). Because limited data are available from high-yield nuclear test explosions at middle latitudes, the cloud heights obtained by interpolating observations from low and high latitudes (and calibrating against limited hydrodynamic model calculations) can be uncertain by as much as several kilometers.

1.3.5 Nitrogen Oxide Production

Nitrogen oxides (NO_x) are produced when air, which consists primarily of N_2 and O_2, is heated above approximately 2000°C and then cooled rapidly. This can occur in two ways in a nuclear explosion: when air is compressed by the passing shock wave, and when air is entrained into the rising central fireball. On average, about 1×10^{32} NO_x molecules are generated for each megaton of explosive yield. The photochemical effects of this NO_x are discussed in Chapter 6.

1.3.6 Water Bursts

Nuclear explosions on water surfaces are similar phenomenologically to explosions on land surfaces. Here, water instead of soil is entrained by the fireball, and surface waves can be generated. Deep underwater explosions produce a shock wave with a greater peak overpressure and shorter duration than an equivalent shock wave in air at the same range. As in underground explosions, underwater bursts also create an airblast whenever the fireball breaks through the surface. In addition, wave trains carrying up to 5% of the original explosion energy can be generated. Waves with heights of ten meters or more can propagate away from the explosion site. These waves could cause significant destruction, particularly if they were to propagate into estuaries or harbors.

1.4 RADIOACTIVITY

1.4.1 Origins of Nuclear Radiation

In a nuclear detonation, several types of energetic ionizing radiation are produced:

1. Prompt (fast) neutrons which escape during fission and fusion reactions.
2. Prompt gamma rays created by fission/fusion processes, including neutron capture and inelastic scattering, and by early fission-product decay.
3. Delayed gamma and beta radiation from induced activity in materials bombarded by prompt neutrons.
4. Delayed gamma and beta radiation emitted through the decay of long-lived radionuclides (lifetimes greater than minutes) produced by nuclear fission and carried in the bomb residues.

At Hiroshima and Nagasaki, where the nuclear detonations were of relatively low yield, the prompt neutrons and gamma rays had important effects on survivors of the heat and blast within a few kilometers of ground zero. However, for greater yields, the prompt radiations still do not propagate beyond a few kilometers because of their strong attenuation over such pathlengths in air. Thus, with existing nuclear weapons, greater concern centers on the delayed nuclear radiation of fallout debris.

When a typical fission or fission-driven fusion weapon detonates, several hundred distinct radionuclides are generated (Glasstone and Dolan, 1977). These unstable species decay at different rates, emitting gamma rays and beta particles in the process. Inasmuch as gamma rays readily penetrate through both air and tissue, they pose a hazard even at a distance. On the other hand, beta particles are not nearly as penetrating, and thus pose a danger principally when the particle sources are close to living tissues (either externally or internally).

The fission radionuclides associated with fallout consist mainly of refractory elements that readily condense on particle surfaces as the fireball cools. Hence, any dust or debris entrained into the fireball is likely to be contaminated with radioactivity. The largest debris particles fall out quickly, while the smallest ones can remain aloft for months or years. The initial rapid deposition of the radioactive fission debris, or fallout, represents the most serious threat of delayed radiation. By contrast, gaseous radionuclides produced by fission and fusion (e.g., carbon-14 carried in carbon dioxide, and tritium carried in tritiated water vapor) and fission fuel residues (i.e., ^{235}U and ^{239}Pu) are less important, but not negligible.

The standard measure of exposure to radioactivity is the rad, equivalent to the absorption of 0.01 Joule of ionizing radiation per kilogram of material (Glasstone and Dolan, 1977). The rem is a biological dose unit equal to the absorbed energy in rads multiplied by a "relative biological effectiveness" factor for a specific type of radiation compared to gamma radiation. For gamma rays, X-rays, and beta particles, units of rads and rems are approximately equivalent. The term "whole-body" radiation is applied in cases where the entire organism is exposed to a (fairly) uniform external radiation field. For gamma rays, which are quite penetrating, all cells and organs are affected by exposure to whole-body radiation.

The impact of a radiation dose also depends on its rate of delivery. Roughly 450 rads delivered at the surface of the body within a few days time (an acute whole-body dose) would be lethal to half the exposed population of healthy adults; 200 rads would produce radiation sickness but would not by itself be lethal (Glasstone and Dolan, 1977). Such total exposures spread over a period of months or years (a chronic dose) would not cause acute effects, but would eventually contribute to a greater frequency of pathologies such as leukemia, other cancers, and birth defects. A far more comprehensive discussion of the biological effects of ionizing radiation is given in Volume II.

1.4.2 Radioactive Fallout

The Bravo nuclear test (15 Mt surface burst, Bikini Atoll, March 1, 1954) was the first to create serious fallout problems. Inhabitants of Rongelap

Atoll, which was downwind of the explosion, were inadvertently exposed to intense nuclear radiation (Figure 1.5). Even though they were evacuated soon after the event, the Marshall Islanders received substantial external and internal radiation doses—none lethal (Glasstone and Dolan, 1977). A Japanese fishing vessel, the Lucky Dragon, also found itself under the fallout plume. The fishermen, unaware that the white ash-like fallout was dangerous, took no special protective measures, As a result, one died of the exposure and a number of others received acute doses of several hundred rads.

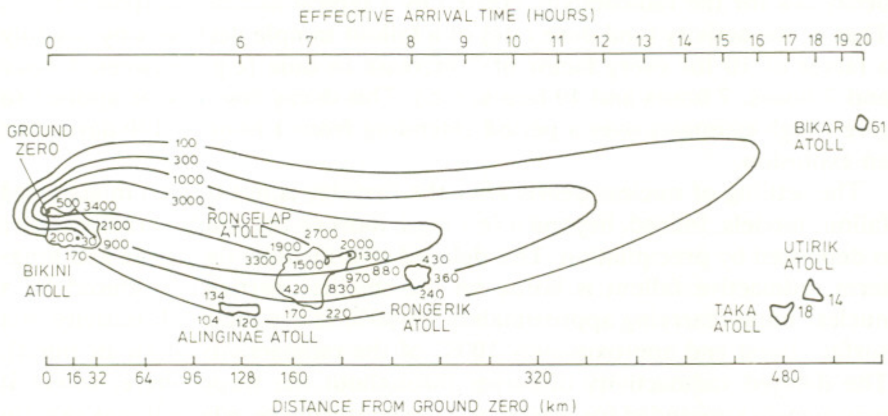

Figure 1.5. Contours of total (accumulated) fallout radiation dose in rads for continuous exposure up to 96 hours after the Bravo test explosion (15 Mt surface burst, March 1, 1954). One rad is equivalent to the absorption of 0.01 joule of radiation per kilogram of matter. The doses corresponding to longer exposure times (beyond 96 hours) would be greater than those shown (from Glasstone and Dolan, 1977)

The approximate pattern of radioactive fallout caused by the Bravo test, reconstructed from fallout measurements, is shown in Figure 1.5. The general pattern is typical of that expected for a surface detonation, although wide variations could occur in specific meteorological situations. The zone of potentially lethal radioactive fallout (for individuals continuously exposed to the fallout for up to 4 days) extended several hundred kilometers downwind of the Bravo test site, and covered an area of perhaps 5000 km^2. The doses illustrated in Figure 1.5 correspond to external exposure to whole-body gamma radiation. Shielding would have reduced the actual dose, although longer exposure times would have increased the dose. Additionally, there is a chronic internal radiation dose associated with the fallout due to ingestion and inhalation of radionuclides with food, water, and air. The most important of the ingested radionuclides are ^{131}I, ^{90}Sr, ^{137}Cs and ^{140}Ba (Glasstone and Dolan, 1977). Most of these elements tend to accumulate in specific internal organs (e.g., the thyroid for ^{131}I), which may thereby receive chronic doses exceeding the whole-body external dose (Lee and Strope, 1974).

Data obtained during the nuclear test series of the 1950s and 1960s (data such as that in Figure 1.5) have been used to construct standard fallout models for nuclear surface explosions (Glasstone and Dolan, 1977). These empirical radioactivity models account for the rate of fallout of contaminated debris, the decay in activity of the radionuclide mixture comprising the fallout, and the integrated exposure to the emitted gamma rays over time. For land surface bursts, approximately 40–60% of the fission products fall out the first day, constituting the early or local fallout. The approximate decay law for the radioactivity created by a typical nuclear weapon is $t^{-1.2}$. That is, the activity (and dose rate) of a fallout sample decreases by roughly a factor of 10 for every factor of 7 increase in time (e.g., between 1 hour and 7 hours, 7 hours and 49 hours, etc.). This decay law may be applied to give rough estimates over a period extending from 1 hour to 180 days after an explosion.

The settling of nuclear debris after the first day is not treated in standard fallout models. Indeed, beyond a few days, most of the residual radioactivity is deposited by precipitation. This delayed intermediate time scale and long-term radioactive fallout is borne on the smallest particles produced by a nuclear burst (carrying approximately 40–60% of the total radioactivity of a surface burst and approximately 100% of the radioactivity of an air burst). The delayed radioactivity disperses throughout the troposphere, where it may remain suspended for weeks, and the stratosphere, where it may remain for months to years (Glasstone and Dolan, 1977).

The potential radiation doses from intermediate time scale and long-term fallout are smaller than those from early local fallout because the contaminated debris is diluted over a wider area and the radioactivity decays significantly before it reaches the ground. In the long term, ^{90}Sr and ^{137}Cs are the primary sources of lingering radioactivity, with both radionuclides having a half-life of about 30 years. Because the threat of delayed contamination extends over years or decades, and the long-lived fallout may be concentrated in "hotspots" caused by precipitation and local deposition patterns, the incremental health effects of widespread fallout should not be ignored.

Detailed estimates of potential fallout areas and radiation doses in a major nuclear exchange are provided in Chapter 7. Further descriptions of the related phenomenology are also given there.

1.5 EFFECTS OF HIGH ALTITUDE NUCLEAR EXPLOSIONS

1.5.1 Electromagnetic Pulse

A nuclear explosion above an altitude of 40 km can expose a large area of the Earth to an intense pulse of electromagnetic radiation. The physical origin of the electromagnetic pulse (EMP) is illustrated in Figure 1.6.

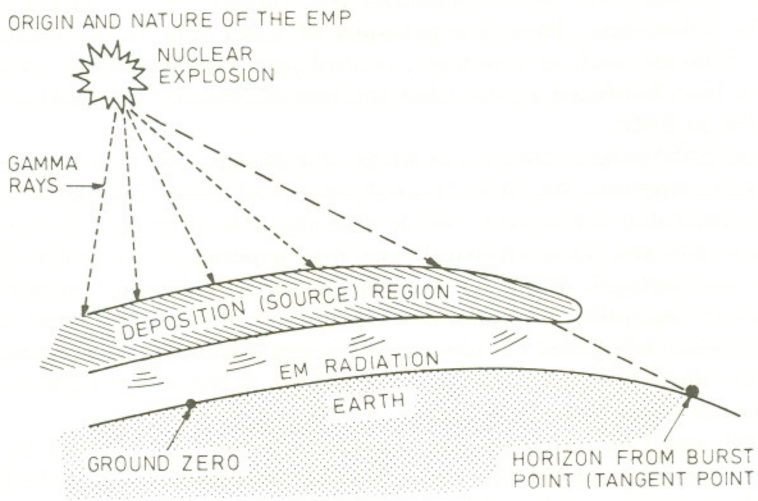

Figure 1.6. Schematic representation of the electromagnetic pulse (EMP) created by a high altitude nuclear explosion. The gamma rays emitted at the instant of detonation are absorbed in the stratosphere (the deposition region). The absorption process releases Compton electrons, whose intense currents are deflected by the geomagnetic field, creating powerful electromagnetic radiation fields (from Glasstone and Dolan, 1977)

The prompt gamma radiation from a burst above 40 km is absorbed in the Earth's atmosphere at heights of approximately 20 to 40 km. This deposition region for gamma rays is also the source region for EMP (Glasstone and Dolan, 1977). Through collisions with air molecules, the gamma rays produce high energy Compton electrons. The Compton electron currents interact with the Earth's magnetic field, thereby generating electromagnetic fields that propagate (toward the surface) as a coherent pulse of electromagnetic energy. Because the rates of gamma ray emission and deposition are so rapid, the electromagnetic pulse has an extremely short rise time (a few nanoseconds) and brief duration (a few hundred nanoseconds). The magnitude of the EMP is limited primarily by the enhanced electrical conductivity of the atmosphere caused by secondary electrons released in collisions of Compton electrons with air molecules. Nevertheless, EMP field intensities can reach several tens of kilovolts per meter over the exposed areas of the Earth. The electric field strength of the pulse can therefore be 10^9 to 10^{11} times greater than typical field strengths encountered in radio reception (Wik et al., 1985). The nuclear EMP frequency spectrum is also very broad and covers the entire radio frequency communication band.

Other forms of EMP include magnetohydrodynamic EMP (MHD-EMP), which can induce quasi-D.C. currents in very long conducting structures, and low altitude EMP, which generates very intense fields over distances of several kilometers. These are generally of lesser importance except in specific instances such as command, control and communication facilities that have been hardened against blast and thermal effects but might still be vulnerable to EMP.

Nuclear EMP induces currents in all metallic objects, which by accident or design act as antennas. Aerial and buried power and telecommunication networks in particular can collect considerable amounts of energy. Even short radio antennas and other electrical lines may experience unusual induced currents and voltages. The collected EMP energy could upset, breakdown, or burn out susceptible electrical and electronic components. Today many systems contain integrated circuits and other semiconductor devices that are subject to failure at very low energy surges (down to the order of a millionth of a joule for short pulses) (Wik et al., 1985).

In 1958 and 1962, high-altitude nuclear tests were carried out by the United States over the Pacific Ocean. During these events, some electrical and electronic systems suffered functional damage or operational upset, even hundreds of kilometers from the test sites (Glasstone and Dolan, 1977). No open reports exist on possible EMP effects during similar tests in the U.S.S.R. Lacking detailed observations, it is difficult to assess with a high degree of certainty the impacts that nuclear EMP might have on modern electronic hardware.

Apart from the difficulties inherent in designing accurate experiments of EMP effects over large spatial volumes, there are serious difficulties in applying theoretical models and calculations to real systems, which are exceedingly complex and undergo frequent modification. Most research on EMP is also classified and unavailable for analysis.

It is unlikely that EMP would incapacitate all of the exposed communication systems, power networks, and electronic equipment. However, a small number of failures distributed through a large and complex system can disrupt the entire system, or degrade its stability and performance. In this regard, power and communication networks are particularly susceptible. Moreover, the ability of nuclear power stations to withstand nuclear EMP effects safely is undetermined (Wik et al., 1985).

EMP could create confusion and isolation at precisely the time when critical decisions would have to be made regarding the use of nuclear weapons. Communications among diplomats, political leaders, and military commanders could be disrupted. EMP could also degrade sophisticated military command, control, communication and intelligence (C^3I) systems within minutes of the first detonations. Such effects could hinder a military response and/or might encourage looser control over nuclear weapons in the field.

Strategic nuclear C^3I systems are being "hardened" against EMP. At the same time, enhanced EMP weapons are being considered. Hence, the question of survivability of critical C^3I systems remains unresolved. Because telecommunications would play an important role in national and international crisis management, any major disruption of communication networks could affect the course of a nuclear conflict.

Space has a growing role in military planning for communication, navigation, and surveillance missions. Possible future deployments of space-based defensive systems against intercontinental ballistic missiles may imply an increasing potential for multiple explosions at high altitudes (tens to hundreds of kilometers) in a nuclear conflict. Hence, the importance of EMP interactions and other high-altitude effects of nuclear explosions may be increasing.

1.5.2 Radiowave Propagation and Satellite Systems

Nuclear explosions in space can disturb radiowave propagation in a number of frequency bands from tens of hertz (Hz) to tens of gigahertz (GHz). Shortwave radio signals can be degraded by power absorption, and microwave signals by phase scintillation. A high-altitude nuclear burst increases the background electron and ion densities and causes large- and small-scale structural modifications of the ionosphere (as well as longer-term chemical changes). Thus, communication, navigation, and intelligence systems may be affected intentionally or unintentionally by nuclear bursts in space. The radiowave propagation and absorption effects can lead to black-outs lasting for several hours in certain frequency bands, especially those used for long-distance high-frequency radio communications. The potential distortion of satellite signals traversing the ionized layers created by high-altitude nuclear bursts is still uncertain. Geosynchronous satellite communications near the horizon, grazing the ionosphere, at frequencies above 10 GHz might also be at risk (Wik et al., 1985). In addition, nuclear explosions would create interfering bursts of intense radio-frequency noise.

In outer space, communication satellites and other electronic systems could be exposed to direct nuclear radiation at considerable distances from a high-altitude burst. Penetrating radiations (gamma rays and X-rays) can interact with various materials to produce strong electromagnetic fields that may be incapacitating. This interaction is termed System Generated EMP (SGEMP). Space systems could also be affected by dispersed EMP (DEMP), which is associated with the propagated and reflected (dispersed) fields of the usual EMP generated by a high-altitude explosion.

Transient-radiation effects on electronics (TREE) are caused when the prompt gamma rays, neutrons, and X-radiation of a nuclear detonation interact directly with electronic parts. Transient, and sometimes permanent, changes can occur in the performance of semiconductor and optical components. For example, high-energy neutrons can displace atoms in a crystal lattice and create disabling defects. Hardening of satellites against TREE is difficult because shielding is limited by weight, and newer electronic circuits have often proven to be more vulnerable than older components (Wik et al., 1985).

The Earth's natural ionosphere and electron belts would be greatly perturbed by the widespread ionization and hydrodynamic motions associated with high-altitude nuclear explosions. Enhanced electron concentrations could be generated that might persist for months or years. Satellites operating within the enhanced ionization belts would suffer accelerated degradation due to intensified bombardment by energetic charged particles.

1.6 RESUMÉ OF NUCLEAR EFFECTS

In the previous sections, a general description was given of the most important physical effects of nuclear explosions. In this section, a quantitative summary of the spatial extent of these primary effects is provided as a function of weapon yield for air bursts and surface bursts. Estimates of the areas that would be subject to levels of thermal irradiation, blast overpressure, and radioactive fallout exceeding specific minimum values are given in Table 1.1. These estimates are approximate, and are presented only as rough indications of the potential impacts.

The sequence of physical effects that would accompany the detonation of a nuclear weapon is: thermal irradiation, blast, winds, radioactive fallout (particularly in the case of surface bursts), and fire growth and spread. In the explosion of a typical strategic nuclear warhead over a military or industrial target the effects of initial nuclear radiation (gamma rays and fast neutrons) and electromagnetic pulse, can generally be ignored, except in specific cases as already noted. The other nuclear effects occur in more-or-less distinct time intervals (over most of the area involved) (Glasstone and Dolan, 1977). The thermal pulse is delivered in the first 1–10 seconds. The blast is delayed by the travel time of the shock wave, and generally follows the thermal pulse; the positive duration of the blast wave lasts for approximately 1 second. Afterwinds then blow for several minutes. The most intense and lethal radioactive fallout occurs during the first hour after a surface detonation. Although many fires would initially be ignited in the ruins, it could take several hours for mass fires to develop. In the case of surface bursts, during the latter period, dense radioactive fallout would continue in areas downwind of the blast destruction zone.

From the data in Table 1.1, it can be seen that modern nuclear weapons (i.e., those having yields less than about 1 Mt) detonated as air bursts would create moderate to heavy blast damage over an area of approximately 500 km^2/Mt, and ignite fires over a similar area. In general, smaller weapons

TABLE 1.1.
AREAL IMPACTS OF NUCLEAR WEAPONS EFFECTS[a]

Yield (Mt)	Area (km^2) of thermal irradiation[b] 20 cal/cm^2	10 cal/cm^2	Area (km^2) of blast overpressure[c] 5 psi	2 psi	Area (km^2) of 450 rad fallout dose[d] 48 h	50 yr
0.1	35 (17)	65 (32)	34 (14)	100 (40)	(100)	(200)
0.3	105 (50)	190 (100)	70 (30)	200 (80)	(300)	(600)
0.5	160 (75)	290 (140)	100 (42)	300 (115)	(500)	(1000)
1.0	250 (120)	450 (220)	140 (65)	480 (180)	(1000)	(2000)
5.0	1150 (520)	2000 (950)	415 (190)	1410 (525)	(5000)	(10000)
10.0	2200 (1000)	3800 (1800)	660 (300)	2240 (835)	(10000)	(20000)

[a] Areas are given in square kilometers for airbursts and surface bursts (in parentheses); in the case of radioactive fallout, areas are given only for surface bursts (the early fallout from airbursts is negligible, and prompt and long-term radiation effects are ignored). Within the areas quoted, the magnitudes of the nuclear effects are greater than the limiting values shown above each column (e.g., 20 cal/cm^2); for thermal irradiation and blast overpressure, the limiting values apply at the perimeters of the circular contours centered on the explosion hypocenter which define the area of each effect. For example, the thermal irradiation (fluence) within the 20 cal/cm^2 contour is greater than 20 cal/cm^2, and can be much greater closer to the fireball. The data were obtained from Glasstone and Dolan (1977).

[b] A ground level visibility of 20 km is assumed. The thermal irradiance applies to a surface perpendicular to the fireball line-of-sight. In the outer 90 percent of the irradiated zone, more than 80% of the thermal energy is received before the arrival of the blast wave. The height of burst is chosen to maximize blast effects, as described in footnote c.

[c] For airbursts, the optimum explosion height has been chosen to maximize the area subject to the overpressure indicated.

[d] Areas are given only for surface bursts. No protection or shielding from fallout radiation is assumed. A fission yield fraction of 0.5 is adopted. A dose reduction factor of 0.7 is also applied for surface "roughness". The area in which an acute 48 hour whole-body dose of greater than 450 rad could be received is estimated from standard fallout patterns (Glasstone and Dolan, 1977). The area in which a long-term integrated total dose of more than 450 rad could result is also calculated from local fallout patterns. Cumulative global fallout is not included.

produce greater blast and thermal effects per unit energy yield than larger weapons. The area in which blast overpressures exceed a given value (e.g., 2 psi) scales approximately as $Y^{2/3}$, where Y is the yield in megatons (Glasstone and Dolan, 1977). The area affected by a specific minimum level of thermal fluence (e.g., 10 cal/cm^2) scales very roughly as $Y^{0.8}$ for yields between approximately 0.1 Mt and several megatons.

The areas of blast and thermal effects for surface bursts are about one-half the areas for airbursts of the same yield (Glasstone and Dolan, 1977). Surface bursts also create large local areas of potentially lethal radioactive fallout. Doses of up to 450 rad in 48 hours are possible over an area of approximately 1000 km^2/Mt in the fallout plumes. Lesser doses occur over much larger areas. The problem of accumulated radiation doses in overlapping fallout plumes is discussed in Chapter 7.

1.7 INTEGRATION OF EFFECTS

Previous sections of this chapter have focused on the effects of individual nuclear explosions, particularly the effects that might be relevant to an assessment of global physical and biological impacts. The effects of nuclear detonations are fairly well characterized by theoretical principles and by measurements taken during nuclear tests. The unique experiences at Hiroshima and Nagasaki have led to a general consciousness of the magnitude and power of nuclear weapons.

The damage areas summarized in Table 1.1 imply that approximately 6,000 Mt, which is less than the current world nuclear stockpile, could destroy, through direct effects alone, an area of up to about 3×10^6 km^2, assuming no overlap. This is equivalent to about 2–3 percent of the total land area of the Northern Hemisphere. Major urban zones occupy approximately 1 percent of the landmass (NRC, 1985), and thus would be directly vulnerable if attacked. Nevertheless, as will be discussed in later chapters and in Volume II, the survival of global civilization may be more dependent on the indirect effects (e.g., climate change) caused by nuclear explosions than on the direct effects (e.g., blast). The occurrence of indirect effects is obviously related to the occurrence of direct effects, which are manifested by the generation of smoke, dust, and radioactivity.

In order to integrate the individual weapons effects discussed here into a global model of the aftermath of a nuclear war, a number of additional pieces of information are needed:

1. A scenario for the nuclear exchange, including the weapon sizes, targets and heights-of-burst.
2. The physical state of the target zones, including adjacent combustible fuels, soil characteristics, and local meteorological conditions.

3. Descriptions of related physical phenomena, including fire growth and spread, smoke production and properties, microphysical evolution of smoke and dust aerosols, chemical responses, and so on.

In subsequent chapters, much of the required information is developed to the extent that is possible given current scientific knowledge, and to a depth that is consistent with the goals of this report. A detailed integration of these individual nuclear effects would require an enormous research effort and would be impractical at this time. Accordingly, the approach taken here is to consider, in each chapter, the essential global-scale consequences of specific effects of nuclear weapons; for example, fire damage in cities, climatic effects of smoke clouds, and contamination by radioactive fallout in a nuclear exchange. This approach emphasizes the plausibility of specific impacts, as well as the range of potential outcomes.